THE CHORNOBYL ACCIDENT REVISITED: SOURCE TERM ANALYSIS AND RECONSTRUCTION OF EVENTS DURING THE ACTIVE PHASE

by

ALEXANDER ROMAN SICH

B.S., Rensselaer Polytechnic Institute, Troy, N.Y., USA
(May 18, 1984)

M.A., Harvard University, Cambridge, MA , USA
(November 17, 1992)

SUBMITTED TO THE DEPARTMENT OF NUCLEAR ENGINEERING
IN PARTIAL FULLFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

January 1994

© Massachusetts Institute of Technology, 1994.
All rights reserved

Signature of Author: _____
Department of Nuclear Engineering
January 7, 1994

Certified by: _____
Dr. Norman C. Rasmussen
Thesis Supervisor

Certified by: _____
Dr. Alexandr Alexandrovich Borovoi
Thesis Supervisor

Accepted by: _____
Dr. Allan F. Henry
Chairman, Departmental Graduate Committee

MASSACHUSETTS INSTITUTE
OF TECHNOLOGY
JAN 31 1994

ERRATA

It has been called to my attention that the initial core inventory of yield of Cs-136 (169 MCi) as calculated by the British codes CACHE and WIMS (see section VI.2.2. "Chornobyl Unit-4 Core Inventory Calculation") is seriously in error.[1] Upon investigation, it appears the source of the error is in the codes: because Cs-136 is a special case (so-called shielded nuclide) and comes largely from the activation of Cs-135, only a small contribution arises from fission. Apparently, the codes do not take this into account. Using the cumulative fission yield of the 136 mass chain yields an incorrect result since the chain terminates at the stable nuclide Xe-136 that, of course, does not decay to Cs-136. The initial inventory of Cs-136 in previous studies is estimated to be in the range of 2.2 to 3.6 MCi, so that a relatively good estimate should be about 3.0 MCi.

It should also be noted that the assumption implied by the table that I-131 and I-133 have the same fractional release is only true if the total iodine release takes place over a time period short compared to the 20.8 hour half-life of I-133. From measurements taken shortly after the accident, it appears that a large part of the core's iodine inventory was released in the first day. If this is not the case, then a correction must be made for the I-133 released. As a bounding case, assume that all the iodine is released in 20.8 hours so that to a rough approximation one-half of the I-133 decays before it can be released. The true value of the release should lie somewhere between 67.7 MCi and 33.8 MCi. An average of these bounding values yields a total release of 50.8 MCi. The uncertainty noted here combined with the uncertainty in values for the release fractions shown in Table VI.15 (although, as emphasized in the text of the dissertation, these are *conservative* release fraction estimates) produce a substantial uncertainty in the iodine release value.

---

[1] The incorrect inventory appears in the following tables:

Table VI.1	column: "Core Inventory at t = 0"
Table VI.2	column: "Core Inventory at t = 0"
Table VI.4	column: "Current 1993"
Table VI.15	column: #4 "Activity"
Appendix VI.B	column: "Activity [t = 0]"

Taking these changes into account, Table VI.15 has been altered and is shown in its revised form on the third page of this errata. As a rough estimate, the release value is approximately 120±50 MCi for the three volatile elements iodine, cesium, and tellurium. This still contrasts significantly with the Soviet *total* release value of 50 MCi (which includes the three elements considered in the table plus others). One may therefore conclude roughly (albeit biased toward a lower release – see Chapter VI) that the *total* activity released into the environment as a result of the Chornobyl accident was approximately 150±50 MCi MCi – more than three times that reported by the Soviets. Moreover, this result agrees with the central argument of the thesis that (1) significantly more radioactivity was released because the core was not covered during the approximately ten-day period of the Active Phase of the accident (Chapter IV), (2) the results of radiochemical analyses indicate that approximately 65% of the initial radiocesium core inventory was released from the solidified corium (Chapter V) implying that possibly an even greater fraction of radioiodine was released, (3) western suspicions that more volatiles must have been released from an accident the magnitude of Chornobyl based solely on physico-chemical principals.

Alexander R. Sich
Cambridge, MA
21 July 1994

Table VI.15

Estimated Activity Releases from Chornobyl
[radionuclides with significant half-lives ($t_{1/2} \geq 1$ day)]

1	2	3	4	5	6	7	8	9	10	11	12	13
Basic / Initial (t = 0) Data				**Fuel-Containing Materials (FCMs)**				**Central Hall & Outside Reactor Building**				**Total**
Isotope	Half-life	Activity (MCi)	Mass (kg)	fractional contribution	fractional release	fractional (1 - plateout)	release (MCi)	fractional contribution	fractional release	fractional (1 - plateout)	release (MCi)	**Release (MCi)**
Ru-103	39.25 d	102	3.2	0.71	0.95	??	??	>0.2	??	??	??	**??**
Ru-106	372.56 d	23.2	7.0	0.71	0.95	??	??	>0.2	??	??	??	**??**
Te-129m	33.6 d	28.1	0.93	0.71	(0.50)	(0.5)	5	>0.2	(0.30)	(0.9)	1.5	**6.5**
Te-132	78.03 h	121	0.40	0.71	(0.50)	(0.5)	21.5	>0.2	(0.30)	(0.9)	6.5	**28**
Te-134	41.8 m	208	0.006	0.71				>0.2				
I-129	1.57 e7 y	(2.0 e-6)	(11.3)	0.71	(0.50)	(0.5)		>0.2	(0.50)	(0.9)	–	–
I-131	8.04 d	83.2	0.67	0.71	(0.80)	(0.5)	23.6	>0.2	(0.50)	(0.9)	7.5	**31.1**
I-132	2.284 h	121	0.012	0.71				>0.2				
I-133	20.8 h	181	0.16	0.71	(0.80)	(0.5)	39	>0.2	(0.50)	(0.9)	11.8	**50.8††**
I-134	52.6 m	208	0.008	0.71				>0.2				
Cs-134	2.062 y	4.6	3.5	0.71	0.65	(0.5)	1.1	>0.2	(0.30)	(0.9)	0.2	**1.3**
Cs-136	13.16 d	3	0.003	0.71	0.65	(0.5)	0.7	>0.2	(0.30)	(0.9)	0.02	**0.7**
Cs-137	30.0 y	7	80.4	0.71	0.65	(0.5)	1.6	>0.2	(0.30)	(0.9)	0.4	**2**
Cs-138	32.2 m	177	0.004	0.71				>0.2				
Cs-139	9.27 m	167	0.001	0.71				>0.2				
Total		**1435**	**96**				**92**				**28**	**120 ± 50**

NOTE: Figures in parentheses are conservative estimates; shaded radionuclides have ($t_{1/2} < 1$ day).

Columns 4 – 7 FCM = Fuel-Containing Materials, i.e., that portion of the core currently located in the lower regions of the reactor building.

Columns 8 – 11 Central Hall & Outside Reactor Building = that portion of the core located on the floor of the Central Hall, outside the reactor building but within the bounds of the station, and beyond the bounds of the station.

fractional contribution Mass fraction of the entire core contributing to this release.

fractional release Fractional release from that portion of the fuel (as obtained or estimated from chemical analyses).

fractional (1 - plateout) release Fraction that escaped from the fuel and debris into the environment.

= (Initial Activity) 3 (fractional contribution) 3 (fractional release) 3 (fractional (1 - plateout)).

†† I-133 roughly estimated considering a substantial release (within one day) and radioactive decay.

THE CHORNOBYL ACCIDENT REVISITED: SOURCE TERM ANALYSIS AND RECONSTRUCTION OF EVENTS DURING THE ACTIVE PHASE

by

ALEXANDER ROMAN SICH

Submitted to the Department of Nuclear Engineering on January 7, 1994
in partial fullfillment of the requirements for the degree of
Doctor of Philosophy in Nuclear Engineering

ABSTRACT

Accident Management Actions (AMAs) taken during the first days after the Chornobyl accident either proved ineffective or were not fulfilled as reported by the Soviets at the IAEA Meeting of Experts in Vienna in August 1986. Most significant to source term analyses and estimates is that it is now believed at least 71% of the initial 190.3 tonne UO_2 fuel load was exposed to a high-temperature oxidizing environment because the core was neither covered with various materials thrown from helicopters to smother the fire, nor was the core purged with (liquid) nitrogen. Both these actions were originally believed (based on Soviet reports) to have effectively brought the crises to an end.

The approximately 135 tonnes of the 190.3 tonne initial core fuel load (≈71%) that melted and flowed into the lower regions of the reactor building formed various kinds of now solidified Lava-Like Fuel-Containing Materials (LFCMs or corium). A more precise core inventory estimate and radiochemical analyses reveal that only 5% of the corium's inventory of Ru-106 was retained – the balance appears to be contained in a solidified metal layer located below the corium. Moreover, a surprisingly high 35% of the corium's inventory of Cs-137 was retained. These analyses also support the fact that little if any of the over 5020 tonnes of materials dropped from helicopters during the Active Phase ever made it into the core area – there is virtually no lead or boron found in the matrix of the corium. The results also support earlier western source term estimates that significantly more volatile radionuclides may have been released as a result of the accident than reported by the Soviets in August 1986.

Presented also are the results of a refined core inventory calculation that incorporates individual fuel channel burnup values, and that accounts for the core's axial flux distribution and its impact on the non-linear accumulation of transuranics. Reviewed are far-field release measurements and their inconsistency with initial Soviet reports, and these are compared against preliminary results of radioisotopic analyses of Fuel-Containing Masses (FCMs) found within the sarcophagus. Newly available release-rate data for a number of fission products are introduced, and source term release curves over the Active Phase (t = 0 – 10 days) for these fission products are presented and compared to previous models. A lower bound for the release of the three volatile elements iodine, cesium, and tellurium is estimated to be approximately 185 MCi – significantly higher than the 50 MCi total release presented by the Soviets at Vienna in August 1986. A possible sequence of events is postulated for the Active Phase of the accident.

Thesis Supervisors:

Dr. Norman C. Rasmussen	Title: McAfee Professor of Nuclear Engineering
Dr. Aleksandr Aleksandrovich Borovoi	Title: Director of the Department of Radiation and Nuclear Safety of the Ukrainian Academy of Sciences's Inter-Branch Scientific and Technical Association "Shelter", Chornobyl, Ukraine; Head of the Division of Radiation Research Methodologies and Technologies, Kurchatov Russian Research Center, Moscow, Russia

Thesis Readers:

Dr. David D. Lanning	Title: Professor of Nuclear Engineering
Dr. Scott A. Simonson	Title: Assistant Professor of Nuclear Engineering

ACKNOWLEDGMENTS

May I share with you one of the principles that governs my life? It is the realization that what I receive I must pass on to others. The knowledge that I have acquired must not remain imprisoned in my brain. I owe it to many men and women to do something with it. I feel the need to pay back what was given to me. Call it gratitude.

– Elie Wiesel

This dissertation could not have been written without the help of many people to whom I am indebted. Although the research and writing were quite independent and oftentimes solitary, the spirit of this undertaking was more corporate than individual in character. As such, by its very nature this dissertation can amount to little more than the sum total of the opportunities for research, study, reflection, and writing placed at its my disposal by those to whom it is my first duty to praise. I cannot, of course, evade in this way a personal responsibility for its defects. But whatever information, knowledge, and even a tiny bit of wisdom it may be found to contain is due, in largest measure, to those in whose company it was made so agreeable to aquire. There are innumerable friends, colleagues, and acquaintances over the course of my one and one-half year stay at Chornobyl who generously shared their views and offered advice. Unfortunately, because memory fails to serve me, not all can be named. To those whom I have not cited here by name, I offer sincere apologies.

I would first like to thank my parents, Dr. Dmytro and Mrs. Oksana Sich as well as my grandmother, Mrs. Natalia Vlasov, for the love, support, and boundless patience shown through thirteen and one-half year of higher education. They never permitted their modest means to become a barrier that could have obstructed my aspirations and strivings to surpass even my wildest dreams. Most importantly, though, I am grateful to them for

gently instilling in me a deep love for a батьківщина (homeland) I was only able to see for the first time when I was twenty-eight years old.

My wife, Nataly Maria, and two sons, Markian Dmytro (who was born in Ukraine) and Matthew Peter, deserve special thanks for enduring difficult living conditions, physically exhausting and seemingly incessant travel, and long periods of separation from our families in the United States. My wife is, in the fullest sense, a hero and dearest companion. Shortly after we married, she gave up her personal ambitions to follow me to Ukraine, and directed her energy, patience, and unending love toward raising our children and supporting her husband. Through the completion of this project and beyond, it has never ceased to amaze me how she could have remained cheerful and supportive despite having sacrificed so much quality sleep time to keep the children from crying during the middle of the night so that daddy could be well rested for work. There are no words to express my gratefulness for her devotion, support, and self-sacrificing love. Markian's giggles were also especially valuable. Through them he continuously reassured me and helped me to focus my energies onto the task at hand, while at the same time keeping my thoughts and prayers dedicated to the most important thing, next to God, in my life – my family. Finally, I must praise little Matthew for being a generally happy baby – somehow realizing that his father and mother needed to sleep at night.

This project actually had its genesis during summer following the Chornobyl accident. Dr. Lubmyr Hajda, then of the Russian Research Center and now of the Ukrainian Research Institute at Harvard University, challenged an eclectic group of mostly undergraduate students (attending his seminar on Soviet nationalities) to complement their current work with a Master's degree in Soviet Studies. It was this challenge that sparked in me the dream to study the accident from the perspective of both a nuclear engineer and a Sovietologist. I owe him a debt of gratitude – the fruit of his advise has yielded a M.A. in Soviet Studies and, in part, a Nuclear Engineering Ph.D. thesis.

By prayer and by deed my Harvard graduate student roommate of approximately five years, Borys Gudziak, gently supported me through the intellectually stimulating though exhausting graduate programs at MIT and Harvard. His quiet example demonstrated the far more important Truth we ought to strive for in our intellectual pursuits – whatever those pursuits may be. Moreover, that Borys was able to endure the quirky insecurities of a sometimes pesky and prank-filled roomate, outrageous "moon statements," my "don't you touch those" high-tech toys, and the incessant use of the word "very" are certainly to his credit. My sole regret is that because of his patience and sacrifice, he only managed to earn a degree from the "second-best institution of higher learning on Massachusetts Avenue!"

I am especially grateful for the help provided by Professor Bohdan Ivanovych Sokolovskyj of the L'viv State University. Professor Sokolovskyj was called to help in the Chornobyl accident mitigation efforts during the first few months after the accident as a materials specialist. The important scientific contacts he made during his stay in the 30-kilometer exclusion zone were of paramount importance to me: it was he who arranged for my first visit to the zone in October 1991 where he introduced me to my future dissertation advisor, Alexandr Alexandrovich Borovoi. Only toward the end of my stay did I begin to understand how much behind-the-scenes maneuvering had taken place (initiated by Professor Sokolovskyj) to keep me "safe and sound" at Chornobyl despite the interference of certain bureaucrats for whose best interests my presence and "poking around" were not tolerable. Moreover, this dissertation would not have seen the light of day without Professor Sokolovskyj's optimism and gentle but persistent prodding. For him (as for many others), helping a westerner gain access to Chornobyl and the "secrets" it contained was seen as part of the larger struggle to free Ukraine from the Soviet occupation of their homeland. I am at the same time very proud and yet profoundly humbled to have taken a small part in this monumental struggle and to have helped Ukrainians such as Professor Sokolovskyj achieve their dream.

Several members of the small group of researchers at Chornobyl deserve special recognition. For more than a year and one-half they tolerated the idiosyncrasies of an American graduate student whose inquisitiveness at times stretched their ability to answer my endless stream of questions. These scientific colleagues and *druzi* (Ukrainian for *deepest of friends*), Sergei Bogatov, Alexander Yevstratenko, Alexandr Kheruvimov, Yura Cherepantsev, Edvard Denysenko, Konstantin Checherov, Boris Gorbachev, Edvard Pazukhin, Alexandr Ivanov, Viktor Popov, and Alexandr Surin made the research portion of my stay a fruitful and fulfilling adventure. Thanks to them, life in the zone was not all work. These friends also made an oftentimes difficult life at Chornobyl quite enjoyful. I shall never forget and will be eternally gratefully to them for sharing with me humorous stories and anecdotes, swimming at the indoor pool at Prypjat, saunas and mineral water at Chornobyl, tea and candy (and sometimes a nip of vodka!) during breaks, showing interesting "things" in the zone by sneaking me around when I lacked the proper permission, and for enduring MASH 4077-like meals together at the *Energetic* cafeteria. My gratitude and thoughts will always be with them and with all the researchers at Chornobyl. To themselves, their efforts may appear trivial and unappreciated. As far as I am concerned they are no less heros than the firefighters who gave their lives containing the radioactive fires of the accident.

If there is one person to whom I can point to as the one rightly deserving recognition for making this dissertation possible, it would have to be my thesis co-supervisor and Head of the Division of Nuclear and Radiation Safety at Chornobyl, Dr. Alexandr Alexandrovich Borovoi. Without his gentle guidance and assistance, this dissertation would have remained an unfulfilled dream. Dr. Borovoi deserves particular credit for allowing me unrestricted access to all the data available at Chornobyl along with access to the station, the destroyed Unit-4 and its sarcophagus, and other areas of the 30-km exclusion zone surrounding the station. His main concern is to understand the accident and to learn from it as much as possible; and he is a man dedicated to the love of his intellectual life – physics. He is also an

ethnic Russian to whom Ukraine and its people should be grateful for spending many long years in relative obscurity sequestered in the 30-km exclusion zone investigating the accident. Dr. Borovoi is one of the most modest people I've ever met. While some of his collegues in Moscow and Kyjiv may enjoy the limelight and recognition that is based mostly on his group's work, Dr. Borovoi is content to remain quietly dedicated to his work. In fact, he knows more about the consequences of the accident within the 30-km exclusion zone than anyone else. Moreover, although certainly frustrated by the bureacracy, politics, and self-interest on both sides, he remains far above the petty frays raging between advocates and opponents of nuclear energy.

I will be eternally grateful for the concern, interest, and support provided by Monsignor Ivan Dacko, Reverend Kenneth Nowakowsky, and others at St. George's Cathedral in L'viv. The Ukrainian Greek-Catholic Archeparchy's extensive computing facilities enabled me to complete a significant amount of work on this dissertation while in Ukraine. Andrij Tymchuk, Roman Hera, Andrij Olinyk, Volodja Hykavyj, and others at the Church's Publications, Information, and Architectural Divisions provided access to the computers, printers, and scanners during very odd hours.

I am particularly grateful for the kindness and hospitality offered my family by Halja, Volodja, and Olena Sokolovskyj. Even though they only have a two-room apartment, they kept me warm, dry, fed, loved and provided me with a "base of operations" during my frequent visits to Kyjiv over the last few months of my stay. Their neighbors and other people that visited shared with me, usually through tears, stories of how Chornobyl has affected life in Kyjiv ever since the accident. As laypersons they offered a unique perspective from which to understand the accident's impact on the average Ukrainian citizen.

I consider it an honor and a priviledge to have had as my disseration co-supervisor at MIT Professor Norman C. Rasmussen. Professor Rasmussen is a unique individual – not only as concerns his renowned nuclear engineering expertise, but also because of his genuine care and concern for students. The excitement he expressed at my having managed to

get into Chornobyl, his early realization of the significance of the findings contained in this disseration, his gentlemanly demeanor spiced with dry wit, and his willingness to cover my travel expenses (as well as those of Dr. Borovoi who, as a result, was able to attend my defense), reflects the character of a truly great man.

The erudite nuclear engineering scholars, Professors David Lanning and Scott Simonson, gave a final reading to the thesis – saving me the embarrassment of some errors. Their superb attention to engineering detail helped turn this dissertation into a first-class piece of work. They also gently toned down the anger (directed at those who took advantage of the accident) that popped up from time to time in the text. Additionally, I cannot forget the help and advise of Professor Larry Lidsky who encouraged the writing of this preface to express my sentiments and share my experiences at Chornobyl with other nuclear engineers.

I would like to thank several members of the Nuclear Engineering Department's secretarial and support staff for their interest in this project and for their administrative and moral support throughout. Clare Egan, Elizabeth Parmelee, Gloria Rook, Anne Hudson, John McGuire, Sonia White, Paula Cornelio, David Dorr, Pat Reeves, Linda Arduino, and Jennifer de Vries Gwinn helped me to remain excited about the work (even though at times it looked far too overwhelming to complete successfully) and listened to some of the horror stories about life in the former Soviet Union.

I want to briefly thank a number of people for all the "little things" they helped me with during my stay in Ukraine, and without whose help this dissertation would have barely turned out to be a meager and colorless report. I thank Chrystia Freeland, correspondent in Kyjiv for the *Financial Times of London* for helping me gain access to people and places; and Marta Kolomayets, correspondent in Kyjiv for *The Ukrainian Weekly*, for a place to crash and for listening to my gripes about life in Ukraine. For access to and help in obtaining important photographs from the archives of the Kurchatov Institute in Moscow, I will always be grateful to Valentine Ivanovich Obodzinskyj. Special thanks to Rostyslav Ivanovych Hrynjuk and others at the Dispatcher Division of Ukrainian Ministry of Energy and

Electrification for allowing me access to the archives and energy records in Kyjiv. I will be always grateful for the fantastic humor as well as the solid support of the First Deputy Minister of the Ukrainian Chornobyl Ministry, Borys Samojilovych Prister. Mykola Deychakiwsky saved me a tremendous amount of time and grief by allowing me to photocopy documents at his office. Because of their direct and early involvement in the mitigation efforts, Serhij Vasyl'ovich Shirokov, Vadym Vasyl'ovych Hryshenko, and Nikolai Aleksandrovich Shteinberg shared with me their very interesting and unique perspectives on the accident. Thanks to Anatolij Stroganov for running the burnup codes that produced the core inventory estimates. Oleh Vojtsykhovych arranged for a thrilling yet sobering helicopter tour of the 30-km exclusion zone that broadened my appreciation for the devastation caused by the accident. I am grateful to Gary Dunbar, Executive Vice-President of Los Alamos Technical Associates, for pulling me out of a financial crisis by taking me on as a consultant for his company, and for being a great person to work for. Sasha Stoljarov in Kyjiv deserves a medal for cutting through the murkiest of bureacracies to obtain letters of support and visas for me. I am thankful to the support staff at Chornobyl for keeping my house clean, helping me avoid some of the worst features of the "bureacratic mafia," and for "wheeling and dealing" to get me information otherwise impossible to obtain. Tania Pryakhina's deep love for her homeland and native tongue helped me to capture the essence of my emotions in the dedication. Finally, the illustrations in this dissertation would have been of sub-standard quality if it were not for the kindness of Professor Ronald Ballinger. Although not connected with this project, he endured frequent interruptions and graciously permitted me to invade his office at odd hours to scan photographs and print the draft and final versions of the dissertation.

This Page Has Been Left Intentionally Blank.

PREFACE

Exploiting Fact, Fiction, and Fear

> *Even when the facts are available, most people seem to prefer the legend and refuse to believe the truth when it in any way dislodges the myth.*
>
> – John Mason Brown

Recent developments in the (former) Soviet Union mark the beginning of an era of new political, cultural, social, scientific, and economic potential. The dramatic changes in Eastern Europe (which now includes several newly-emerged countries that previously made up the Soviet Union) constitute a break with the patterns and realities of the preceding decades. For the nuclear engineer, the closure of this historical interval creates new opportunities, setting before him or her the task of making sense of previously inaccessible information on the Soviet nuclear energy industry, and in particular, studying the consequences of the accident at the fourth unit of the Chornobyl Nuclear Power Station.

This dissertation, which endeavors to clear up some of the confusion and obfuscation surrounding the Chornobyl accident, and to bring to light new data and evidence recently made available, is unusual in scope and content. It is, first of all, the culmination of eight years of graduate studies at the Massachusetts Institute of Technology and Harvard University – the synthesis of an independent interdisciplinary program that spanned subjects as diverse as Soviet Studies and Nuclear Engineering, and introduced me to the world of critical intellectual inquiry under the tutelage of some of the most knowledgeable and respected researchers in their respective fields. Second, it reflects scientific research on the world's worst commercial nuclear power accident conducted during one of the most interesting and

trying periods in modern history – the turmoil leading up to and following the collapse of communism in Eastern Europe and the dissolution of the Russian-Soviet Empire. Finally, for researchers it serves as a reference to literature and people in the hope that others may have a guide through the layer upon layer of the poorly organized, ideologically encumbered, overly-bureaucratized, and somewhat suspicious character of scientific research in Russia and Ukraine.

Getting invited to work at Chornobyl was itself an arduous, albeit interesting adventure that began in August 1990. In the end, it was not my own or other people's interest in supporting research on the accident but rather "who I knew" that opened doors. From the onset I suspected more was at stake than just a doctoral research project. For example, upon my arrival in the 30-km exclusion zone in October 1991 (five and one-half years after the accident), I was surprised to learn that I was to be the first western scientist invited to live and research the accident in the town of Chornobyl – I had had no predecessors, and for the duration of my stay, I had no western colleagues with whom to corroborate my findings. In fact, the situation remains the same to this day; and it is indeed disturbing that almost eight years after the accident, the first and only nuclear engineer from the West permitted to conduct research at Chornobyl was an American graduate student.

It is true that the (former) Soviets had a notorious history of discouraging contacts with western specialists except on the "official" level, and of not revealing relevant data or not allowing access to it even to their own investigators – let alone to foreign researchers. However, the economic, political, and social instability in the former Soviet Union (especially the rapid political changes leading to its demise), although complicating my attempts to make contacts with the relevant people, at times actually enabled me to take advantage of the confusion and even to enter the 30-km exclusion zone with little effort. Ultimately, by invitation from the Head of the Scientific Division of the then *Chornobyl Complex Expedition* under the Kurchatov Institute of Atomic Energy in Moscow (later reorganized and renamed the *Inter-Branch Scientific & Technical Center "Shelter"* under the Ukrainian Acade-

my of Sciences) Professor Alexandr Alexandrovich Borovoi, I became a member of the Expedition as a "scientific co-worker" or research associate. This presented an unparalleled opportunity to work directly with scientists most intimately acquainted with the accident.

On and off for more than a year and one-half I was sequestered within the 30-kilometer exclusion zone surrounding the destroyed reactor working with poorly equipped scientists and technicians, tracking down and reviewing obscure Soviet preprints, photographs, laboratory reports and analyses, oftentimes incorrect reactor building and construction plans, helicopter-pilot logs, and talking with witnesses and participants in the accident cleanup effort – all while the political and economic world around the zone was collapsing. In contrast with initial expectations, I was given unrestricted access to virtually all parts of the zone – including operating and abandoned units, radioactive material and machinery dump sites, and to the infamous fourth block with its sarcophagus. Although at times some "wheeling and dealing" was necessary to acquire it, all Soviet data and literature on the accident located *in the zone* were made available for examination.* I had access to scientists at research institutes in Moscow, St. Petersburg, Minsk, and Kyjiv. Moreover, late night conversations over *horilka*† (Ukrainian vodka) with colleagues in the zone – some of whom have worked there since a few days after the accident – have broadened my appreciation of the human side of the Chornobyl accident. These sincere personal accounts, although not readily adaptable to computer data banks, brought to light aspects of the accident that are all too often ignored by some researchers for want of "hard evidence." (To gain this insight I found it advantageous, at times, to avoid some of the overly-conservative qualifications academic training usually carries with itself.) And so, because of the unique social and political environment in which research for the project was undertaken, I feel compelled to round out this dissertation in a rather lengthy preface by sharing with nuclear engineering colleagues and others in the West my experiences in Ukraine.

---

* Unfortunately, much valuable information remains inaccessible as part of the former Soviet Government's Chornobyl Commission archives – including important parts of Academician Valerij Legasov's personal journals.

† *horilka* — in Ukrainian, "little one that burns."

All too often, in my experience, Sovietologists and the anti-nuclear power elite alike have failed to understand the technical aspects of nuclear issues and how they influence governmental policy and the decision-making process. On the other hand, most technical experts do not have the necessary background in Russian or Ukrainian history, culture, and politics to place these technical issues in proper perspective. This has impressed upon me the need to consider the affect of Soviet energy policy (in particular, Soviet safety "culture") as a vital factor influencing the Soviet nuclear energy industry, and to determine to what extent this influence may have paved the way for an accident such as Chornobyl to have occurred in the former Soviet Union. The West may profit greatly by not focusing only upon the technical aspects of the accident (which has limited impact on the public in the current debate over nuclear energy safety) but by also paying more attention to the cultural and political influences that led to the accident – and this will ultimately shed more light upon the germane question, "Could a Chornobyl-type accident occur in the West?"

Truly Winston Churchill's assertion that Russia [the Soviet Union] is [was] a riddle wrapped within a mystery shrouded by an enigma is even more relevant today when *peoples* of the former Soviet Union themselves are coming to terms with a past either skewed to reflect communist ideology, or, as was usually the case, simply concealed from them.[1] The Chornobyl accident is only one of many misfortunes altered by official Soviet government policy to shape public perceptions. Naturally, the question then arises whether Chornobyl was representative only of the nuclear power industry in the former Soviet Union; or does this accident perhaps point to even deeper, more fundamental problems that faced Soviet society? It is convincingly argued now, for example, that because Chornobyl brought to the surface many – but far from all – of the injustices, inefficiencies, and secrets of the Soviet system, it was a watershed event that forced then General Secretary Gorba-

[1] Václav Havel has observed, "It is truly astonishing to discover how, after decades of falsified history and ideological manipulation, nothing has been forgotten. Nations are now remembering their ancient achievements and their ancient suffering, their ancient suppressors and their allies, their ancient statehood and their former borders, their traditional animosities and affinities – in short they are suddenly recalling a history that, until recently, has been carefully concealed or misrepresented." [Václav Havel, "The Post-Communist Nightmare," *New York Review of Books*, May 27, 1993.]

chev to strengthen his commitment to *glasnost* or "openness."[2] The accident exposed glaring weaknesses in the Soviet system: its backward technology, its sloppy safety standards, its inability to admit failure. Gorbachev was thus left with little other than to prove to the West his sincerity and dedication to reform by more fully implementing his policy of *glasnost.* This policy, in turn, was a major factor that led to the demise of the communist system and the USSR – a system that was fundamentally at odds with freedom of expression and accessible information. Chornobyl occurred in a secretive society; and secrecy is not compatible with the safe management of complex technologies because engineers need information if they are to learn from their mistakes.

Inasmuch as this is a technically-based nuclear engineering dissertation, it is not the intent here to definitively address, let alone to answer, these social and political questions. It is also unrealistic to afford (for those interested in deepening their appreciation of cultural and political influences upon the Soviet nuclear industry) the benefits of immersion in a Ukrainian cultural milieu for extended periods of times. It is for this reason I want to share the benefits of my experiences at Chornobyl in the hope that some light may be shed upon these cultural factors. I hope to call attention to the more essential and unique aspects of political and cultural life in Ukraine – the non-quantifiable so-called *human* aspects – with the ultimate hope of increasing understanding among researchers studying the accident and the Ukrainian nuclear energy industry.

* * * * *

It is difficult to understand the mentality of the average Ukrainian or the depth of traumatization when he or she calls to mind Chornobyl. Many discussions (especially among the elderly or less informed people in villages all over Ukraine and Belarus) concerning mishaps or illnesses and even bad weather – things unrelated to the Chornobyl ac-

[2] See David Marples, *Ukraine Under Perestroika: Ecology, Economics, and the Workers' Revolt,* New York: St. Martin's Press, (1991): xv, 135–136, 171–174, 218–224.

cident – in one way or another are blamed on the accident. Fear of the accident's effects permeate everyday life. Most Ukrainians still fiercely cross-examine vegetable and fruit vendors to ensure their food does not come from anywhere near Chornobyl. Moreover, to properly grasp the impact of Chornobyl, one must also take into account other misfortunes and tragedies that have occurred on Ukrainian soil and that have left the people psychologically and spiritually exhausted. The twentieth century alone for Ukraine has been a succession of human disasters: World War I, the failed war for independence, and an artificially produced famine (1914-1922 – approximately 1.5 to 2.0 million lives lost);[3] dekulakization and the collectivization campaign which resulted in an artificial famine that physically and morally destroyed the peasantry – the very basis of Ukrainian society (at least five million victims of starvation in 1932-33 and an additional three million deaths attributable to the deportation of the *kulaks* (allegedly prosperous peasants) in 1926-37);[4] the great purges of the thirties that obliterated the vast majority of the political, intellectual, and cultural elite; the Second World War (estimates for the number killed or taken as slave laborers or prisoners of war – including Ukrainian Jews and Gypsies – range from seven to ten million);[5] the liquidation of the Ukrainian Orthodox Church in 1926 and the Ukrainian Greek-Catholic Church in 1946; the post-war Stalinist repressions and deportations of large segments of the Ukrainian population to Siberia and the Far East; and a new wave of repressions during the Brezhnev period from the late sixties to the early eighties. It is not surprising, therefore, that Ukrainians view the Soviet legacy with an emotional intensity not unlike that of Jews contemplating Nazi Germany, or as blacks considering the South African policy of apartheid.

---

[3] Roman Serbyn, "The Famine of 1921-1923: A Model for 1932-1933?" in Roman Serbyn and Bohdan Krawchenko, eds., *Famine in Ukraine, 1932-1933*, Edmonton: Canadian Institute of Ukrainian Studies (1986): 147-148.

[4] In their fanatical drive to collectivize the land, Soviet officials branded anyone opposed to their policies as a "kulak". This eventually led to labeling anyone owning one cow or horse as a kulak. [Robert Conquest, *The Harvest of Sorrow – Soviet Collectivization and the Terror-Famine*, New York, Oxford: Oxford University Press (1986): 299–307.]

[5] Yury Boshyk, ed., *Ukraine During World War II: History and its Aftermath*, Edmonton: Canadian Institute of Ukrainian Studies, University of Alberta (1986): xiii.

Apart from the physical destruction, for more than seventy years Ukrainians were also inculcated with a materialist philosophy and a Marxist-Leninist ideology which sought to create a new Soviet culture and nation. Fueled in part by Russian nationalism, this self-congratulatory propaganda was generally primitive but over the decades not completely ineffective. Although people learned to accept skeptically the content of the ideological message, Soviet concepts and ways of behavior were, by the time of the collapse of the system, largely internalized and to a great extent determine the people's subconscious or conscious mental categories. For example, up until just four years ago the Christian, Jewish, or Muslim calendars were not vital. Time was marked by a series of Soviet political holidays. Lent or Passover was a time which had meaning for one's grandmother or great-grandmother. Ukrainian culture and history, when not expropriated by the Russians, were subjugated to the goal of building a "greater and brighter" Communist future; while the Ukrainian language was relegated to the status of a village tongue not worthy of use by the "serious" citizens. Ethical behavior, although somewhat influenced by regional traditions, was not defined by a higher good but by a morally bankrupt official ideology.[6]

The chauvinistic tactic by Russians to "Sovietize" (read: "Russify") other cultures and languages has had tragic consequences. The Belarusian language, although trying to recover from these policies, is rarely heard now even in Belarus itself. In Ukraine, although the situation is not as bad, most of the citizens of the Ukrainian capital, Kyjiv, speak Ukrainian with some difficulty. In fact, Ukrainian was reinstated as the state language of Ukraine as late as on January 1, 1990. There was particular intense pressure generated by Soviet rule to assimilate, and nowhere was the policy of Russification more prevalent than in the areas of language and publications. According to the 1989 Soviet census, only 50.8 percent of the population of the Soviet Union was Russian. Yet, of the 2.2 billion books printed in the USSR in 1986, 86 percent were in Russian while only 14 percent were in the over 100 non-Russian languages. In Ukraine (a nation with a population of approximately

[6] In part, paraphrased from the keen observations of Borys Gudziak in an unpublished memorandum he prepared on the basis of an IREX-sponsored research stay in Ukraine during the first half of 1988.

52 million or 18% of the former USSR's population), during the 1980s only one hundred magazines were published in Ukrainian. In the RSFSR alone, Russians had *fourteen times* as many periodicals to choose from in their native language as the Ukrainians did. The situation was far worse in the Central Asian republics, where in some cases Soviet officials altered national alphabets. In the case of the Uzbeks, for example, a Turkic-based alphabet had its letters "cyrillicized" to look more like Russian letters.[7]

My training in Sovietology did little to prepare me for the level of Russian chauvinism I encountered during the almost three years I lived in Ukraine and while visiting other republics of the former Soviet Union. For example, the belittling of the Ukrainian language and "village" customs on an almost daily basis in eastern Ukraine and in the Crimea, and the crude jokes about its very existence as an independent state by many (though not all) Russians even in Ukraine's capital, Kyjiv, are just a few of the tormenting barbs Ukrainians continue to put up with for fear of appearing "nationalist" and "discriminatory" before a world community that understands little of what Ukraine has faced from Russia over the course of the past three hundred years. On the daily interpersonal level, these verbal assaults upon their homeland do nothing to allay the Ukrainian's fear of Russian aggression – not to speak of outright aggression and provocation in the Baltics, Moldova, Georgia, and the Black Sea Fleet. (Unfortunately, in isolated incidents not indicative of the general population in Ukraine, Russian provocations have sparked responses from Ukrainian nationalists that are equally reprehensible.) On the official level, inflammatory and threatening statements against Ukrainian sovereignty and independence by members of Russia's government and parliament (not only by the anti-semitic Russian ultra-nationalist Vladimir Zhirinovsky, but also by Russia's Foreign Minister Andrei Kozyrev[8]) strengthen the Ukrainian lawmaker's conviction that Russia will not quickly rid itself of a deeply-

---

[7] See the stunning account of Russification in the section "The Politics of Culture" in Nadia Diuk and Adrian Karatnytsky, *New Nations Rising: The Fall of the Soviets and the Challenge of Independence*, New York: John Wiley & Sons, (1993): 50–55.

[8] Kozyrev told reporters that Sevastopil, home port of the Black Sea Fleet in the Crimea, Ukraine, has always been a Russian base and would remain so. *Radio Free Europe/Radio Liberty Daily Report*, December 7, 1993.

rooted complex of imperialism. Although certainly not commendable, it is then understandable why Ukraine may be attempting to hedge its nuclear bets by imposing strict conditions on the transfer and destruction of its nuclear weapons.

The destruction of personal ethics and "cultural ethnocide" was exacerbated by a political, economic, and social system which bred dishonesty and corruption, punished originality and ingenuity, and rewarded lack of character and unscrupulousness. For every goal or task there was an official means or channel for its realization which was bound to fail without the requisite bribe or favor in return. The average citizen was, and continues to be, demoralized by the economic hardships, endless queues, housing shortages, periodic unavailability of everyday necessities, scandalous medical treatment, and ubiquitous bureaucratic harassment. The result of all of these social pressures is the spiritual and moral impoverishment of all but the most vigilant, and courageous citizens of the former USSR.

Finally, the Communist economic and social system led to the ruin of the work ethic. Communism is in essence a radical egalitarianism which interposes the state between the individual and the consequences of his actions. In return for cushioning him or her from the privations of failure, the state demands he or she shall never enjoy the rewards of success by subordinating this success to the glory of the state. An honest worker could hardly expect a just reward for his work. The typical worker came home at the end of a long day thoroughly exhausted knowing little of lasting value had been accomplished – pride in one's work became an anomaly. Dishonesty, speculation, theft, and corruption resulted and became the primary means of securing basic needs for everyday life. Lying became a way of life. By being forced to take part in this unprincipled struggle for existence, moral bankruptcy, apathy, and even psychological damage naturally followed. Because the system for so many years took advantage of and manipulated people on the basis of demagogic slogans (e.g., *With An Iron Hand We Will Drive Mankind to Happiness!),* it undermined respect to lawful authority. Everyday interpersonal relationships become artificially strained by the suspicion of hidden motives. Bickering and complaining over the most innocuous

things became a way of asserting one's demand for respect as a human being. Unfortunately, as a result of constantly being forced to defend one's dignity against a demeaning system and the society it has created, the typical Soviet citizen learned to wield power arbitrarily (no matter how little of it he or she has) to ensure all persons share his or her misery – perpetuating this humiliating cycle.

These simple, often neglected, *human* aspects of everyday life in the former Soviet Union served as major factors that influenced and even produced problems more easily suited to quantification and scrutiny in formal policy studies. The Chornobyl Power Station was no stranger to personal workplace problems. For example, a young man who worked at the Chornobyl Station complained about the low morale among the work force, "Our socialist democracy has provided Soviet man with one unusual advantage, among others, which is not normally discussed. It is very difficult, and sometimes impossible, to dismiss a rank-and-file worker, even if he is an idler... The trade union becomes involved and even the legal organs, demanding that the person should be re-educated, that he should be defended. A worker can be dismissed only after he has received three reprimands in the course of a year, and these reprimands must be uncontested and not subject to appeals. However, a manager can be dismissed from his job without any reprimands."[9] Almost exactly one month before the accident, an article appeared in a major Ukrainian newspaper, forewarning about the possibility of more serious problems arising at the station, brought to light the fact that the station's work force was demoralized and fed up struggling with humiliating bureaucratic trivialities, labor discipline was poor, and that there was a chronic shortage of essential equipment and building materials – due as much to theft as to the inefficient industrial supply system.[10]

* * * * *

[9] "The System Failures," *Soviet Labor Review* , Vol. 4, No. 2 (July 1986): 5.

[10] Любов Ковалевська, «Не приватна справа...,» *Літературна Газета*, (27-го березня 1986): 1.

Because the system encouraged it, by the time of the Chornobyl accident Soviet citizens had become masters at avoiding accountability for mistakes and failures. To anyone who has lived and worked in the former Soviet Union for any length of time, perhaps no other statement best captures the essence of this lack of responsibility as one made by a NIKIET* specialist whose organization was pressed into service to aid in clean-up and accident mitigation efforts. After their team arrived at the site and reviewed the extent of the damage, one of the engineers is alleged to have caustically remarked, "This is no longer a nuclear reactor. Our expertise is in nuclear reactors... so let others clean it up."[11]

And so began an accident containment and mitigation effort ostensibly portrayed as one of the most difficult and heroic engineering tasks ever undertaken. In reality, the period to the end of November 1986 during which the sarcophagus was constructed may best be categorized as an inept and reckless desire to conceal the extent of the accident – this despite the fact that unwitting "volunteers" (including former Soviet dissidents and political prisoners forced into clean-up operations) risked their lives in several ineffective accident management actions. In fact, some of those who are charged with investigating leading Soviet officials who took part in the creation of this modern-day "Potemkin's village" argue that the accident, ensuing clean-up efforts, and the cover-up brought together, at one time and in one place, an incarnation of all the "evil" in the former Soviet system.

For possibly the first time since World War II, the accident also forced into contact the two major social strata in Soviet society – the *nomenklatura* and the everyday citizen – so that the public man and woman (at least those taking part in the cleanup effort) were able to witness how decisions were made at the top. For those who had a real and selfless desire to help, Chornobyl revealed the corruption and incompetence of an upper caste of rulers who

---

* NIKIET – (Научно-исследовательский и конструкторский институт энерготехники) the Moscow-based Scientific Research Institute of Power Engineering headed by Yevgenij Olegovich Adamov is the primary designer of RBMK reactor series.

[11] Although it remains undocumented, several researchers in Moscow, Kyjiv, and Chornobyl have shared this anecdote with me – and based on my experiences there, I find no reason to believe that it is not true. Much of what is portrayed in this preface, in fact, has come from long hours of lending a sympathetic ear to those who, even if they were a direct part of the system, felt obligated to share some of their bitter criticism of the system in the wake of the accident.

long before the accident had lost interest in the average person's welfare. This ruling elite became desensitized by comfortable and protected lifestyles far removed from the everyday realities of Soviet life. Its ability for critical self-examination was dulled by a system that promoted avoidance of all too obvious problems and getting along with those in power above them. It soon became clear to those who tried to help with the accident and its consequences that these "leaders" were more concerned with how the accident might threaten their cushy lifestyles, than with the safety and welfare of the general public; and it was for this reason they had to downplay and cover-up the consequences of the accident.

The USSR Governmental Chornobyl Commission (headed by Deputy Chairman of the USSR Council of Ministers, Borys Yevdokimovich Shcherbina)† was formed during the morning of April 26, 1986, and in a manner that resembled a cry to arms, rallied major Soviet organizations and people to mitigate the consequences of the accident. Although the Commission was formed early on, it was quite clear that no concrete emergency plans had been formulated – no one was prepared to respond to an accident of this magnitude. According to Serhij Vasyl'ovich Shirokov,* it was not until midday (but more likely early evening) on Sunday, April 27 (at least 36 hours after the accident) that anyone had any *official* idea what had happened. People from the station had surveyed the remains of the reactor building in the early morning hours of April 26th, but either were afraid to report what they thought had happened or simply were not believed. The Deputy Minister of the Ministry of Energy and Electrification, Gennadij Shasharin, through most of the first day

† Other members of the Commission were the USSR Minister of Energy and Electrification, A.I. Majorets; First Deputy Minister of the Ministry of Medium Machine Building (*MinSredMash*), A.G. Meshkov; First Deputy Chairman of the USSR Atomic Energy Oversight Committee (*Gosatomenergonadzor*), V.A. Sidorenko; Deputy Minister of the USSR Ministry of Internal Affairs, V.I. Drugov; First Deputy Minister of the USSR Ministry of Health Protection, Ye.I. Vorob'ëv; Head of the Main Administrative Division of the USSR Committee of State Security (KGB), F.A. Shcherbak; Deputy Attorney General of the USSR, O.V. Soroka; Deputy Chairman of Ukrainian Council of Ministers, N.F. Nikolajev; Chairman of the Kyjiv Olbast Executive Committee, I.S. Pljushch; Chairman of the USSR Central Committee's Trade Union of Electrical Energy Stations and Energy Technologies Industry, N.P. Simochatov; and from the USSR Academy of Sciences, Valerij Alexandrovich Legasov. Note that only one of the twelve members of the Commission was a scientist – the rest were government bureaucrats and administrators.

* At the time of the accident, Head of the Nuclear Energy Division of the Ukrainian Ministry of Energy and Electrification. Taken from a personal conversation March 29, 1993.

thought the core was being effectively cooled by water. Unfortunately based on this and other incomplete information, Moscow central authorities did not immediately sense the urgency of the situation and delayed, for example, the evacuation of residents from the thirty-kilometer exclusion zone for fear of inciting "panic."

After the first attempts by local firefighters to contain the more than thirty fires burning in the area of Unit-4 had proved successful, efforts were then directed at stopping the continuing release of radionuclides into the surroundings. For example, a siege mentality was employed to rally workers to smother the still-raging fire (the infamous "red glow" thought to be the reactor core) within the reactor building. The most startling revelations, however, are that the over 5,000 tonnes of materials dropped by helicopters over the burning reactor core from the second through the seventh day after the accident never entered the core shaft; and that an attempt to cool the core as well as to displace oxygen with (ostensibly) liquid nitrogen most likely occurred *after* the end of the Active Phase.† The implication of the fact that these attempts failed is that approximately seventy-one percent of the core (≈135 tonnes) burned virtually in the open for nine days until it melted through the lower part of the core region, flowed downwards along piping of the Pressure Suppression System, and quickly solidified. (As suspected by some in the West, considerably more radioactivity was released into the atmosphere than previously reported – see Chapter VI). These findings undermine one of the central tenets of the official version of the Chornobyl clean-up campaign: the cult of the brave Chornobyl helicopter crews who took actions meant to put out the fire, and whose youthful deaths are honored by a special museum in Kiev. Clearly, these "liquidators" truly were brave and selfless. They were also, unfortunately, used by Soviet authorities to create an impression (for their own peoples and for the West) that something was being successfully done to contain the accident.*

---

† Both these measures were credited by the Soviets in Vienna in 1986 as having effectively "smothered the fire, and cooled and sealed the core." The section on "Accident Management Actions" in Chapter IV will review in detail the mostly failed attempts by the Soviets to mitigate the consequences of the accident, how these failed efforts are seriously affecting cleanup work today, and why western post-accident analyses based on the success of these efforts are flawed.

* Academician Valerij Legasov, head of the Soviet delegation to Vienna in August 1986, when faced

The mistakes and deception, however, did not stop at this. There seemed to be an overriding desire by the Soviet government to convince the peoples of the Soviet Union and of the world that things were under control, and that the heavily damaged reactor building was isolated. As it was being constructed (and even to this day), the most visible and attention-drawing symbol of triumph over the accident – the sarcophagus – was constantly portrayed as a tremendous concrete-and-steel engineering achievement[12] that tightly retained radioactive debris protecting the surrounding environment from further releases, and that there was a complete accounting of the initial inventory of fuel and fission products.[13] The net effect was to draw attention away from the affected people and extensive contamination of the environment – including great tracts of agricultural land – and focus it

---

with the fact that releases of radioactivity began to increase on April 30th and May 1st and that mitigation efforts were apparently unsucceful in stemming these releases, is reported to have exclaimed in exasperation, "The people would not understand. We have to be seen doing something!" [Piers Paul Read, *Ablaze*, New York: Random House, (1993): 133.] Academician Legasov committed suicide by hanging himself at home on April 26, 1988 – two years to the day after the accident.

In retrospect, given the chaotic situation western efforts may have been similarly desparate and confused, although more forthright.

[12] Indeed, one Soviet preprint (internally published) actually calls it "the concrete cube 'sarcophagus'" [Л. М. Векслер, В. К. Попов, "Авария на Чернобыльской АЭС и её уроки (1986 – 1990)," (припринт) Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990.] This myth was propogated in the Soviet press which was later carried into the western press. The amount of concrete *claimed* to have been used to construct the sarcophagus ranges from 300,000 to 410,000 cubic meters. However, if one simply takes the cube root of this range of values, the dimensions of a pure block of concrete with these volumes would be in the range of 66.9 to 74.3 meters on a side! This is larger (and certainly taller) than the current sarcophagus – which is mostly empty space (see Figures V.5b and V.6b) even if one considers the reactor building itself. The actual amount of concrete used was approximately 161,000 cubic meters – a great deal of which leaked through holes in the reactor building out onto the immediate grounds of the station. See the following references:

(a) Ацуми Коди (Асахи), «Хотя зарплата высока – трудности с набором кадров,» в Г. Малкин (составитель), *Ядерный след*, Москва: Энергоатомиздат, (1990): 47.

(b) «Нет ничего, что бы побредило народу,» в Александр Коваленко и Юрий Рисованный, Чернобыль – Каким его увидел мир, Киев: Издательство ЦК ЛКСМУ «Молодь», (1989): 88.

(c) Zhores Medvedev, *The Legacy of Chernobyl*, New York: W.W. Norton and Company, (1990): 80.

(d) Harold Denton, "The Causes and Consequences of the Chernobyl Nuclear Accident and Implications for the U.S. Regulation of Nuclear Power Plants," *International Energy Seminar on, "Chernobyl: The Implications for Nuclear Power and the International Nuclear Regime,"* Johns Hopkins Foreign Policy Institute, Washington, D.C., (July 9, 1986): 10. as referenced to Richard Masters, "Chernobyl Has Less-Than-Expected Impact on Orders and Future Plans," *Nuclear Engineering International*, (June 1987): 28.

[13] Academician Spartac Timofeëvich Belayev (of the Kurchatov Institute and Chairman of the Inter-Branch Coordinating Council Regarding Chornobyl Scientific Problems in the Presidium of the USSR Academy of Sciences) in a *Pravda* article states quite categorically that 185 tonnes (>97%) of nuclear fuel are contained within the sarcophagus (В.С. Губарев, И. Камеока, И.К. Лаговский и др.; Сост. Г. Малкин, *Ядерный след*, Москва: Энергоатомиздат, (1990): 49–50). Yet, in September 1991 he "corrects" himself by stating that in the haste to construct the sarcophagus in an extreme radiation environment, there was no way to estimate how much fuel there was and where it was located. (Bill Thomson, "International Effort Needed On Sarcophagus," *Nuclear Engineering International*, (September 1991): 17).

upon the monolith representing "victory" over the accident. The Soviet leaders themselves wanted more than anyone else to believe that most of the contamination was contained within the sarcophagus – and so the stage was set for the creation of a myth that would remain unquestioned for several years.[14]

"They should have given a little thought to the problem before acting so haphazardly," is the restrained but oft-repeated assessment of the Governmental Commission's methods to mitigate the consequences of the accident. Rather than carefully thinking through whether to "launch a series of immediate attacks" (in the words of one of my colleagues)† to contain the accident – throwing at it all the forces at their disposal, the leaders intentions were dictated by the passion to remain in control. Rather than waiting for several months after the releases had stopped (to permit short-lived isotopes to decay away to decrease the exposure rates in the extreme radiation environment and to carry out thorough dust-suppression work), people were immediately pressed into projects that the leaders hoped would effectively isolate the area and remove as many traces of the accident as possible.

For example, one must question the wisdom of the construction of the 30 meter-deep, 8.4 kilometer perimeter wall in the ground known as *Casa Grande* (which was abandoned when only partially complete) surrounding the station to stop the spread of radionuclides to nearby bodies of water. This project was undertaken immediately – ignoring the pleas of chemists and hydrogeologists. Apparently no forethought given to the fact that radionuclides bind chemically in the surface layers of the topsoil. These contaminants would mi-

---

[14] To see how effective this deception was, a French radiation specialist, Professor Pierre Pellerain, commented on what he learned during a brief two-week fact-finding mission at Chornobyl: "You [Soviet scientists] have acquired a unique experience that may be used in other countries if someone else has to deal with a similar situation. In France I speak about the fact that if an accident occurs in our country, then the best advisors in the areas of technology and medicine will be Soviet specialists. As of yet, no one else has the accident mitigation experience you have." [An article entitled "Why the French Do Not Fear Nuclear Power Plants," translated from the Russian in А. А. Карасюк и А. И. Сидоренко, *Вокруг Чернобыля: диалог с учёными*, Издат (Ядерное Общество): Москва, (1991): 112.]

† This same colleague recounts how, during the hectic months of the construction of the sarcophagus, the Russian Academy of Sciences authorized even contradicting projects and solutions, once alledgedly ordering, "We should try everything because then at least something may work!" Actually, given the situation and the lack of reliable information on the state of the reactor core, this is not a bad strategy if the resources are available.

grate only very slowly through the clay and sand sublayers (that characterize the area of the station) into the ground water located approximately 15 meters below the surface at the time of the accident. In fact, seven years after the accident, measurements of radionuclide migration into the ground have shown that the vast majority of isotopes have descended to a depth of only 20 – 40 centimeters below the surface. Unfortunately, because the project was abandoned*, the partially-constructed section of the wall between the station and the Prypjat River behaves like a dam. As a result, the level of the ground water has risen to within 4.5 meters of the surface – and is actually slightly *above* the base of the turbo-generator building's foundation; i.e., much closer to the contaminants that ever would have been if the project had not been undertaken.

Another line of defense that, in hindsight, was as ineffective as *Casa Grande* was the now well-known and valient attempt by miners and engineers to construct a flat-bed heat exchanger below the foundation of Unit-4.** The reasoning was that in the event of a much feared "China Syndrome" there would be one more barrier between the ground water and the molten core. The project was completed well after the Active Phase of the accident (around May 25th); and when it was clear there was no danger of a melt-through, this was also abandoned.

No one actually knew how much nuclear fuel was inside the sarcophagus, nor did anyone know its condition well enough to predict its future behavior. Preliminary analyses of hot particles in Sweden and Germany indicated that approximately 3 – 6% of the *mass* of the core (approximately 6.7 tonnes) was released beyond the bounds of the station; and based on these results, a *decision* was made that 96.5% of the initial UO_2 190.3-tonne fuel load was located within the sarcophagus. This decision became the ultimate arbiter, the ultimate criteria to support the notion that the fuel was accounted for and tightly held within

---

* The project was abandoned because by the time the workers were ready to extend the wall further through the infamous "Red Forest," the army had not yet gotten around to decontaminating this area for them to continue escavating. One bureaucratic tie-up led to another so that the project was eventually "forgotten."

** The heat exchanger is jokingly referred to in Ukraine as the "Moonshine Still" because of its shape and function – see Chapter IV.

the sarcophagus, and it was the key bit of data by which to convince the West that everything was under control.

The Soviet leaders themselves, it seems, wanted to believe this – even if based on questionable evidence. For example, one of my colleagues recalls an incident (at the Kurchatov Institute in Moscow) in which measurement results by the *Igla* System† were presented and interpreted. According to this data it was concluded that the largest amount of fuel was contained within the reactor core area. Following this, an internal document was prepared detailing the locations and quantities of fuel within the reactor building.[15] This document, seemingly, was used to provide information to the IAEA's Meeting of Experts in August 1986. Unfortunately, not only is there almost no fuel in the reactor core area (the core shaft is virtually empty – see Chapter V), but a few years later when researchers entered the area of the Central Hall to examine more closely the remains of the reactor, the *Igla* detector wand was found to be jutting partially out of the southern spent fuel pool, approximately 12 meters from the reactor shaft, and remains there to this day (Figure IV.9).

* * * * *

† The Igla System consisted of a long (≈2 meters) wand-like detector lowered by cable from a helicopter into the reactor building. After initial results indicated a temperature of about 30°C and a dose rate of 300 R/hr, it was declared that the core was found. Someone immediately pointed out that the Igla probably did not find the fuel because much higher readings were to be expected. After an hour recess, the team came back with "new" figures: a temperature of 300°C and a dose rate of 3000 R/hr! Apparently, someone had "forgotten" to carry the decimal point. (From a personal conversation with Konstantine Pavlovich Checherov, research scientist at Chornobyl representing the Kurchatov Institute, November 1992.)

[15] *Working Document: "Project for the Entombment of the 4th Block of the Chornobyl Nuclear Power Station: Main Reactor Building (Reactor Area & Turbo-Generator Hall),"* Volume I – General Explanatory Notes, (August 8, 1986), signed by Mykhail Aleksandrovich Sedov (now general director of NVO-Prypjat) and Vladimir Aleksandrovich Kurnosov (General Director of PO-VNIPIET – The Industrial Association – (All-Union) Scientific Research and Design Institute of Power Engineering). The document states the following: "According to currently available information regarding a Kurchatov Institute letter dated July 3, 1986, the fuel is distributed as follows:

- reactor shaft, lower water communication area, spent fuel pool, steam distribution corridor, pressure suppression pool – 95%,
- Main coolant pumps and auxiliary building "V" – to 1%,
- Debris in the area of the ECCS – to 1%,
- On top of roof – to 1%.

And on page 22, the following statement is made: "... according to measurements taken of radiation fields within the reactor core area by the *Igla* system, an appraisal of the data showed that the largest amount of fuel is contained within the reactor core area, and represents 20 – 30% of the total fuel charge."

Almost eight years after the accident, Chornobyl is plagued by the legacy of the former régime whose bureaucratic inertia continues to hamper cleanup efforts and the work of scientists at the site. A word must therefore be said about the conditions under which these researchers work at Chornobyl and the problems against which they struggle everyday – problems I also have had to cope with.

One of the most persistent and, unfortunately, unchallenged myths arising in the wake of the accident is the assumption that most Soviet scientists are poor physicists and unrepenting communists whose only concern is the exploitation of nuclear energy for the glory of Soviet power at the expense of innocent lives. (One need only consider the cases of Anatolij Sharansky or Andrei Sakharov to see the fallacy of this argument.) In reality, as in many parts of the world, political agendas, rather than actual or demonstrated energy needs and safety concerns, dictate nuclear energy policy. The scientists I have worked with have either been used by some politicians as pawns in a power game, or they and their work are simply ignored. Based upon what the former Soviet Union was, it is difficult not to believe this myth because, up until the dissolution of the USSR (though somewhat less so during the period of *perestroika*), the West was carefully spoon-fed disinformation about most aspects of Soviet life – not the least of which was the Chornobyl accident. So-called scientists and medical experts, such as Yurij Izrael and Anatolij Romanenko (who now, along with Mikhail Gorbachev, are under investigation for taking part in a cover-up of the extent of the accident), constantly downplayed the extent of the accident – even when faced with contradictions in their arguments. Yet these people spent little if any time at Chornobyl studying the situation as it really was. The scientists studying the accident at the site are largely ignored, as is their work – which contradicts official assessments of the extent of the accident. This, indeed, is one of the tragedies of Chornobyl.

Although incorrect to question the competence of scientists and technicians working at Chornobyl as "physicists,"[†] it is another thing altogether to question whether or not the

[†] To people in the former Soviet Union, those with a degree in any of the "hard" sciences were considered a physicists. It is important to realize that there, the title "physicist" covers a much wider range of

proper specialists are there to tackle the specific problems Chornobyl poses. For example, a dilemma I have personally faced is getting people to understand that there exists a substantial and essential difference between "physicists" and "nuclear engineers" – at least as far as the West is concerned. The fact of the matter is that there are no nuclear engineers studying the accident at Chornobyl. None of them have any training in nuclear reactor systems (especially concerning balance-of-plant and safety systems), nor in accident and source term analysis – although most have adequate training in nuclear physics and are quite eager to learn more. For example, the director of the Division of Nuclear and Radiation Safety and my dissertation supervisor in the zone, Alexandr Alexandrovich Borovoi, is a neutrino physicist. Several of the people under him earlier were part of a research group that conducted neutrino physics experiments in a specially-equipped laboratory under one of the reactors at the Rivne Station in western Ukraine. Although these are quite competent physicists and have learned a great deal in their exploration of the remains of Unit-4, reactor safety problems and accident management questions I needed to address for this dissertation oftentimes fell on quizzical, albeit sympathetic, ears. Obviously, there are many lessons to be learned from the Chornobyl accident that may clear up severe accident analysis (especially source term) problems, and may even have a direct impact on improving the safety of western reactors. Unfortunately, this point was difficult to get across, and I found it quite frustrating conducting research independent of specialists in my own field. Information that was vital to my research, therefore, was more difficult to obtain if not somehow related to the narrower aspects of research and monitoring work at Chornobyl.††

---

specialties and competence than it does in the West.

†† Curiously, I often felt people prodding me in the right direction – no one actually came out and told me specifically what to look for. For instance, I vividly recall first finding out that the core fire had not been smothered with the materials thrown from the helicopters... and then not being able to sleep that night. It seemed to me (after being shown a number of overhead photographs of the destroyed reactor) that something was wrong with my visualization of the layout of the reactor building. I politely asked why the Upper Biological Shield was not covered by the materials even though it appeared to be resting in the mouth of the reactor shaft. It wasn't immediately obvious why, so I naturally assumed I would need to go back to better study the plans of the building. With a poor attempt at lightening the mood I jokingly asked, "Could it be that the pilots missed the core?" My collegues looked at me straight in the eyes and retorted, "What!? You mean you didn't know this?"

The conditions under which scientists work at Chornobyl can only be described as tragic. There are about thirty of them struggling with, in the words of one of my colleagues, an "invincible" bureaucracy that serves only to impede their work. Until my arrival in the Fall of 1991, no western nuclear engineer (or any scientist, for that matter) was permitted to conduct research on the accident at Chornobyl or to work directly with these scientists; and as mentioned previously, I remain the only one – although a number of ecology, radiobiology, and hydrogeology specialists from South Korea, Norway, Japan, and other states have been part in short-term research "visits" on environmental contamination and migration of radionuclides in the water and soil. However, even these research efforts, in addition to not studying the accident itself, are sanctioned under the auspices of an organization named *NVO Prypjat* – the Prypjat Scientific and Industrial Association. Formerly, this organization was called *"Kombinat"* and was created in 1987 as a division of the former Soviet Ministry of Medium Machine Building (*MinSredMash* – designers, among others things, of Soviet nuclear weapons) to conduct decontamination work and provide support services within the 30-km zone. In reality, little decontamination work has been done in the zone since the accident, while *NVO Prypjat* organizes sightseeing excursions to the sarcophagus for westerners eager to pay $100/day per person or more, and indirectly interferes in the work of scientists trying to conduct research at the sarcophagus. In addition, *NVO Prypjat*, through its International Contacts Division, portrays itself to unsuspecting Western researchers as a legitimate scientific research organization that has the authority to sponsor scientific research within the 30-km zone – again, for exorbitant fees.

Today, a brief tour of the zone will show anyone that little work has been done to properly dispose of now radioactive equipment used during construction of the sarcophagus. Located just to the west of the fourth unit is an entire field of uncovered and thus rusting contaminated machinery and supplies. Moreover, located approximately 25 kilometers southwest of the station near the small village of Rasokha are two "machine graveyards" – shopping center-sized areas full of fire trucks, military vehicles, and helicopters

used during construction of the sarcophagus and decontamination of the surroundings in 1986. All of these are contaminated and standing in the open surrounded by a double barbed-wire fence.* Even near the building where the scientists work we still see the remains of an abandoned tank-plow used to remove contaminated top soil immediately after the accident. In 1989 this Soviet firm bought expensive equipment from the Swiss to decontaminate stainless steel equipment, whose steel was then to be sold abroad at a profit, but nothing came of this (if they found out, who would buy metal from Chornobyl?) aside from a few "freebie" trips abroad for the *nachal'stvo* (bosses). Monitoring the zone has been another disappointing failure. In 1989, *NVO-Prypjat* designed a system of detectors that were to be linked by radio to a central data bank for later reporting to the government. Because of the poor quality of the detectors, to say nothing of the radio relay system, the project failed. *NVO-Prypjat* agreed to fix the detectors, but to date, nothing has come of it. The list goes on and on. In short, though articles are now written in local papers criticizing the "non" activity of this organization, the general director and his team remain in place – along with the few thousand badly utilized people who work for them – also receiving small but definite doses of radiation while there.

NVO-Prypjat's main concern seems to be obtaining hard currency. Located not far from where I lived, in a building where part of the sarcophagus construction command center was housed in 1986, is the organization's Division for International Scientific Contacts. Quite often I saw delegations from Japan, the United States, Canada, and various other countries who visit the zone for the day to discuss various proposals for research. However, as far as I could tell, no formal long-term research projects were being conducted by westerners in the zone, though the South Koreans are reportedly to begin an ecological research venture. "Visitors" to the center pay about $40 dollars per person for a bus trip from Kyjiv to Chornobyl and back (which, given local prices, was at that time

* Astonishingly, workers in the zone – including some of my colleagues – frequently cannibalize this equipment for scarce spare parts.

equivalent to spending approximately four thousand dollars for a school bus trip from New York to Philadelphia) and up to $85 per night to stay at a rather run-down dormitory located 50 km from Chornobyl in a town called *Zelenyj Mys* (Green Cape). No one could tell me to where the money was going.

I witnessed first-hand their attempts to collect money from a westerner in November 1991. Academician Ihor Rafajilovych Yukhnovs'kyj (at that time, Ukrainian presidential candidate, with my advisor from L'viv, Bohdan Ivanovych Sokolovs'kyj, and a few other specialists from Kyjiv, visited Chornobyl the same day on a pre-election fact-finding trip. Upon our arrival, Dr. Sokolovs'kyj and Dr. Borovoi were informed that I was to pay $85 per night for the "pleasure" of living at *Zelenyj Mys* and commuting into the zone every day to conduct research. Academician Yukhnovs'kyj, upon hearing of this wrote a letter to the Minister of Chornobyl, Hryhoryj Hotovchyts, granting me permission to become a member of the Complex Expedition as *their* researcher, i.e., not obligated in any way to *NVO Prypjat.*

After a somewhat pointless discussion, Yukhnovs'kyj, along with a television crew, were to be driven by car to the sarcophagus to ask some rather pointed questions about the condition of the station. The NVO-Prypjat people organized three cars: one for Yukhnovs'kyj and his aides, one for the specialists from Kyjiv, and another for the television crew. Yukhnovs'kyj and the second car departed earlier because the camera crew's car had not yet arrived. In fact, their car never arrived, and they were later asked to leave the zone. Yukhnovs'kyj's car conveniently ran out of gas along the way. If it had not been for a passing driver who siphoned some gasoline from his own truck, they never would have arrived. Though they arrived a half an hour late, they were the first ones there because the second car went by a "different" route. No television interview of Yukhnovs'kyj was ever taken at the station though two hours were wasted waiting for a camera crew that could never arrive. *NVO-Prypjat* was obviously not interested in Academician Yukhnovskyj asking the "right" questions on television.

Much of the confusion as to what organization or which branch of the Ukrainian government had authority over the exclusion zone during my stay there stemmed from the fact that the Ukrainian Parliament had not formulated a concrete policy regarding the zone and has only recently (end of January 1993) designated a specific organization or authority to administer it – the Ukrainian Chornobyl Ministry. Before this, the Ukrainian Academy of Sciences supported scientific research in the zone, *NVO Prypjat*, although having taken upon itself additional unauthorized powers, allegedly managed decontamination work and provided support services for people living in the zone. In addition, after the collapse of the Soviet Union, for a brief period the Ukrainian Atomic Energy Concern, *UkrAtomEnergo-Prom*, had authority over the remaining operating RBMK units and the station's grounds. The newly-formed Ukrainian State Committee for the Utilization of Atomic Energy has taken over *UkrAtomEnergoProm's* responsibilities; however, since the Ukrainian government has not established a concrete energy policy, the powers of this committee are limited. Finally, the organization "Object Shelter," now under the direction of the Chornobyl Station, is charged with monitoring activities within the sarcophagus. To add to the confusion, from the time of the accident to the collapse of the Soviet Union the International Atomic Energy Agency (IAEA) in cooperation with the U.S. Department of Energy, the Soviet Ministry of Atomic Energy, and a number of international research centers have apparently attempted to coordinate severe accident analysis at Chornobyl. These efforts, unfortunately, broke down with the collapse of the Soviet Union. It is no wonder, then, why people in Ukraine describe the zone and work there as a *bardak* – a Russian word that literally means "whorehouse" but colloquially implies complete confusion and disorder.

To give you some idea of how poorly equipped these people are, I, as a graduate student, arrived proudly toting my Apple Macintosh personal computer only to realize that there was more computing power in my hands than the few older-model IBM PCs belonging to the Expedition. Imagine my position: a graduate student going to a foreign country to conduct research – barraged with inquiries by scientists there on how to get their materials

published in the West so that information gets out. As an consequence of the Three Mile Island accident in the United States, one of the most comprehensive and costly research efforts ever undertaken has produced valuable design improvements that have been implemented in western reactors, and has motivated research into the design of the next generation of "inherently safe" power reactors. At Chornobyl, because of bureaucratic tangles and a lack of funds or general interest, not even all of the melted fuel has been positively located.

It is indeed unfortunate that, to this day, the academic yield attributable to the accident pales in insignificance when compared with the din produced in the popular press – often focusing attention away from the real problems at Chornobyl while calling attention to irrelevant comparisons with much safer western nuclear reactors. Scanning the voluminous research reports on the Three Mile Island accident, I am nearly brought to tears with the realization that if an accident similar to Chornobyl had occurred in France, for example, the entire world would have engaged its experts in studying the accident, limiting its consequences, and learning its lessons; while at Chornobyl, only thirty or so dedicated scientists struggle to find enough gasoline to drive to the reactor to check the progress of work being conducted there.** Arguably, although Chornobyl itself produced a shock in the right direction, *perestroika* did not affect research on the accident until 1989. It was then that the Soviets published for the first time, albeit in preprint-form (see Chapter VI), an admission that more radionuclides were released as a result of the accident than previously reported. At international conferences, Soviet "experts" continue to this day to assert that over five thousand tons of lead, dolomite, sand, and clay covered and smothered the smoldering core of the reactor – when in reality almost none of this material hit a core that burned virtually uncovered for approximately ten days. The Soviet scholarly establishment's "scientific plan" coupled with traditional ideological strictures, confined research or the release of in-

** For an indication of how little has been done to clean up the 30-km exclusion zone other than the immediate territory around the station, Ukraine began its first large-scale decontamination project in 1993 – seven years after the accident! [Janet Wood, "Ukraine Takes On the Burden," *Nuclear Engineering International*, (August 1993): 25]

formation to that deemed "acceptable" by the powers that be. Because the Soviet government was insecure of its image and unsure of its ability to maintain public order†, it tried to hide the extent of the accident from its own citizens and the people of the world (see Chapter I.) This served only to compound the consequences of the accident and hasten the fall of the régime – its position compromised, as in other cases, when the truth of the extent of the accident began to leak.

The lack of contact with western colleagues for these scientists has also taken its toll. Whereas earlier the controlling régime discouraged and controlled such scientific interchanges, today, with the economies of the newly-emerged republics barely struggling to fulfill basic needs, rather than an iron curtain, a "dollar" curtain effectively prevents the important exchange of information. The small research team at Chornobyl cannot afford, for example, to obtain western scientific journals and scientific and engineering handbooks, let alone the proper computers and the money to pay for the dangerous work of core sample drilling within the sarcophagus. This, of course, greatly limits the researcher's ability to compare their assumptions and hypotheses against the experience of others. The result is that several researchers at Chornobyl cling to models of the accident (some physically groundless) with an oftentimes irrational mania, and they stake their careers on proving their version of the accident is the only correct one. Naturally, this kind of an environment breeds personal conflicts and even the sabotage of contamination monitoring work. Those researchers who take a more rational approach are despondent over the situation. Conversations with them have a subtext that is typically Soviet: there is a degree of cynicism, coupled with shame about ordinary life; and there is the omnipresent regret, "See how we live..."[16] For example, almost everyone in the former Soviet Union today uses the adjec-

---

† The Russian penchant of concealing misfortunes has antecedents reaching far back into history. For example, the French nobleman Marquis de Custine Astolphe, commenting in 1839 about a lethal storm that may have killed up to fifteen hundred people remarked, "We shall never ascertain the exact circumstances of the event. Every accident here is treated as an affair of state: it is God who has failed in his duty to the emperor.... A silence more frightful than the evil itself, everywhere reigns.... Russia is a nation of mutes." As quoted in Murrary Feshbach and Alfred Friendly, Jr., *Ecocide in the USSR*, New York: Basic Books (1992): 13.

[16] Nadia Diuk and Adrian Karatnytsky, *The Hidden Nations: The People Challenge the Soviet Union*,

tive "civilized" when speaking about the West – implying quite strongly that their lives are somehow uncivilized and uncultured.

Yet despite the self-deprecation and the endless stream of complaints about daily life and its oftentimes humiliating difficulties, these few researchers continue to struggle in their work – inextricably bound to it by a determination to get to the truth. However, even this has led to laxity and recklessness with regard to safety. Not having the equipment or the means to safely explore the sarcophagus, for example, several of the scientists risk their lives by collecting samples of melted fuel literally with their hands, or by carrying robots or monitoring equipment into inaccessible and highly radioactive areas because there are no other means to accomplish the work. An anecdote often chuckled about through disheartened tears recalls a photographer forgotten by workers deep within the sarcophagus (without a working flashlight after the lights had been turned off) in a room adjoining a corridor containing several tonnes of melted fuel. This particular story has a happy ending because, fortunately, the heavily-clothed and equipment-laden photographer did not attempt to find his way out of an area where decay heat kept the ambient temperature at over 40° C. The photographer remained in position until others realized that he was missing and returned to find him.

* * * * *

If struggling to conduct research during the painful transition period from a totalitarian régime to some semblance of a democratic order for fifteen newly independent countries were not enough, living and working in Ukraine has also provided me with an opportunity to follow the West's portrayal of Chornobyl from a unique angle – a perspective that has not offered me much to cheer about. I have become exasperated at western perceptions of what the former Soviet Union was, and in particular at western notions about Chornobyl.

New York: William Morrow and Company, Inc., (1990): 81–82.

One problem concerns a need for sensitivity and accuracy about exactly what is being portrayed; the other concerns avoiding obfuscation that seems to be part of a hidden agenda. The manner in which governments and international organizations function has strengthened in me the conviction that, sadly, scientific inquiry and politics are inextricably linked. This has affected me personally when attempting to find even modest funding for research at Chornobyl. The unspoken message appears to me to be that because the U.S. government is fearful of getting involved in cleanup efforts and because U.S. policy is manifestly directed against the prolonged operation of RBMK reactors in the former Soviet Union, no research whatsoever (even if it is as narrowly focused as this dissertation) may be supported, for fear of providing useful information to the Lithuanians, Russians, and Ukrainians that may provide added momentum for the continued operation of the RBMKs.†† Moreover, in the West (although the potential for an accident as severe as Chornobyl is vanishingly small for western LWRs), Chornobyl is considered a futile academic exercise: an accident that could only happen to "them" and not to us.* Witnessing from Ukraine over almost three years both the manner in which the western press has portrayed and interpreted various aspects of the former Soviet Union, and the manner in which largely unprepared western governments have dealt with the collapse of the Soviet Union, my youthful naiveté has gone the way of the USSR – committed to the dustbin of history.

Many in the West were taken almost completely by surprise at the breakup of the Soviet Union, even to the point of considering it an annoyance that so many new countries had emerged in the wake of its collapse.[17] The grossly oversimplified notion that the for-

---

†† This policy has had little effect on these countries given Russia's decision to complete its Kursk Unit-5 by 1994 and Ukraine's decision at the end of 1993 to prolong the operation of the Chornobyl Station. ["Ukraine to Keep Chernobyl in Operation," *The New York Times*, Vol. CXLIII, No. 49,492 (Friday, October 22, 1993): A8; Ann MacLachlan, "Power Shortfall Plus Political Chaos: Good News for Chernobyl," *Nucleonics Week*, Vol. 34, No. 37, (September 16, 1993): 4.] See also Chapter III.2.

* It is chilling to realize that in the wake of the Three-Mile Island accident, the Soviets expressed exactly the same sentiments, namely, that in the "superior" communist order of the Soviet Union a nuclear power accident was impossible (Аварии быть не может!) For a revealing comparison of the Chornobyl and Challenger accidents see Mark Kuchment and Aron M. Berstein, "Chornobyl and Challenger: Trading Disasters," Spectrum, IEEE, (April 1987).

[17] "Typical of such misperceptions were the views of Robert Strauss, the American ambassador to the unraveling USSR, who, in the fall of 1991, commented that the republics seeking independence from the

mer Soviet Union was one nation lead to an oftentimes embarrassing lack of sensitivity demonstrated by the use of the term "USSR" interchangeably with "Russia," and citizens of the former Soviet Union were frequently called Russians in a fashionable shorthand. Unfortunately, such conventions persist to this day in many respected western periodicals.

The western press must take a great deal of responsibility for the resulting naiveté because it neglected for so long to account for national distinctions when reporting events in the Soviet Union. Western reporters, for example, to this day continue to be largely centered in Moscow and primarily exposed to the "central" press which writes relatively little about what is happening in the republics.† Furthermore, the indiscriminate use of the term "Russian" in the western press to describe any or all of the over one hundred nationalities of the former Soviet Union only served to promote the widespread misconception that all Soviet citizens are Russians and that the term "Soviet Union" is equivalent to the term "Russia." The routine use of the label "Russian" in the press for people as different as the Western-oriented, Finnic-speaking Protestant Estonians, the Turkic-speaking Muslim Uzbeks, and the Romance-language speaking Moldovan-Rumanians, has rendered westerners unable to appreciate the cultures and histories of the nations within the newly independent republics, and incapable of understanding social and political developments there. This has left westerners out of touch with half the population of the other former "superpower" and has blinded them to the human and national rights issues there.[18]

USSR were like "teenage children" who had run away from home. Soon they would come back, the ambassador argued condescendingly." [Diuk and Karatnytsky, *New Nations Rising...*, 17.] See also pages 22–23, 26, 268–274 concerning American misconceptions and failings of U.S. foreign policy *vis a vis* the CIS.

† Incidently, this "Moscow-centrism" in westerners is also true of most Russians, the vast majority of whom do not and cannot read the languages of the peoples of other republics. This, in part, has already lead to dangerous and bloody conflicts in Estonia, Moldova, and Georgia because the Russians for some reason feel their rights are denied when a country asserts its native language and culture. Note that Lithuanians, to take only one example of a people who paid dearly for their freedom, did not want to divide themselves (widely perceived in the West as "Russians" separating from "Russia") but to separate from a Russian-dominated empire.

[18] Frank Sysyn, "Russia or the Soviet Union?" Cambridge, MA: Harvard Ukrainian Research Center. In a compelling manner, Diuk and Karatnytsky argue the same point in the section entitled 'What's in a Name?" in *New Nations Rising...*, 21–23, 21–23.

Not surprisingly, as concerns the news media, most of the discussion about the accident has centered on very narrow and unrevealing points – questions on the short-term and immediate consequences such as which pipe ruptured, somewhat irrelevant comparisons to Hiroshima and Nagasaki, how many direct fatalities* resulted, etc. While these questions may have limited importance a narrower understanding of the accident, they do not reveal the overall nature of such an accident. In fact, as is touched upon in Chapter Three, the Chornobyl accident is at least partially rooted in Soviet attitudes toward science and technology, and in the resultant economic and political pressures on the Soviet nuclear energy industry – as well as in the poor and inherently unstable design of the reactor.

Perhaps more importantly for purposes of this discussion, the continued insensitivity of westerners to questions of sovereignty and language (for example, turning to Moscow for information or permission to conduct accident research on the territories of Belarus or Ukraine) serves only to close important channels of information and limit western understanding of the accident. A concrete example of this was the IAEA's almost fawning trust in the Moscow central authorities – while seemingly ignoring information and specialists from other republics not associated with the central governmental commission investigating the accident. In 1987, for example, well before information began to filter out of the former Soviet Union on the extent of the accident, an IAEA report announced, "if anything, there will be a modification downward of early calculations of risks and predictions of health consequences."[19] Many western experts continue to charge that the IAEA is biased toward nuclear power – that data acquired under the auspices of Moscow was published as much to argue a point of view as to advance scientific inquiry. Although the IAEA can hardly be criticized for failing to predict the demise of the Soviet Union, the fact that it only dealt with

---

* Society has always treated accidents in which a number of people are killed or injured in one incident differently from the way they treat the continuous death toll of day-to-day life. One-hundred instant deaths is news, one-hundred fatalities over a year even if by accident is not.

[19] Международное Агентство по Атомной Энергии, "Авария но Чернобыльской АЭС: Год Спустя," *Международная Конференция по Показателям и Безопасности Ядерной Энергетики, Вена, Австрия, 28 сентября – 02 октября 1987*, (IAEA-CN-48/63). See also David R. Marples, "International Atomic Energy Agency and Ukraine: Politics Are Foremost," *The Ukrainian Weekly*, Vol. LVI, No. 21 (May 22, 1988): 2.

the central authorities from the outset was a questionable approach at best. Even as late as 1990–91, it was inadvisable to work mainly with the central government once it became clear that the worst ramifications of the disaster were in Belarus and Ukraine rather than Russia. This policy has not only restricted the IAEA's information, it has also alienated the IAEA from the public of Ukraine and Belarus, and especially those subject to increased radiation fallout. Local residents in such regions certainly do not hold the IAEA in high esteem, and its investigators represent yet one more round of officialdom that compiled reports resulting in little in terms of effective remedies. This sentiment seems to have been confirmed with the IAEA's May 1991 report "The International Chornobyl Project: An Overview," which has been roundly criticized and charged with incompleteness. It is faulted for drawing specific conclusions from a study that a number of experts claim was limited in scope (neither the 240,000 "liquidators" who worked to clean up and build the sarcophagus nor the 116,000 evacuees from the zone were studied*) and partially biased because Moscow, rather than the republics, controlled access to data and people.[20,21,22]

---

* Although it is true that the ICP should have included in its study people who had been evacuated from the 30-km exclusion zone (some as late as eight and one-half days after the accident), it is unfairly criticized for excluding the "liquidators." Its explicitely stated concern was with assessing the health effects in members of the public living in contaminated regions *at the time of the study* – as the ICP team was requested to do by the then Soviet government. The point made by the study's critics, however, that general conclusions about the effects of the accidents should have been withheld until all affected people were studied, is correct.

[20] See, for example, (1) John W. Gofman, "Beware the Data Diddlers," *The Bulletin of the Atomic Scientists*, (May 1993): 43; (2) Read, Piers Paul, *Ablaze*, New York: Random House, (1993), 308–319; (3) David R. Marples, "Chornobyl Six Years After: A New Era of Investigation," *The Ukrainian Weekly*, Vol. LX, No. 17 (April 26, 1992): 8–9; and (4) Ann MacLachlan, "Chernobyl Project Wrapup Marked by Protests From Two Republics," *Nucleonics Week*, Vol. 32, No. 22 (May 30, 1991). Jeremy Webb, "Chernobyl Findings 'Excessively Optimistic'," *New Scientist*, Vol. 130, No. 1771, (01 June 1991): 17.

[21] An informative and well-balanced article is Steven Dickman's "Chernobyl Effects Not As Bad As Feared," *Nature*, Vol. 351, (30 May 1991): 335. A similar article, although not as well-balanced is, Felix Eijgenraam, "Chernobyl's Cloud: A Lighter Shade of Gray," *Science*, Vol. 252, (31 May 1991): 1245–1246.

[22] Testifying before the Nuclear Regulations Subcommittee (part of the Senate Committee on the Environment and Public Works) on July 22, 1992, Dr. Fred Mettler, Chairman of the Department of Radiology at the University of New Mexico Medical School and leader of the International Advisory Team that traveled to Ukraine in 1990 to study the health impact of the Chornobyl accident and prepare the IAEA's report, conceded that the study "... never examined the populations most endangered by radiation – namely, the [163,000] evacuees and the 650,000 clean-up workers." He further agreed that this study could have been either premature, or too limited in scope [to come to a reasonable conclusion, and] to detect the increases in cancers, leukemias, and birth defects others had observed.

Particularly damaging to the validity of the study's assumptions was the revelation [at the hearing]

The report examined the health consequences of the accident in twenty-eight selected villages of Ukraine and Belarus, including seven control settlements – all outside the exclusion zone. Much to the chagrin of Ukrainians and Belarusians, the charge of "radiophobia" was leveled against local activists calling attention to the significant health anomalies now appearing in contaminated areas of Belarus and Ukraine.[23]

Two of the twentieth century's most misunderstood and hotly debated phenomena – the former Soviet Union and Nuclear Energy – have countless times served the special interests of those willing to take advantage of such complex issues to promote their own agendas. It is no surprise, therefore, that Chornobyl has served the popular press as a forum for obfuscation and exaggeration since the time of the accident – as if the accident can be neatly defined or categorized within a particular ideological framework. It is not my intention here to respond to the myriad semi-truths one encounters in popular books and journals about Chornobyl[†] nor to moralize but to implore readers to be more objective and sen-

---

that "six months after the IAEA study was completed, the federal prosecutor of the USSR disclosed the sale of 47,500 tonnes of contaminated meat, and 2 million tonnes of milk produced between 1986 and 1989 on contaminated territories. A secret memorandum from the Politburo revealed that these products exceeded by several hundredfold the maximum permissible limits for radioactive cesium. Yet the IAEA concluded that 'doses actually received due to the ingestion of contaminated foodstuffs were substantially lower than the prescribed intervention levels... and... foodstuffs may have been restricted unnecessarily'."

[Alex Kuzma, "Senate Hearing: Information from Ukraine Shows Rise in Cancer, Birth Defects," *The Ukrainian Weekly*, Vol. LX, No. 49 (Sunday, December 6, 1992): 9.]

[23] In Belarus, for example, the incidence of thyroid cancers in children has increased from approximately two cases per year before Chornobyl to thirty cases in the first half of 1992 alone. More than half (71) of the 131 cases reported to mid-1992 since 1986 were in the Homel oblast (state) just north of the Kyjiv oblast in Ukraine where the Chornobyl Station in located. [Gamini Seneviratne, "WHO Says Belarus Cancers May Stem From More Than Chernobyl," *Nucleonics Week*, Vol. 33, No. 51 (December 17, 1992): 12.] In another article, a group from the World Health Organization states that "The Belarus experience 'suggests that the consequences to the human thyroid, especially in fetuses and young children, of the carcinogenic effects of radioactive fallout are much greater than previously thought'." [Ann MacLachlan, "Rising Children's Thyroid Cancers Indicate Growing Chernobyl Link," *Nucleonics Week*, Vol. 33, No. 37 (September 10, 1992): 8.]

[†] For those interested, refer to the second photograph and accompanying caption in David Marples's, *Ukraine Under Perestroika: Ecology, Economics, and the Worker's Revolt*; the oftentimes embellished and self-aggrandizing account of the accident by Grigori Medvedev in, *The Truth About Chornobyl*; William Sweet's "Chornobyl: What Really Happened" in the July 1989 issue of *Technology Review*; the UPI claim of over 10,000 deaths directly attributable to the accident as only one of many exaggerated accounts in various newspaper articles and journals, and a host of other examples.

One of the worst abusers, who has taken advantage of the public's general lack of knowledge regarding the accident and has used his own limited experience at Chornobyl for personal gain, is the self-proclaimed Chornobyl "expert" Vladimir Chernousenko. A physicist specializing in semiconductors and hydrodynamics, Chernousenko worked in the 30-km exclusion zone for three months beginning in July 1986 – more than two months after the accident. He held a minor position as a member of a group providing organiza-

sitive to the details and real issues concerning the accident. One need not fantasize about the effects of radiation to know that tremendous damage has been done. Arguing over the definition of a nuclear vs. non-nuclear explosion doesn't help decontaminate tens of thousands of square kilometers of farm land. To quibble over the body count that can be attributed directly to this disaster, besides being somewhat morbid, misses the point completely. Is not one victim enough – let alone the thirty or more already undisputed – to condemn a reactor design long known to be deficient? Examples of poor and incomplete writing serve only to exploit a public that, in general, is poorly informed about nuclear energy, and spreads disinformation about the accident that has clouded the nuclear energy debate.

Chornobyl should be placed in a category of its own – a category much better suited for sociologists, psychologists, political analysts, and scientists to ponder *together* when they ponder the question of whether technology should serve humankind or whether it should become its master. The answer, it may seem, is clearly the former; but in practice, this is not always the case. Technocrats *alone* are little better suited than politicians *alone* are in choosing what form of energy we should exploit. Americans remember well, through the Challenger disaster, the effects of bureaucratic pressures imposed by politicians upon NASA scientists. These politicians, it appears, were more interested in preserving the prestige associated with a space program than in protecting seven human lives.

Ideally, it seems to me, scientists and engineers are to provide unbiased and accurate information on a level which is understandable for the layman without compromising the truth by concealing it behind technical jargon or promising salvation through a "cheap,

---

tional assistance to researchers of the Ukrainian Academy of Sciences.

Upon his arrival in the West in early 1991, Mr. Chernousenko has been making largely unsubstantiated and at times fantastic claims, ascribing to himself, for instance, the title of "Chief Scientist in Charge of Research in the 30-km Zone," or "Chief Liquidator" – positions that have never existed. He has also claimed, without supporting evidence, that 7,000 – and then later 15,000 – people died as a result of the accident, that 60–80% – and then changing his story to 100% – of the core was ejected into the environment as a result of the accident (in fact he is quoted as saying that more activity was released that was in the reactor at the time of the accident!), that he was "run out of the country by Soviet authorities for telling the truth about Chornobyl" – later found to be untrue, and several other false assertions. Mr. Chernousenko has largely discredited himself among serious researchers in the West, and Ukrainian authorities have disavowed themselves from his statements. Unfortunately, he continues to enjoy the support of radical environmental groups and to trivialize the accident and its victims' suffering by these false claims.

clean, and bountiful supply of energy" – be it nuclear fission, nuclear fusion, solar, wind, etc. Government policy makers, in turn, *ought* to make decisions based not on the prestige of high-technology energy, but upon what is best suited for people and their environment. Finally, voters living in a democratic society bear the responsibility of taking an active role in making such choices. This obligates every person to understand the issue as well as possible to make a clear and sober choice. This is a huge responsibility. We owe it to ourselves, but more importantly to future generations, to consider the question as a whole – for the good of humanity and for a planet already devastated ecologically. Focusing upon only the technological or political aspect of such a serious and complex issue as nuclear energy may lead to the creation of a false idol. Such idols have already taken too many human and demanded environmental sacrifices (Bhopal, Alaska Valdez, etc.)... and could demand even more.*

* * * * *

1993 saw Ukrainians commemorate the 800th anniversary of the founding of the town of Chornobyl – a town less than half as old and far smaller than their capital city, Kyjiv. Ukrainians now recall bittersweet memories of a national tragedy that, in a sense, redeemed their freedom and marked the beginning of the end of a long and sad period of their history. As this anniversary year draws to a close and I find time to muse over my work at Chornobyl, I empathize with the Ukrainians over this small portion of the heavy price exacted for their freedom: the loss of a sixty or so villages and towns, the contamination of thousands of square kilometers of beautiful land, and the continued health hazards posed by this accident.

---

* At a May 6, 1986 press conference (eleven days after the accident) held in Moscow, the cult of high technology was unabashedly preached to a auditorium full of shocked correspondents and invited guests. When questioned on the number of fatalities and their impact on Soviet society and on the Soviet nuclear industry, A. M. Petrosyants (then Chairman of the Soviet State Committe on the Utilization of Atomic Energy) responded with the crass remark, "Science requires victims."

In his book *Ten Days that Shook the World*, American correspondent and communist activist, John Reed, depicted the Russian Revolution as marking the beginning of a worker's paradise and of a just and equal society. But by one of those strange twists history is prone to make, it is ironic that the traumatic ten days of radionuclide release from the destroyed unit following the accident arguably marked the beginning of the end of this "paradise" and of the Russian-Soviet Empire.[24] Ukrainians, as well as other peoples of the former Soviet Union, took advantage of the accident and its concealed consequences as a springboard from which to launch a greater push for *perestroika* (initially through various environmental action groups) and eventually for complete independence in the only peaceful collapse of an empire in the history of mankind. The clarification of national aims and the penetration of Ukrainian political consciousness into the masses began to occur in earnest after the accident – it was the final, damning indictment of Soviet rule that sharply focused the determination of a people long suppressed under Russian rule.[25]

Imagine being one of the few fortunate Westerners able to experience firsthand the rebirth of an Eastern European nation. On the 24th of August, 1991 in the wake of the failed hard-line coup in the former Soviet Union (which besides demonstrating the infirmity of the Soviet system and the ineptitude of its leaders, led to the breakup of the Soviet Empire), Ukraine reentered (for the third time in its history**) the international arena of free nations by declaring herself independent of Moscow. For almost three years I shared with Uk-

---

[24] Never at a loss for exalted pronouncements, Medvedev declares, "... the RBMK reactor was the nuclear time bomb, whose explosion signaled the death throes of an entire historical period;" and later, "... the reactor was not all that was finished. An abscess, long hidden within our society, had just burst: the abscess of complacency and self-flattery, of corruption and protectionism, of narrow-mindedness and self-serving privilege. Now, as it rotted, the corpse of a bygone age – the age of lies and spiritual decay – filled the air with the stench of radiation." Grigori Medvedev, *The Truth About Chernobyl*," New York: Basic Books, Inc., (1990): 90, 161.

[25] See Chapter Three "Ukraine: The Pivotal Nation" and in particular this chapter's section 'After Chernobyl' in Diuk and Karatnytsky, *New Nations Rising...*, 71–107.

** Besides the proto-Ukrainian state of Rus'-Ukrajina during the 10th through 13th centuries, Ukraine existed as a politically independent entity on two previous occassions. The Ukrainain Cossack State arose in the early 17th century in the wake of peasant revolts against Polish landowners that spurred a general revolution. This state progressively lost its independence and autonomy in the latter half of the 17th century and during the 18th century to an expanding Russian Empire. The Ukrainian National Republic, which existed briefly during 1917–21 after breaking away from the Czarist-Russian Empire, was reconquered and subsequently made part of the Soviet-Russian Empire.

rainians (primarily in the western Ukrainian city of L'viv and in the capital of Ukraine, Kyjiv) their anxieties, frustrations, prayers, and determination to build a brighter future. To partake in the euphoria of newfound liberty is something that no words can convey. I have witnessed a people summon their courage and faith and demonstrate to the rest of the world that they too have gifts to share, that they are worthy to join other nations in seeking to build a peaceful, just, and democratic world.

On August 24, 1991 the Ukrainian Parliament declared the country's independence (which over ninety percent of Ukraine's citizens affirmed in a referendum on December 1, 1991) because seventy-four years of political repression, economic mismanagement, cultural stultification, and even genocide have left it near economic, moral, and spiritual ruin. Yet despite all this, Ukrainians have come through the ordeal with hope for the future and a determination never to allow a political ideology to go unchecked – especially if that ideology places technology and the progress of science before the dignity and individual worth of persons. Liberty's initial euphoria has been tempered with the knowledge that a long and arduous rebuilding process lies ahead, and that Ukraine's fledgling independence must be vigorously defended against a Russia seemingly bent on reconstituting its lost empire through unabashed territorial encroachments and economic pressures.[26] However, Ukrainians know they must continue to uphold justice and truth for all of their citizens – regardless of nationality or religious persuasion – or face fading from the world as a nation once again. History rarely presents a second, let alone third, opportunity for any nation to survive that which Ukraine has endured.

Alexander R. Sich
Cambridge, MA
January 5, 1994

---

[26] See Jon Auerbach, "Russia Tightening its Grip on Former Republics," *The Boston Globe*, Vol. 244, No. 159 (December 6, 1993): 1, and Paul Quinn-Judge, "Russia Trying to Regain Grip Over Republics, US Aides Say," The Boston Globe, Vol. 245, No. 5 (January 5, 1994): 1. See also the accompanying op-ed article by former Secretary of State James A. Baker 3rd, "NATO Expansion Can Launch a New Era in Europe and the Ex-Soviet Lands," (17). Refer also to the myriad of popular and scholarly articles spawned in the wake of the frightening and unexpected results of Russia's Parliamentary elections held December 12, 1993 in which the ultra-nationalist and revanchist, Vladimir Zhironovsky, claimed the largest block of seats

This Page Has Been Left Intentionally Blank.

TABLE OF CONTENTS

ABSTRACT 3

ACKNOWLEDGMENTS 5

PREFACE 13

TABLE OF CONTENTS 49

LIST OF FIGURES 53

LIST OF TABLES 57

TERMINOLOGY AND TRANSLITERATION 61

DEDICATION 65

CHAPTER I INTRODUCTION: BACKGROUND AND BASIS FOR THIS DISSERTATION 67

I.1. Contradictions and Cover-up 67

I.2. Defining the Problem 75

I.3. Objectives of this Dissertation 80

CHAPTER II A SYNOPSIS OF THE MAGNITUDE AND CONSEQUENCES OF THE ACCIDENT 83

II.1. Direct Physical Effects 83

II.2. Environmental Contamination from the Fallout of the Accident 88

II.2.1. General Extent of the Fallout 89

II.2.2. Fallout in Major Cities 103

II.2.3. Fallout in Other Countries 106

II.2.4. Contamination of Bodies of Water 107

II.3. Population Resettlement and Cleanup Costs 116

II.4. Casualties, Fatalities and Other Health Effects 121

II.5. Chornobyl's Impact on the Nuclear Industry and on the Public's Perception of Nuclear Energy 133

CHAPTER III THE RBMK AND THE CHORNOBYL NUCLEAR POWER STATION: HISTORICO-POLITICAL & TECHNICAL DEVELOPMENT AND DESCRIPTION 137

III.1. Soviet Nuclear Energy and the Development of the RBMK 138

III.1.1. Political and Economic Backdrop 138

III.1.2. Brief History of the Soviet Nuclear Energy Program and Development of the RBMK 143

III.1.3. Advantages and Disadvantages of the RBMK 156

III.2. Nuclear Energy in Ukraine 162

III.2.1. Chornobyl's Impact in Ukraine and the Former Soviet Union 162

III.2.2. Ukrainian Nuclear Energy: Facts and Figures 166

III.3. The RBMK-1000: Technical Description and Characteristics 178

III.3.1. Core Design 178

III.3.2. Major Reactor Systems and Reactor Building Description 188

III.4. The Vladimir I. Lenin (Chornobyl) Nuclear Power Station 196

III.4.1. Physical Geography of Regions Surrounding the Station 196

III.4.2. History of the Chornobyl Station 203

CHAPTER IV CHRONOLOGY OF EVENTS AND ACCIDENT SCENARIO 207

IV.1. Introduction 207

IV.2. Chronology of Events and Actions That Initiated the Accident 209

IV.3. Chronology of Events and Assessment of Mitigation Efforts Taken Following the Initial Destruction of Unit-4 235

IV.3.1. Appraisal of the Situation and Fire Containment 236

IV.3.2. Active Phase Accident Mangement Actions 239

IV.3.2.1. Material Dumping to Smother the Reactor Fire 239

IV.3.2.2. (Liquid) Nitrogen Purge of the Core Region 251

IV.3.2.3. Water Release from the Pressure Suppression Pool 257

IV.3.2.4. Sub-Foundation Flat-Bed Heat Exchanger 259

IV.3.3. Reassessment of Active Phase AMAs 263

CHAPTER V A DESCRIPTION OF THE SARCOPHAGUS "SHELTER" AND STATE OF UNIT-4 AND ITS NUCLEAR FUEL: A POSTMORTEM 269

V.1. The Sarcophagus "Shelter" 269

V.1.1. Construction and General Description 269

V.1.2. Radiation Hazards: Impact of Shelter Upon the Surrounding Environment 283

V.2. Remains of the Unit-4 Core Shaft and Adjacent Areas 286
V.3. The State of Nuclear Fuel Located Within *Shelter* 311
V.3.1. Overview and Material Balance 311
V.3.1.1. Summary 311
V.3.1.2. Dust and Hot Particles 313
V.3.1.3. Contaminated Water 315
V.3.1.4. Quantities and Locations of LFCMs 316
V.3.2. Classification and Analysis of the Lava-Like Fuel-Containing Materials 321
V.4. Discussion 330

CHAPTER VI THE CHORNOBYL SOURCE TERM REVISITED 337
VI.1. Basic Principles of Source Term Analysis 337
VI.1.1. Introduction to the Case of Chornobyl 337
VI.1.2. Elements of Source Term Theory 339
VI.2. Chornobyl Unit-4 Core Inventory Estimates 348
VI.2.1. Review of Previous Core Inventory Estimates 348
VI.2.2. Chornobyl Unit-4 Core Inventory Calculation 354
VI.2.2.1. State of the Unit-4 Core Just Prior to the Accident 354
VI.2.2.2. Computational Basis for Estimating the Core Inventory 354
VI.3. Source Term Releases 357
VI.3.1. Review of Previous Source Term Estimates 358
VI.3.2. Appraisal of Soviet Release Data 364
VI.3.3. Active Phase Release Dynamics 373
VI.3.4. Source Term Estimate 390

CHAPTER VII CONCLUSIONS AND RECOMMENDATIONS 395
VII.1. Introduction 395
VII.2. Active Phase Scenario 398
VII.2.1. Mechanical-Dynamic Stage 398
VII.2.2. Source Term Stage 402
VII.2.2.1. The Hypothesis 403
VII.2.2.2. Further Work to Confirm or Disprove the Hypothesis 407
VII.3. Final Conclusions and Recommendations 409
VII.3.1. Results of the Investigation 409
VII.3.2. General Conclusions 411

APPENDIX II Chornobyl: A Nuclear or Non-Nuclear Explosion?.....413

APPENDIX III.A Text of Internal Security Memorandum Concerning Construction Flaws at the Chornobyl Nuclear Power Station.....419

APPENDIX III.B Chornobyl Unit-4 Design Parameters.....421

APPENDIX III.C Nuclear Power Reactors of the Commonwealth of Independent States.....433

APPENDIX V Detailed Classification of LFCMs and Results of Radiochemical Analyses....443

APPENDIX VI.A Chornobyl Unit-4 Technological (Fueled) Channel Burnup Data.....471

APPENDIX VI.B Initial Core Inventory Data for Sixty-Five Selected Radioisotopes for Chornobyl Unit-4 at the Time of the Accident.....479

APPENDIX VI.C Results of Correlation Analysis Applied to Fractional Mass Release Data Derived from the Combined PROBA & Legasov Data Base (Table VI.12).....487

SELECTED BIBLIOGRAPHY.....**489**

I. Western Popular Press.....489

II. Western Scientific & Technical.....490

III. Soviet Scientific & Technical (In English).....493

IV. Soviet Popular Press (In Belarusian, Russian, and Ukrainian).....495

V. Soviet Internal Scientific Reports & Preprints.....497

LIST OF FIGURES

CHAPTER II

II.1 Photograph of the Destroyed Chornobyl Unit-4 Reactor Building — I 86

II.2 Photograph of the Destroyed Chornobyl Unit-4 — II 87

II.3 Cs-137 Contamination in Belarus, Russia, and Ukraine 92

II.4 Cs-137 Contamination of Agricultural Land in Belarus, Russia, and Ukraine 95

II.5 Contamination Map Showing γ-isolines (mR/hr) on April 29, 1986 101

II.6 *Izvestia* Map of Pu-239 & Pu-240 Contamination in December 1989 102

II.7 Average Outdoor Exposure Rate in Kyjiv During April & May 1986 105

II.8 Relative External Dose Rates for Various Points in the Northern Hemisphere 106

II.9a The Kyjiv Reservoir and Its Feed Rivers 111

II.9b The Dnipro River Reservoir-Cascade System 111

II.10a Surface Concentrations of Cs-137 in the Black Sea (June 12 – July 6, 1986) 114

II.10b Surface Concentrations of Cs-137 in the Black Sea (October 1986) 114

II.11a Surface Concentrations of Cs-137 in the Baltic Sea (June–July 1986) 115

II.11b Surface Concentrations of Cs-137 in the Baltic Sea (October–November 1986) 115

CHAPTER III

III.1 *Pravda* Graphic Glorifying Electrification, Labor, and the Communist Party of the Soviet Union One Week after the Accident 139

III.2 The 2400 MWe RBMK 145

III.3 USSR Electricity Generation 154

III.4 USSR Installed Electrical Generating Capacity 154

III.5 USSR Five-Year Plan Fulfillment for Installed Electrical Generating Capacity 155

III.6 Map of Ukraine and Locations of Nuclear Power Stations 171

III.7 Nuclear-Based Electricity Generation in Ukraine, 1977–1992 174

III.8 Electricity Generation in Ukraine, 1967–1992 175

III.9 Fractional Contribution of Electricity Generation in Ukraine, 1967–1992 176

III.10 Fossil Fuel Consumption in Ukraine, 1971–1992 177

III.11 Cross-Sectional Views of the Chornobyl Unit-4 Reactor Shaft 179

III.12 Cross-Sectional Views of an RBMK-1000 Technolgical (Fueled) Channel and Fuel Assembly 181

III.13 RBMK-1000 Fuel Rod 183

III.14 RBMK Control Element Design 186

III.15 RBMK-1000 Core Coordinate System, and Technological Channel and Detector Mapping 187

III.16 North-South Cross Section of the Chornobyl Unit-4 Reactor Building As Viewed from the East Prior to the Accident 190

III.17 East-West Cross Section of the Chornobyl Units 3 & 4 As Viewed from the East Prior to the Accident 191

III.18 The Chornobyl Nuclear Power Plant As Viewed from Above and Prior to the Accident 192

III.19 Sectional View of Chornobyl Unit-4 Prior to the Accident 193

III.20 Map of the Kyjiv Oblast Showing the Location of the Chornobyl Station and the Ukrainian Capital, Kyjiv 197

III.21 Map of the Region in the Immediate Vicinity of the Chornobyl Nuclear Power Station 198

III.22 Map of the Chornobyl Nuclear Power Station 199

CHAPTER IV

IV.1 Normalized Axial Neutron Flux for the Chornobyl Unit-4 Core After the Emergency Control Rods Were Scramed 233

IV.2 Schematic of a Scram (AZ) B_4C Control Rod and its Graphite Follower 234

IV.3 Technological Channel Cover Blocks and Central Hall Floor Over the Reactor 234

IV.4 Total Chornobyl Unit-4 releases Over the Active Phase — The "Bathtub" Curve 242

IV.5 Cross Section (Looking North) of the Damaged Chornobyl Unit-4 Reactor Building and Sarcophagus 245

IV.6 Schematic of the Central Hall Area and Sarcophagus at Level 35.5 m 246

IV.7 Schematic of the Central Hall Showing the Location of Materials Dropped from Helicopters 247

IV.8 Photograph of the Destroyed Chornobyl Unit-4 Reactor Building in July 1986 As Viewed From Directly Above the Reactor Shaft 249

IV.9 Photograph of the Upper Biological shield Viewed from the South-by-Southeast in September 1986 250

IV.10 Map of the Chornobyl Nuclear Power Station Showing the Location of the Nitrogen Purge Line 253

IV.11 Sectional View of Chornobyl Unit-4 255

IV.12 Photograph Showing one of Three Steam Distribution Headers with Waterfall-like Formations of Solidified Corium 256

IV.13 Top-View Schematic Showing the Relative Position of the Sub-Foundation Flatbed Heat Exchanger 262

IV.14 Summary of Accident Mangement Actions 266

CHAPTER V

V.1a Photograph of the Nearly Completed Chornobyl Unit-4 Sarcophagus "Shelter" in November 1986 As Viewed from the Northwest 270

V.1b General View of the Chornobyl Unit-4 Sarcophagus "Shelter" 271

V.2a Photograph of the Sarcophagus and Construction of the Northern "Cascade" Wall in early October 1986 274

V.2b Top-View Schematic of the Chornobyl Unit-4 Sarcophagus "Shelter" 275

V.3a Photograph of the 92-tonne Contraforce Wall Panels Before Installation in October 1986 276

V.3b Chornobyl Unit-4 Sarcophagus "Shelter" Silhouette Along Axis 47 277

V.4a Installation of Roofing Panels With a Partial View of the "Mammoth" Block 278

V.4b Schematic of the Chornobyl Unit-4 Sarcophagus "Shelter" (North-South Cross Section Along Axis 47) 279

V.5a Photograph Showing Damage to the Southern Areas of the Unit-4 Reactor Building 281

V.5b Schematic of the Chornobyl Unit-4 Sarcophagus "Shelter" (East-West Cross Section Along Axis L) 282

V.6 Upper Limit of Total Radioactive Aerosol Releases from Chornobyl Unit-4 Through Openings in the Sarcophagus 284

V.7 A Core-Sample Drilling Schematic 287

V.8 Sectional View of Chornobyl Unit-4 In Its Current State 288

V.9 Sectional Schematic of the Chornobyl Unit-4 Reactor Shaft 289

V.10 Locations of Fuel Containing Masses in the Sub-Reactor Region and Adjoining Areas 294

V.11 Locations of Fuel Containing Masses in the Steam Distribution Corridor and Adjoining Areas 295

V.12 Locations of Fuel Containing Masses in the on the 2nd Floor of the Pressure Suppression Pool and Adjoining Areas 296

V.13 Locations of Fuel Containing Masses in the on the 1st Floor of the Pressure Suppression Pool and Adjoining Areas 297

V.14 Three-Dimensional Representation of Lava-Like Fuel-Containing Material Flow Paths 298

V.15 Photograph of the Two-Tonne Accumulation of Melted Nuclear Fuel Dubbed the "Elephant's Foot" 301

V.16 Photograph of a Nuclear Fuel "Stalactite" Located in Corridor 217/2 302

V.17 Photograph of a Nominal Sub-Reactor Region 304

V.18 Photograph of a Typical Steam Distribution Header and Openings to the Telescoping Steam Distribution Pipes Leading to the Pressure Suppression Pool 305

V.19 Photograph Showing one of Three Steam Distribution Headers with Waterfall-like Formations of Solidified Corium 306

V.20 Photograph of a Steam Distribution Header Showing Solidified Nuclear Fuel and a Crushed Service Ladder 307

V.21 Photograph Showing A Pumice-Like Formation of Nuclear Fuel Located on the 2nd Floor of the Pressure Suppression Pool 309

V.22 Lava-Like Fuel-Containing Material Flow Paths Schematic 322

CHAPTER VI

VI.1 Total Calculated Core Fission Product and Transuranic Inventory and Specific Heat Generation Rate 353

VI.2 Calculated Specific Activity and Heat Generation Over the Period of the Active Phase 353

VI.3 Schematic Representation of an RBMK-1000 Technological (Fueled) Channel 357

VI.4 Release Rate Curve Presented by the Soviets in August 1986 at Vienna The "Bathtub" Curve 373

VI.5 Normalized Mass Release Over the Period of the Active Phase 374

VI.6 Normalized Mass Release Over the Period of the Active Phase for the Volatiles 377

VI.7 Normalized Mass Release Over the Period of the Active Phase for the Non-Volatiles 378

VI.8 Fractionation Factor, $k_{i\text{-}95}$, for the Volatiles Over the Active Phase 383

VI.9 Fractionation Factor, $k_{i\text{-}95}$, for the Refractory Metals Over the Active Phase 384

VI.10 Fractionation Factor, $k_{i\text{-}95}$, for the Refractory Oxides Over the Active Phase 385

VI.11 Average Normalized Mass Release Curves for the Volatiles and Non-Volatiles 388

VI.12 Average Fractionation Factor, $k_{i\text{-}95}$, for the Volatiles, Refractory Metals, and Refractory Oxides 389

CHAPTER VII

VII.1 Hypothesized Accident-Progression Scenario During the Period of the Active Phase 404

APPENDICES

AVI.1 Contour Mapping of Corelation Analysis Results 488

LIST OF TABLES

PRELIMINARY

0.1 Transliteration of Belarusian, Russian, and Ukrainian Into English 63

CHAPTER II

II.1 Extent of Cs-137 Contamination in Belarus, Russia, and Ukraine 92

II.2 Agricultural Land in Belarus, Russia, and Ukraine (by Oblast) Contaminated with Cs-137 as a Result of the Chornobyl Accident (as of January 1, 1991) 93

II.3 Cs-137 Contamination of Agricultural Land in Ukraine (as of June 1, 1991) 95

II.4 Cs-137 and Sr-90 Contamination in Belarus 97

II.5 Cs-137 Agricultural Land Contamination in Belarus 97

II.6 Cs-137 Contamination of the Brjansk Oblast of Russia in 1986 99

II.7 Contaminated Areas Associated with Measured γ Activities 100

II.8 Maximum Observed Exposure Rates in Several Soviet Cities 104

II.9 Estimated Cs-137 Accumulation After the Accident on the Territories of Various Countries in the Northern Hemisphere 108

II.10 Concentrations of Various Radionuclides in the Prypjat River, (nCi/l) 109

II.11 Maximum Concentration of Various Radionuclides in Rivers of the Kyjiv Reservoir Basin, (nCi/l) 109

II.12 Concentration of γ-Sources in Rivers of the Kyjiv Reservoir Basin, (nCi/l) 110

II.13 Cs-137 and Sr-90 Concentration Ranges for Rivers of the Kyjiv Reservoir Basin 110

II.14 Cs-137 and Sr-90 Average Concentration for the Dnipro River Reservoir-Cascade System 113

II.15 Throid Gland Absorbed Dose in the Mohiljow and Homel Oblasts of Belarus 125

II.16 Distribution of Absorbed Dose for People Living in Areas of Strict Radiation Control for the Period 26 April 1986 to 1 January 1990 126

II.17 Frequency of Oncological Diseases in the Zhytomyr Oblast of Ukraine and Cases of Childhood Thyroid Cancers in Belarus 132

CHAPTER III

III.1 USSR RBMK-Prototype Basic Data 146

III.2 Design Evolution of Channel-Type Uranium-Graphite Reactors 147

III.3 USSR RBMK-Series Reactor Construction and Startup Schedules 148

III.4 Comparison of RBMK-1000 and RBMK-1500 Basic Design Characteristics 149

III.5 USSR Electrical Energy Generation Data 153

III.6 Five-Year Plan Electrical Generating Capacity Fulfillment Data 155

III.7 Basic Data on Ukrainian Nuclear Power Reactors 172

III.8 Summary of Nuclear-Generated Electrical Energy in Ukraine 173

III.9 Control Assembly Specifications 184

III.10 Summary of Reactor Channels and Sensors 185

III.11 The Dnipro River Reservoir-Cascade System 200

III.12 Meteorological Characterization of the Chornobyl Administrative Region 202

CHAPTER IV

IV.1 Summary of Materials Dropped Into the Unit-4 Reactor Building 241

IV.2 Design and Construction Schedule for the Chornobyl Unit-4 Reactor Building Sub-Foundation Flatbed Heat Exchanger 260

IV.3 Summary of Accident Management Actions Taken During the Active Phase of the Chornobyl Accident 265

CHAPTER V

V.1 Fuel Particle Activities 314

V.2 Chornobyl Unit-4 Fuel Distribution and Mass Balance 318

V.3 Density-Variation of LFCMs in Several Locations 325

V.4 Chemical Compound Composition of the LFCM1 Silicate Matrix 326

V.5 Elemental Composition of Bulk Lava-Like Fuel-Containing Materials 327

V.6a Statistical Summary of Fuel-Containing Material Radiochemical Data — I 328

V.6b Statistical Summary of Fuel-Containing Material Radiochemical Data — II 329

V.7 Comparison of Calculated-to-Measured Relative Quantities of Cs-137, Ru-106, and Ce-144 330

CHAPTER VI

VI.1 Partial Core Inventory Listing at t = 0, and Radionuclide Grouping by Elemental Volatility 345

VI.2 Basic Chemical Compound Volatility Data for Radioisotopes with Release Data for the Chornobyl Accident 347

VI.3 Chornobyl Unit-4 Fuel Assembly Group-Average Burnup 350

VI.4 Core Inventory Estimates for Chornobyl Unit-4 at the Time of the Accident 352

VI.5 RBMK-1000 Equivalent Cell Dimensions and Material Concentrations 356

VI.6 Radioisotope Composition of Releases from Unit-4 According to the Soviet's Vienna Report 359

VI.7 Far-Field Estimates of Chornobyl Unit-4 Releases 359

VI.8 Warman Composite Source-Term Estimates for the Chornobyl Accident 360

VI.9 Ilyin et al, I-131 and Cs-137 Chornobyl Unit-4 Release Estimates 362

VI.10 Soviet/IAEA Radioisotope Release Data 365

VI.11 PROBA Fractional Activity, ∂_i, Release Data 368

VI.12 Combined Data for the Fission Product Fractional Activity, ∂_i 371

VI.13 Soviet Data Consistency Check 372

VI.14 Radioisotope Fractionation Factor, $k_{i\text{-}95}$, During the Active Phase 382

VI.15 Estimated Lower-Bound Activity Releases from Chornobyl 394

APPENDICIES

III.B Chornobyl Unit-4 Design Parameters 421

Reactor 422
Power Generation 423
Technological (Fueled) Channels 424
Control System 425
Cooling Circuit 426
Reactor Shaft Construction 427
Chemical Composition of Soviet Concretes 430
Composition of Soviet Stainless Steels 431

III.C Nuclear Power Reactors of the Commonwealth of Independent States 433

V Detailed Classification of LFCMs and Results of Analyses 443

VI.A Chornobyl Unit-4 Technological (Fueled) Channel Burnup Data 471

VI.B Selected Radioisotope Core Inventory Data for Chornobyl Unit-4 479

This Page Has Been Left Intentionally Blank.

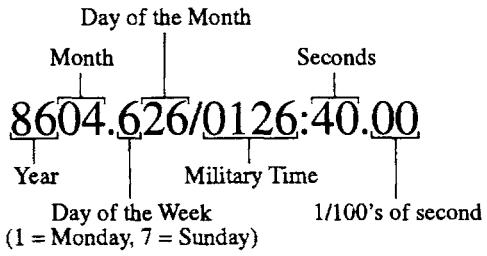
TERMINOLOGY AND TRANSLITERATION

This dissertation endeavors to be faithful to Ukrainian, Russian, and Belarusian language transliteration systems based on slightly modified versions of ones employed by the Library of Congress and the National Geographic Society. (See the Transliteration Table below.) It is hoped the convention adopted here will help to alleviate the obfuscation caused by Russian place names being used for Belarusian and Ukrainian ones before the dissolution of the Soviet Union.

For readability, the non-palatalizing "hard sign" that appears in the middle of certain Russian words (which indicates a hard separation between certain consonant-vowel pairs as in отъезд – ot"yezd [departure]), as well as the Ukrainian apostrophe (e.g., in п'ятниця – p"jatnytsja [Friday] that serves the same purpose) are dropped. Furthermore, the plural forms of Ukrainian and Russian words appearing in the text are given as English plurals, i.e., they end in "s". (References, bibliographic entries, and block quotes, however, are transliterated directly, or, if originally in English, remain in this, albeit incorrect, form.) Consequently, an exception to the usual system of transliteration is made in the case of words in which the final consonant is soft. The apostrophe that ordinarily indicates the "soft sign" following certain consonants at the *end* of East Slavic language words (as, for example, in the Ukrainian and Russian word *oblast'* – a major territorial administrative unit in Ukraine or Russia similar to a state in the United States) is omitted, because the "s" in the plural preceded by an apostrophe could easily be confused with the English genitive. Finally, as indicated in the table by letter pairs within parentheses, a transliteration exception is made for East Slavic soft vowels (я, ё, є, ї, ю) and the consonant й that appear as the first letter in a word because no independent English equivalent exists for them. Thus, by convention, the Ukrainian word ясно [clear, bright] is rendered as *Yasno* rather than *Jasno*.

With slight exceptions as noted above, all place names in Belarus and Ukraine are rendered in transliterations from the Belarusian and Ukrainian. For example, the original Ukrainian form is retained in the following words: Chernobyl becomes Chornobyl; the Dniepr River becomes the Dnipro River; and Kiev becomes Kyjiv. This is done for two reasons. First, because it is incongruous to use non-Belarusian or non-Ukrainian place names when writing about geographic locations within these two countries – at the very least, with the breakup of the USSR, the emergence of Belarus and Ukraine as independent nuclear powers requires this; and second, this eliminates the confusion that would result where the place name corresponding to a historical period in question is to be used. For example, depending on the period and the controlling régime, the city of L'viv could have been referred to as Lwów, L'vov, or Lemberg. Certainly, the use of "L'viv" alone is simpler. The article "the" preceding the proper name "Ukraine" is omitted to conform with the accepted Ukrainian form;† while names of places outside East Slavic lands are given in the accepted English form or are transliterated from the language of the country where they are located. For the more commonly used words in the literature that are socio-politically *de origine* Russian (such as *glasnost* and *perestroika*), the Russian form is retained. (The Ukrainian forms of these words are respectively *hlasnist* and *perebudova*.)

The convention adopted for presenting the date and time is as follows:



† "The AP will also drop the article 'the' that has preceded the word 'Ukraine.' This is in line with the English-language usage preferred by Ukraine's government." For a summary of news agencys' adoptions of the correct editorial style, see "The 'the' is Gone", *The Ukrainian Weekly*, Vol. LIX, No. 49 (Sunday, December 8, 1991): 5.

Table 0.1

Transliteration of Belarusian, Russian, Ukrainian Into English

Ukrainian	English	Russian	English	Belarusian	English
А	A	А	A	А	A
Б	B	Б	B	Б	B
В	V	В	V	В	V
—	—	—	—	у	W
Г	H	—	—	Г	H
Ґ	G	Г	G	—	—
Д	D	Д	D	Д	D
Е	E	Е	E (Ye)†	Е	Je (Ye)
Є	Je (Ye)	—	—	—	—
—	—	Ё	Ë (Yo)	Ё	Ë (Yo)
Ж	Zh	Ж	Zh	Ж	Zh
З	Z	З	Z	З	Z
И	Y	—	—	—	—
І	I	И	I	І	I
Ї	Ji (Yi)	—	—	—	—
Й	J (Y)	Й	J (Y)	Й	J (Y)
К	K	К	K	К	K
Л	L	Л	L	Л	L
М	M	М	M	М	M
Н	N	Н	N	Н	N
О	O	О	O	О	O
П	P	П	P	П	P
Р	R	Р	R	Р	R
С	S	С	S	С	S
Т	T	Т	T	Т	T
У	U	У	U	У	U
Ф	F	Ф	F	Ф	F
Х	Kh	Х	Kh	Х	Kh
Ц	Ts	Ц	Ts	Ц	Ts
Ч	Ch	Ч	Ch	Ч	Ch
Ш	Sh	Ш	Sh	Ш	Sh
Щ	Shch	Щ	Shch	—	—
—	—	Э	E	Э	E
Ю	Ju (Yu)	Ю	Ju (Yu)	Ю	Ju (Yu)
Я	Ja (Ya)	Я	Ja (Ya)	Я	Ja (Ya)
—	—	Ы	Y	Ы	Y
Ь (soft sign)	’	Ь (soft sign)	’	Ь (soft sign)	’
’	”	Ъ (hard sign)	”	—	—

† If it appears as the initial letter in a word, or after vowels and after ь or ъ, e = ye, otherwise e = e.

This Page Has Been Left Intentionally Blank.

Присвячується

багатостраждальному Українському Народові –

жертві злочинного комуністичного режиму,

що на віки залишив

на землі,

у водах,

в крові теперішніх і

в плоді майбутніх поколінь

радіоактивний слід чоронобильської аварії;

З вірою в те,

що Бог не відрікся від своїх дітей

і через їхнє духовне відродження

зцілить їхні тіла та їхню землю...

This Page Has Been Left Intentionally Blank.

CHAPTER I

INTRODUCTION: BACKGROUND AND BASIS FOR THIS DISSERTATION

"Information about the unfavorable ecological impact of energy-related facilities (the effects of electromagnetic fields, irradiation, contamination of air, water, and soil) on operational personnel, the population, and the environment shall not be reported openly in the press or broadcast on radio or television."

– Order signed on 19 May 1985 by Anatolij Ivanovich Mayorets, USSR Minister of Energy and Electrification.

"Extensive, timely, and frank information is evidence of trust in the people, respect for their intelligence and feelings, and of their ability to understand events of one kind or another on their own."

– Mikhail S. Gorbachev, (former) General Secretary of the Communist Party of the (former) Soviet Union, from his keynote statement to the 27th Soviet Communist Party Congress.

Let's consider this: If the official version of the reason for the accident is accurate and fair, then why was all evidence about the accident made secret?

– Anatolij Stepanovich Djatlov in *Komsomol Banner*, April 20, 1991; Former Deputy Chief Engineer for ChNPS–4, sentenced to 10 years imprisonment for criminal negligence, released in 1991 on good behavior.

I.1. Contradictions and Cover-up

Nuclear engineers have reached a consensus that the main cause of the Chornobyl accident (from the technical point of view) was reactor instability – due mainly to design shortcomings of the RBMK-1000 reactor combined with violations of operating procedures.* More broadly, the accident was a direct result of fundamental design and adminis-

* In their INSAG-7 report published January 1993, the IAEA's International Nuclear Safety Advisory Group identified the root cause of the Chornobyl accident as the RBMK reactor design, and firmly shifted the blame from the operators to the designers. (Their original report, written on the basis of partial and slanted material provided by Soviet officials a few months after the accident, laid a large part of the blame on the Chornobyl-4 operators.) It is also clear that the design faults identified in the report are associated with features of the RBMK that were intended to make it a more efficient reactor. The most serious indict-

trative deficiencies. Strong management emphasis had been given to the importance of running the safety test before Unit-4 was shutdown for scheduled maintenance. Management and operator actions placed a reactor of deficient design into progressively more unsafe configurations.

Various aspects of the accident that led to the destruction of Chornobyl Unit-4 have, to a greater or lesser extent, been studied and understood. The possibility of a large-scale imbalance in the neutron flux, the influence of thermo-hydraulic instabilities and pump cavitation, the faulty design of the emergency control (scram) rods, operator actions, etc. – all of these played an important role in the development of the accident. Although certain unknown details may not change the general overview of the processes and main conclusions on the causes of the accident, their careful re-examination should be conducted with emphasis placed on the study of initial data on the operation of Unit-4 just prior to the accident that is now becoming available.

In contrast, the "Active" or "Source Term" Phase of the accident is investigated to a far lesser extent because little beyond scant descriptive information has been published or made available by the Russians or Ukrainians. The Active Phase of the accident is defined as the period from the initial destruction of the core due to the violent interaction of fragmented or molten fuel as it came into direct contact with the primary coolant and sub-

---

ment in the INSAG report is the revelation that problems now recognized in the RBMK plant design had in fact been recognized before the Chornobyl accident.

Interestingly, Bohdan Bociurkiw, a 1984-85 fellow at the Woodrow Wilson International Center for Scholars and professor of political science at Carleton University, stated immediately after the accident that, "After the smoke clears from the Chornobyl accident Moscow will make strident attempts at 'searching for a scapegoat' for internal purposes. In an attempt to maintain face before its own people, the Kremlin leaders will likely point an accusing finger for the embarrassing mishap not at themselves, but towards the management of the Chornobyl power plant, and possibly the Soviet ministry responsible for energy."[Bohdan Bociurkiw, "Ramifications of the Chornobyl Catastrophe," *The Ukrainian Weekly* , Vol. LIV, No. 18 (May 4, 1986): 1.] As if on cue, *Pravda* (15 July 1986) reported that the director of the Chornobyl power station, Viktor Bryukhanov, and the chief engineer, Nikolai Fomin, were sacked because they were "unable to ensure the correct firm leadership and proper discipline." ["Gorbachev Speaks On Chornobyl Accident. . . ," *The Ukrainian Weekly* , Vol. LIV, No. 20 (May 18, 1986): 1.] *Pravda* continued by saying that the two officials "showed irresponsibility and inefficiency. They were unable to assess what had happened or to take measures to organize efficient work by all sub units following the accident." *Pravda* also said that Alexander Sicharenko, an engineer and local party official from Prypjat, and another party official, Aleksandr Shapoval, had ignored their duties during the evacuation of employees and residents. Mr. Shapoval was stripped of his Communist Party membership while Mr. Sicharenko was given a "sever reprimand."

sequent steam explosion, to the puzzling and very sharp drop in the release of radionuclides into the environment approximately ten days following the accident. It is this stage that determines the distribution and state of the fuel after the explosion(s) and, consequently, the local conditions during the activity releases of the Active Phase. An examination of Chornobyl releases in terms of physical and chemical processes taking place within the reactor fuel during the Active Phase would be useful if a relationship could be established between these processes and the observed releases of radioactivity. In turn, it may be possible to determine if observations during the Chornobyl accident have any relevance or applicability to source term predictions for severe accidents at other types of reactor installations in the West.[1] Finally, if a reliable model can be established, it may be possible to account for discrepancies in far-field measurements of fallout from the accident with those presented by the Soviets at Vienna. This would prove invaluable for radiological experts to determine the extent of contamination shortly after the accident, and by extension, for comparisons with the currently observed rise in children's thyroid cancers in Ukraine and Belarus.[2]

Indeed, one of the frustrating consequences of the accident is the gap between the conclusions of scientific research and the realities of the effects of the accident among the population at large and upon the surrounding environment.[3] While some scientists and

---

[1] D. A. Powers, T. S. Kress, and M. W. Jankowski, "The Chernobyl Source Term," *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 9.

[2] In Belarus, for example, the incidence of thyroid cancers in children has increased from approximately two cases per year before Chornobyl to thirty cases in the first half of 1992 alone. More than half (71) of the 131 cases reported to mid-1992 since 1986 were in the Homel oblast (state) just north of the Kyjiv oblast in Ukraine where the Chornobyl Station in located. [Gamini Seneviratne, "WHO Says Belarus Cancers May Stem From More Than Chernobyl," *Nucleonics Week*, Vol. 33, No. 51 (December 17, 1992): 12.] In another article, a group from the World Health Organization states that "The Belarus experience 'suggests that the consequences to the human thyroid, especially in fetuses and young children, of the carcinogenic effects of radioactive fallout are much greater than previously thought.'" [Ann MacLachlan, "Rising Children's Thyroid Cancers Indicate Growing Chernobyl Link," *Nucleonics Week*, Vol. 33, No. 37 (September 10, 1992): 8.]

[3] Only one of several studies that contradict official Soviet figures presented at the Vienna Meeting of Experts is Edward A. Warman, *Soviet and Far-Field Radiation Measurements and an Inferred Source Term From Chernobyl*, Presented at the New York Chapter Health Physics Society Symposium on the Effects of the Nuclear Reactor Accident at Chernobyl, April 3, 1987, Brookhaven National Laboratory. Warman concludes that, "Approximately 30 to 50 percent of the available radiocesium and at least 40 to 60 percent of the available radioiodine appear to have been released to the atmosphere during the accident."

engineers have concluded that in certain cases radiation fallout was too low to have significant effects, in many villages there has already been a discernible and even alarming rise in oncological sicknesses – even though the latent period for these cancers is somewhat greater than the time since the accident.* In addition, although the Soviets are to be commended for displaying a great deal of candor at the Vienna meeting in August 1986, fission product release information presented there must be reviewed to determine which data may be reliably used to estimate release rates during the Active Phase of the accident. Because of circumstance and the general unpreparedness of the Soviets for an accident of this magnitude – in part, brought on by their relatively lax attitude toward nuclear safety[4] – much of the information, including information on the source term, is presented in a roughly summarized fashion. Moreover, there are many gaps in the information that render some of it (excepting general descriptive accounts of what may have occurred a few days after the accident) virtually unusable.

The advent of what some would call "true" *glasnost* in the wake of the Chornobyl accident has heralded disclosures of cover-ups regarding the magnitude and extent of the accident.[5,6,7,8] Belarusian, Russian, and Ukrainian scientists have intimated in the press

---

This is in stark contrast to the officially reported releases of 10% Cs-134, 13% Cs-137, and 20% I-131 at the IAEA's Meeting of Experts in Vienna in August 1986.

* There is general agreement among cancer researchers that few cancers will appear before a "latent" period. That period is five years for leukemias, fifteen years for some other tumors, but maybe as little as two years for childhood leukemias and thyroid cancers.

[4] See, for example, Chapter 5 "Safety in the Soviet Nuclear Power Industry" in David R. Marples, *Chernobyl & Nuclear Power in the USSR*, St. Martin's Press, New York, 1986; Maurice Strong, "40 Chernobyls Waiting to Happen," *The New York Times*, Vol. CXLI, No. 48913 (Sunday, March 22, 1992): 15; and "Chernobyls-in-Waiting," *The Economist*, Vol. 324, No. 7772 (August 15, 1992): 18. Moreover, INSAG-7 concludes that the Chornobyl accident stemmed from a deficient safety culture – not only at the Chornobyl Station, but throughout Soviet design, operating, and regulatory organizations for nuclear power that existed at that time.

[5] Esther B. Fein, Soviets Curb News About Disasters, *The New York Times*, Vol. CXXXVIII, No. 47,853 (April 27, 1989): A15.

[6] Peter Gumbel, Villagers Suffering Chernobyl's Fallout Face Soviet Silence, *The Wall Street Journal*, Vol. CCXIII, No. 44 (March 6, 1989): A1.

[7] "New criminal charges concerning Chernobyl are being prepared by the Soviet Union's prosecutor general, Nikolai Trubin. In early February, Trubin alleged that the extent of the Chernobyl-4 accident in 1986 was covered up at the time, and also that officials have not sufficiently protected people from the effects of the released radioactive material for years since then." ["Late News in Brief," *Nuclear News*, (March 1991): 99.]

[8] Chrystia Freeland, "Waiting for the Next Chernobyl," *The Financial Times of London*, No. 32,043, Week 16, (April 21, 1993): 20.

and to some of their colleagues in the West that there truly are a number of Chornobyl accident consequences and much data not discussed in the initial Soviet report at Vienna† – despite the apparent openness of the Soviets in describing the accident.[9] For instance, it is now known that several pages detailing large quantities of radionuclides deposited 100 km and more northeast of Chornobyl were removed from the Vienna report following directives from the Soviet Central Committee.[10] The Soviet press in 1989 began carrying more and more articles calling for an investigation into the "real" causes and circum-

---

For a more extensive treatment of these cover-ups, see the section "Coverup and Controversy" and "The Wages of Fear" in Murray Feshbach and Alfred Friendly, Jr., *Ecocide in the USSR: Health and Nature Under Siege*, New York: Basic Books, Inc. (1992): 150–154.

† I have spoken with a number of Russian and Ukrainian scientists over the past three years who assure me there is unreleased information on almost every aspect of the accident – most of which forms the bulk of the as yet inaccessible Soviet Government Commission's archives on the accident.

[9] The first hint that the Soviets were not completely forthright at the meeting of experts in Vienna in August 1986 was Academician Valerij Legasov's statement before the Soviet Academy of Sciences in October 1986, "I did not lie at Vienna, but I did not tell the whole truth." Mallinckrodt Professor of Physics, Dr. Richard Wilson of Harvard University, was quoted this by Academician Andrei Sakharov in February 1987 – confirming what several experts had been cautiously wary of at the Vienna meeting. Even more unfortunate, under the pretext of avoiding mass hysteria and "radiophobia" in the wake of the accident, it was clear from the Soviet press that the central authorities told even less to their own citizens. For example, it was not until February 1989 that the republican governments of Belarus and Ukraine published maps of radiation fallout – followed hastily by the all-union authorities publishing a similar map in *Pravda*. Moreover, in the November 1990 issue of *Природа* (Nature) Kalugin wrote that "The members of the Soviet delegation were strictly instructed not to meet with foreigners, not to answer any questions on their part, and to follow the published word in every respect. Only because of the resolute stand taken by [Dr. Valerij] Legasov was it possible to go away from this policy."

[10] From a private conversation with Prof. Richard Wilson of Harvard University, July 1990. One year later, speaking at the 1st International Sakharov Conference on Peace, Progress, and Human Rights in Moscow (May 22, 1991), Prof. Wilson summarized several aspects of the accident's consequences subjected to secrecy by the Soviet central authorities:

- About six pages concerning radioactivity released in Belarus were removed from the official report just prior to the August 1986 IAEA meeting and were not discussed,
- Several pages detailing large quantities of radionuclides deposited 100 km and more northeast of Chornobyl in the Brjansk oblast of Russia were removed from the report following directives from the Soviet Central Committee,
- Dosimeters in possession of physicians and private individuals were locked up by the KGB,
- Publication of "unauthorized" measurements of radioactivity were forbidden – and *even in 1990 still were forbidden* (emphasis added),
- Scientists who lectured on radioactivity to the public were forbidden to quote foreign sources of information,
- Physicians in Ukraine and Belarus were forbidden to mention radiation in their diagnoses,
- Appeals by private individuals in Belarus to children not to drink milk in the first weeks of May 1986 were stopped for fear they might cause panic,
- All health records of the "liquidators" of the consequences of the accident (soldiers and others who worked cleaning up the 30-km exclusion zone and constructing the sarcophagus) are "missing." [Since the collapse of the USSR, this data has begun to slowly surface.]

The first point in this list is confirmed by Piers Paul Read; and in fact, the removal of the "six pages covering the serious contamination of the area north of G[H]omel had been removed. [Prof. Richard] Wilson was later told that this had been done on Legasov's instructions." [Piers Paul Reid, *Ablaze*, New York: Random House, (1993): 207.]

stances surrounding the accident alleging that the environmental impact was "tremendously downplayed," and that (then) Prime Minister Nikolai Ryzhkov played a "major role in a cover-up of the effects of the accident."[11] These allegations were confirmed in mid-1989 (more than three years after the accident) when, under pressure of public opinion in the wake of *glasnost*, a secret decree of the USSR Ministry of Health (June 27, 1986) ordering a cover-up of the Chornobyl accident and its effects upon the populace and clean-up workers was rescinded.[12] Decisive action, however, had to await Ukraine's independence declaration of August 24, 1991 and its December 1st independence referendum. Almost immediately following the referendum, a special committee of the Ukrainian Parliament presented to Ukrainian and Russian State Prosecutors evidence for a top-level conspiracy to cover-up of the extent and severity of the accident. Included among the conspirators in the cover-up are former Soviet President Mikhail Gorbachev, former Soviet Prime Minister Nikolai Ryzhkov, the former head of the Ukrainian Parliament Volodymyr Shcherbyts'kyj, and former Ukrainian Minister of Health Anatolyj Romanenko.[13]

---

[11] Yevgenia Albats, "The Big Lie: Who Will Answer for Hushing Up the True Causes and Consequences of the Chernobyl Tragedy?" *Moskovskiye Novosti*, (October 15, 1989): 8–9. See also N. Matukovskyj, "Catastrophe: What the Lessons of Chernobyl Teach" *Izvestia*, N° 86 (22989), (March 26, 1990): 3.

[12] Любов Ковалевська, «Лікарі в ролі адвокатів Мінатоменерго,» *Українська Газетта*, № 3 (1–7 квітня, 1993): 4. Disclosed is a document entitled "About the Strengthening of the Regime of Secrecy During the Implementation of Task Regarding the Liquidation of the Consequences of the Accident at the ChNPS," [by order of the Head of the Main Administrative Division of the USSR Ministry for the Protection of Health, Ye. Shul'zhenko, [U-2617 "S"] signed June 27, 1986]. Some points in the document are,

#4. Make secret data about the accident.

#8. Make secret data about the consequences of medical practices provided.

#9. Make secret data about the level of contamination of personnel who took part in liquidating the consequences of the accident at the ChNPS.

In addition, in an *Izvestia* article entitled "Forty Secret Protocols of the Kremlin Wise Guys: The Lie About Chornobyl is as Frightening as the Catastrophe Itself," excerpts from government documents show that party leaders from Mikhail Gorbachev on down concealed the danger to the civilian population from Chornobyl. Soviet leaders effectively denied medical care to tens of thousands of people living in contaminated areas by secretly decreeing a 10-fold increase in the amount of radiation considered safe. They also permitted meat and milk from the contaminated area to be mixed with produce from other regions. [Ярошинская, Алла, «Сорок секретных протоколов кремлевских мудрецов: Ложь о Чернобыле так же страшна, как и сама катастрофа,» Известия, N° 98(23672), (24-го апреля 1992): 3.]

[13] Based upon special investigations by two parlimentary Chornobyl commissions into the coverup of the consequences of the accident, a resolution passed by the Ukrainian *Rada* (Parliament) on December 11, 1991 implicated the former Soviet and Ukrainian leadership in "a criminal disregard for the lives of hundreds of thousands of victims of the Chornobyl catastrophe." The evidence has been submitted to Ukrainian and Russian state prosecutors for further investigation. Implicated on the all-union side are (all former po-

One of the most persistent myths concealing the full extent of the accident – and perhaps the most relevant factor for a proper source term analysis – is the unchallenged claim by the Soviets at Vienna that the 5020 tonnes of sand, clay, dolomite, boron carbide, and lead dropped by helicopters on top of the reactor during the Active Phase of the accident, and a liquid-nitrogen purging of the core, together succeeded in cooling, smothering, and sealing the core almost completely from the environment and stopping the further release of radionuclides.[14] Although INSAG-1 provides a generally positive appraisal of these Accident Management [Mitigation] Actions (AMAs),[15] serious doubts as to the validity of Soviet release estimates arose quite soon after the accident that pointed to the inconsistencies of far-field release estimates with those of the Soviets.[16] Inexpli-

---

sitions) Soviet President Mikhail Gorbachev, Prime Minister Nikolai Ryzhkov, KGB chief Viktor Chebrykov, Yegor Ligechëv, Defense Minister Dimitri Yazov, Chairman of the Soviet Commission on Chornobyl Boris Shcherbyna, Chairman of the USSR State Institute on Hydrometeorology and Enovironmental Control Yurij Izrael, and Chairman of the Soviet National Radiological Protection Board as well as Director of the Moscow Institute of Biophysics of the Academy of Medical Sciences of the USSR Leonid Ilyin. Implicated on the Ukrainian side are (all former positions) Party Chief Volodymyr Shcherbyts'kyj, Prime Minister Oleksander Ljashko, Parliament Chairperson Valentyna Shevchenko, Chornobyl Commission Chairman Victor Kacholovsky, Health Minister Anatoly Romanenko, Kyjiv Oblast Party First Secretary Grigory Revenko, and Ihor Likhtarjov of the Center for Radiological Medicine, as well as others.

[14] U.S.S.R. State Committee on the Utilization of Atomic Energy (comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Part I: General Material,* report presented at the International Atomic Energy Agency Expert's Meeting, Vienna, (August 25–29, 1986): 41. This is not to imply that during the Active Phase it was necessarily known that the core was uncovered. It appears this was a mistake and not known for some time – how much time is not clear. However, certainly by the August 1986 meeting, after Soviet RBMK experts would have had over three months to examine directly the remains of the reactor building by flying over it in a helicopter (well as the hundreds of photographs of the core shaft region), someone would have realized that the core had, in fact, not been covered. See Chapter IV.

[15] "The accident management actions taken at Chornobyl were, generally, quite successful... [the] dumping [of] materials into the reactor well..., supplying nitrogen to bring down the temperature in the core space and to reduce the oxygen concentration, and the construction of a flat heat exchanger beneath the foundations of the reactor building, stabilized the situation at an early stage (about nine days after the initiating power surge) of the accident." [The International Nuclear Safety Advisory Group (INSAG-1), *Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident.* August 30 – September 5, 1986, International Atomic Energy Agency (IAEA): Vienna, Austria, GLC(SPL.I)/3 Safety Series No. 75-INSAG-1, (September 24, 1986): 43.] See also Jankowski, M. W., D. A. Powers, and Kress, T. S., "Onsite Response to the Accident at Chernobyl (Accident Management)," *Nuclear Safety,* Vol. 28, No. 1 (January–March 1987): 36–42.

[16] Warman, 1. See also the 100% core-inventory radioiodine release estimate in an unpublished paper cited in D. A. Powers, "Carburization as a Mechanism for the Release of Radionuclides During the Chernobyl Accident," In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989,* edited by E. P. Velikhov and L. A. Bolshov, Moscow, Russia: Nauka , 117; and a table summarizing release estimates from a number of countries on page 6-12 in U. S. Nuclear Regulatory Commission, comp, *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250), Washington, DC: U.S. Government Printing Office, (1987).

cable in particular (and questioned by western experts) is the curious shape of the total activity release curve (known as the "bathtub" curve and reproduced as Figure VI.4) obtained from Soviet data.[17] Also rather puzzling is that the supposed filtration provided by the materials thrown onto the core and cooling of the core by liquid nitrogen seems not to have been effective in impeding the release of volatile radionuclides – especially if one considers the far-field estimates to be more representative of Chornobyl releases.

In fact, as this dissertation will detail, in contrast to what was reported by the Soviets in August 1986, the material thrown onto the core in an attempt to smother the burning fire and the purging of the core with (ostensibly *liquid*) nitrogen were not successful. The implication is that the core "burned" virtually uncovered during the Active Phase of the accident – releasing radioisotopes into the upper levels of the destroyed reactor building and directly into the atmosphere. This not only calls into question Soviet and western analyses of Chornobyl source term releases,[18] but also may have important ramifications for the planning of western accident management strategies. Moreover, the health impact

---

The widely ranging estimates are partially due to the generally unrefined and sketchy data presented in Vienna by the Soviets, and that most release data was suppressed until approximately 1989–90 – which did not provide a complete picture of how much contamination was deposited on the territory of the former Soviet Union. Only now, as new release data and analyses of fuel masses remaining within the sarcophagus are being made available, is it clear that earlier western suspicions were justified.

[17] U.S.S.R. State Committee on the Utilization of Atomic Energy, Volume II: Accompanying Material, Appendix 4 'Appraisal of the Quantity, Composition and Release Dynamics of Radioactive Materials from the Damaged Reactor,' Table 4-13, (20). The Soviet claim that the data in Table 4-13 of this report has a ±50% margin of error is doubted by some in the West. By implication, this calls into question the shape of the curve and hypotheses that attempt to explain the nature and dynamics of releases during the Active Phase of the accident, as well as the reliability of the Soviet data presented in Vienna. These problems will be addressed in more detail in Chapter VI "Source Term Analysis."

[18] Although lacking the new information about the fact that this material had not entered the core shaft, Powers et al provide an excellent source term analysis of the data presented by the Soviets in Vienna [Powers, D. A., T. S. Kress, M. W. Jankowski, "The Chernobyl Source Term," *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 9–28.] In contrast, a rather complex but poorly substantiated theoretical analysis of the supposed filtration cooling of the core through the dumping of the materials is presented in Maslov, V. P., Myasnikov, V. P., and Danilov, V. G., Filtering Cooling Model for the Pile-Up in the ChAPP Accident Block," *Fission Product Transport Processes in Reactor Accidents, Proceedings to the International Center for Heat and Mass Processes, Dubrovnik, Yugoslavia, May 22-26, 1989.* The conclusion section of this paper is particular poor because it appears to conlcude what the authors wanted in the first place: (1) that their filtration cooling model applies well to explain the drop and subsequent rise in total releases (hence giving the peculiar "bathtub" curve shape), (2) that "the filtration cooling model of the pile-up *completely explains all the phenomena* taking place in the reactor after the accident" (emphasis added), and (3) that "the convective cooling model convincingly explains, why [corium] fragments did not burn through the bottom of the reactor pit [Lower Biological Shield (LBS)]" – when, in fact, the LBS was completely penetrated by the corium.

to former residents of the 30-km exclusion zone surrounding the station (some of whom were not evacuated from this area until 8.5 days after the accident)[19] must be re-examined in light of the greater releases suggested by this scenario.

I.2. Defining the Problem

Because of the extensive gaps in information that exist on the Chornobyl accident, a more rigorous approach to the study of the consequences of the accident should be established. To begin such an investigation, one must have some understanding of the possible release paths available for radioactive nuclei to escape into the environment. Below are outlined five "nodes" in a general release path that must be studied and modeled to determine accurately the extent of contamination as well as to provide a consistent release model for possible future nuclear accidents, and most importantly in the near-term, to provide a scientific basis for the construction of a second, more permanent cover for the destroyed reactor.

1) **source term** – The extent, nature, and rate of radioactive materials released during an accident is known as the "source term" because it is the source in any calculation of dispersion of radionuclides. The inventory of radioactive materials within the reactor core at the time of the accident is assumed to be known or may be confirmed by working this path backward from ground contamination measurements or affects on the environment.

2) **efficacy of release mechanisms** – Given a description of the reactor, surrounding materials and structures, operating conditions at the time of the accident, the physicochemical processes of the accident itself, and actions taken to control and seal-off the core from the environment immediately following the accident, it is possible to devise a model that will predict the most probable paths for the release of radioactive materials into the environment.

---

[19] Ю. В. Сивинцева и В. А. Качалова, общие редакторы, *Чернобыль: Пять трудных лет*, Москва: Издат, (1992): 251. Evacuation of the more 49,000 residents of Prypjat began 36.5 hours after the accident, while evacuation of the remaining towns and villages (including the town of Chornobyl with 12,500 residents) took more than a week. Altogether, from April 27th through August 16th, 90,784 people were evacuated from 75 population centers in Ukraine – 89,489 from the Kyjiv oblast and 935 from the Zhytomyr oblast.

3) **weather conditions** – If weather patterns and conditions are known at the time of the accident and for a given time after the accident, it is possible to devise dispersion models that are capable of simulating dispersion on various spatial scales that range from local to continental scales. These models should ideally include turbulence, precipitation scavenging, and deposition parameterizations as well as wind field derivations, terrain effects, and radioactive decay.

4) **ground and air contamination** – Although there may be abundant data collected through measurements of ground contamination and dose rates collected by Soviet scientists, either not all of this data is officially available or it is of little value because poor measurement techniques were employed. One should also consider that, because of cases reported already, some of the data was improperly selected and may even have been purposely altered to play down the consequences of the accident. The Soviet data published so far seems somewhat inconsistent. It is essential, therefore, not only to check Soviet data against itself and western data, but also to understand the Soviet's data collection and interpretation procedures.

5) **effects on vegetation, animals, and humans** – Effects from radioactive contamination have been observed and documented – although not very extensively. These include observations of an increase (especially in children) in radiation-related illnesses of the thyroid, deficiencies in their immune systems, cataracts, tumor sicknesses; along with deformed animal offspring and mutated plant life. Much more work needs to be done in this area to confirm or reject data collected for ground and air contamination.

The focus of the investigations for this dissertation will be the Active Phase of the accident (nodes 1 and 2 above). As such, the dissertation will reassess accident management actions and their effects on releases, results of chemical and radiometric analyses of materials released, the distribution of fuel and graphite, conditions of areas inside Unit-4, the composition of the "slag" or lava, and fission product and fuel mass balances.

Measurement and study of the remaining long-lived radionuclides located within the damaged unit along with an analysis of fragments of destroyed core (graphite, fuel, zirconium tubes) are currently being conducted by the *Inter-Agency Scientific & Technical*

Center "Shelter" (MNTTs) of the Ukrainian Academy of Sciences (formerly the *Chornobyl Complex Expedition* of the Kurchatov Institute of Atomic Energy in Moscow) to determine as accurately as possible what fraction of the initial core fuel load* remains within the sarcophagus, what state the fuel and damaged building are in, and how the sarcophagus† affects the surrounding environment. Unfortunately, because of an acute lack of qualified specialists and financial support, the extremely dangerous conditions within the debris of the destroyed reactor building, and other problems associated with the collapse of the Soviet Union, approximately eleven tonnes of the fuel have not been positively located to date (Chapter V). The fraction of the core ejected in the form of very large "chunks," and portions of fuel elements deposited on-site and very near to the site remain unquantified, the amount of fuel located in the Central Hall of Unit-4 under approximately 16,500 tonnes of various materials dropped from helicopters in the month following the accident is unknown, and the amount of fuel in the form of small particles and "dust" that coats essentially everything within the sarcophagus can only be roughly estimated. Moreover, only recently has an attempt been made to organize what data has been collected into a viable computer data base. However, problems concerning the disclosure of the former Soviet Government's Chornobyl Commission archives on the accident, propriety of information, economic priorities, and questions of sovereignty for the newly emerged nations of the former Soviet Union are hindering the MNTTs's effort to collect and organize this data.

Finally, to properly pose the problem, it is important to define various time intervals or phases of the accident – from before the start of the safety experiment prior to the initial explosions that destroyed the core and surrounding structures, through the construction of a second, more permanent isolation building "Shelter-II." This was necessary not only to distinguish the Active Phase of the accident for this dissertation, but also for plan-

* Just before the accident, Unit-4's core contained 190.3 tonnes of UO_2 fuel with an average burnup of 10.9 MW·d/kg U.

† The concrete and metal containment or "sarcophagus" covering the destroyed reactor, reactor building, and adjacent structures has been dubbed "Shelter" (in Ukrainian Укриття or 'Ukryttja').

ning purposes in the design and implementation of the final entombment of the damaged reactor. The full history of the accident may be broadly divided into four phases – each concerned with fundamentally different aspects of the accident: (1) actions and events prior to the accident that lead to the physical destruction of the core, (2) the "Active Phase" of the accident, (3) isolation of the damaged reactor from the environment; limitation, localization, and study of the consequences of the accident, (4) the "Shelter-II" period in which the reactor is hermetically sealed from the environment; continued study of the consequences of the accident and cleanup of the surrounding regions. The following outline summarizes the history of the Chornobyl accident as defined for this study.

ACCIDENT HISTORY

Phase I Events and actions prior to the accident itself which lead to the physical destruction of the reactor

a) Phase IA This subphase is signified by the multiple violations of operating procedure (both in the plan of the experiment and in normal reactor operation) by the operators which placed the reactor into increasingly unstable conditions.

8604.525/0100:00	Permission given by dispatcher to operators to proceed with planned power decrease to one-half power.
8604.626/0123:04	Operator trips turbine to begin safety experiment.

b) Phase IB This subphase is signified by the poor and unforgiving design of reactor outpacing any and all efforts by the operators to avert disaster.

8604.626/0123:04	Operator trips turbine to begin safety experiment.
8604.626/0123:44(?)	Start of physical destruction of the reactor.

Phase II The "Active Phase" of the accident

8604.626/0123:44(?)	Start of physical destruction of the reactor.
8605.105	Sharp drop in release of radionuclides from the reactor and stabilization.

Phase III Isolation of the damaged reactor from the environment; limitation, localization, and study of the consequences of the accident

a) Phase IIIA

8605.206	Situation stabilized.
8611	Shelter-I construction completed.

b) Phase IIIB

8611	Shelter-I construction completed.
at present	continued isolation of contaminated areas, study of the consequences of the accident, diagnosis of destroyed Unit-4, location and mapping of materials released, preliminary plans for Shelter-II.

Phase IV "Shelter-II" period

a) Phase IVA

at present	Study and plans for Shelter-II.
early future	Construction of Shelter-II – final isolation of Unit-4 from the surrounding environment.

b) Phase IVB

early future	Construction of Shelter-II.
future	Continued study of accident; continued isolation and clean-up of contaminated regions.

I.3. Objectives of this Dissertation

This dissertation is concerned with reconstructing the sequence of events during the Active Phase of the Chornobyl Unit-4 accident, and with providing a new source term estimate. As such, it hopes to shed some light on a number of puzzling phenomenon that occurred during the Active Phase – such as the sudden and very sharp drop in radionuclide releases from the destroyed reactor approximately nine to ten days following the explosions, the curious shape of the total release rate curve (dubbed the "bathtub" curve) based on Soviet data presented at the IAEA Meeting of Experts in Vienna in August 1986, and the inconsistencies in activity releases as reported by the Soviets and far-field estimates by western specialists. A certain amount of research at Chornobyl has been conducted by Russian and Ukrainian scientists, and a number of hypotheses are proposed to explain processes taking place and radionuclide release mechanisms operating during the Active Phase. However, none of these is fully adequate to explain all aspects of this phase of the accident. Based on what is known or conjectured, the following questions summarize essential details that this study endeavors to clarify to properly reconstruct events during the Active Phase:

1) What were the dynamics of fragment dispersion? Can these fragments be quantified and how are they currently distributed?

2) What happened to the balance of the core material? Can events be adequately reconstructed to hypothesize what processes led to the melting of the core?

3) How did the melted core interact with surrounding materials and what were the dynamics of the flow of the corium? What is the current state of the corium and can it be quantified? What happened to the corium ten days after the accident when a sudden and very large drop in the release of radionuclides occurred?

4) How reliable is the source term release data and the account of accident management actions provided by the Soviets in Vienna? How did accident management actions taken during the Active Phase effect source term release mechanisms?

By answering these questions, this dissertation presents a preliminary yet rigorous analysis of source term release mechanisms operating during the Active Phase of the Chornobyl accident. Based on these analyses, it then hypothesizes to reconstruct the sequence of events during the Active Phase. In turn, it makes a valuable contribution to the modeling of severe accident release mechanisms, provides valuable information on the release of radionuclides into the environment particular to the Chornobyl accident, and furnishes recommendations for the final entombment of Unit-4.

Lastly, as well as the stated objectives and as a natural consequence of the research, the dissertation also provides:

- a synopsis of the magnitude and consequences of the accident;
- a brief history of nuclear energy development in the former Soviet Union and Ukraine, a description of Ukraine's nuclear energy program, and the impact of the accident on nuclear energy in Ukraine and elsewhere;
- a more precise and extensive detailing of Unit-4's specifications and operating parameters, as well as a detailed description of the RBMK-1000 and auxiliary systems;
- a more extensive chronology of events during the accident including an in-depth accounting of accident management actions;
- a more precise core fission product and transuranic inventory prior to the accident, and an appraisal of Soviet data provided at Vienna related to the source term;
- a detailed description of the current state of the Unit-4 reactor building, results of analyses on the remains of the nuclear fuel, and a description of the sarcophagus "Shelter";
- an extensive bibliography of Soviet literature and accident data;
- recommendations for future work.

This page has intentionally been left blank.

CHAPTER II

A Synopsis of the Magnitude and Consequences of the Accident

II.1. Direct Physical Effects

The 1000 MWe RBMK† Unit-4 nuclear power reactor at the Chornobyl Nuclear Power Station (ChNPS-4) was "physically started" on 11 November 1983 and achieved criticality thirty-two days later on 13 December 1983.†† By 25 April 1986 it had reached the end of its first operating cycle (with a core-average burnup of 10.9 MW·d/kg U for its 190.3 tonne UO_2 charge,*) and a maintenance outage was scheduled for the following day. At approximately 01:23:40 on 26 April 1986, after 865 calendar days and 715 effective full-power days in operation,[1,2] the most severe accident in the history of commercial

---

† Deciphering: in Russian РБМ-К (Реактор Большой Мощности – Канальный) translated literally is "High-Power Reactor – Channel-Type." The other major Soviet reactor type, the VVER-VPD, in Russian ВВЭР-ВПД (Водо–Водяный Энергетический Реактор – Вода Под Давлением), translated literally is "Water [cooled]–Water [moderated] Energy Reactor – Pressurized Water."

†† This is considered very fast for the initial startup of a nuclear power reactor. Normally a period of approximately four to six months is prescribed for flushing various systems, repairs, tests, etc. between the "physical startup" and *first* criticality of a power reactor of this size; followed by an additional four to six months between first criticality and full-power operation. In a 13 March 1984 article in *Правда України*, in fact, it was announced that Unit-4 had been introduced into full-power operation two months ahead of schedule. Not only was it rare to complete a project ahead of schedule in the Soviet nuclear energy industry, but the startup date given was incorrect. Unit-4 actually achieved full-power operation on 25 May 1984 – more than two months later. Although some of the dates he presents in his book are incorrect, Zhores Medvedev in *The Legacy of Chernobyl* explains how the usual Soviet "desire to report 'overfulfillment' led to corners being cut in the scheduled programme of tests."

* Out of the total 1661 technological channels in an RBMK-1000, for Chornobyl Unit-4 at the time of the accident, 1659 channels were fueled (more that 57% of which contained first-load fuel assemblies), one was unfueled, and one contained a "supplemental" absorber. (Ю. В. Сивинцева и В. А. Качалова общие редакторы, *Чернобыль: Пять трудных лет*, Москва: Издат, (1992): 102.)

[1] Aleksandr Aleksandrovich Borovoi, "Fission Product and Transuranic Element Release During Chernobyl Accident" (preprint), Presented at *The International Conference "The Fission of* Nuclei – 50 *Years," Leningrad, USSR, October 16–20, 1989*, Chornobyl, Ukraine: The Chornobyl Complex Expedition of the I. V. Kurchatov Institute of Atomic Energy, (1990): 2.

[2] Spartak Timofeëvich Belayev, et al, "Some Aspects of Post-Accident Activity in Control Zone of Chernobyl NPP," in *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, ed. E. P. Velikhov and L. A. Bol'shov (Moscow, Russia: Nauka, 1989), 134.

nuclear power occurred at this unit – characterized as a Level 7 Major Accident (most severe) according to the International Nuclear Event Scale. "The accident can be technically classified as a voiding-induced super-prompt critical power excursion that triggered a fuel-coolant interaction steam explosion that simultaneously breached both the primary system and the containment."[3,4]

As a result of the accident the reactor core was completely destroyed. Approximately 135 ± 30 tonnes (~70–85% of the total 190.3 tonne fuel charge) melted and flowed downward into the reactor building's lower regions and pressure suppression pool (which by that time had been almost completely drained of water); about 3.5% of the fuel (6.7 tonnes) was blown upwards out of the reactor core "shaft" and released into the atmosphere where aerosol-sized particles were eventually carried over the northern hemisphere; an estimated 25–30 tonnes of fuel, in the form "dust" or large, broken pressure tubes imbedded in graphite, are scattered throughout the upper levels of the damaged reactor building mostly under debris or concrete poured in after the accident; the balance of the fuel (≈ 11 tonnes) – most of which is thought to be located inside the reactor building and sarcophagus – has yet to be positively located.†

---

[3] Thomas S. Kress et al, "The Chernobyl Accident Sequence," *Nuclear Safety* Vol. 28, No. 1 (January–March 1987): 6. Actually, the Chornobyl Unit-4 had no containment to speak of as far the West defines a containment. The reactor central hall (the region above the upper shielding cover plates of the reactor with dimensions of approximately 24 m wide x 80 m long x 35 m high) is constructed of reinforced 1.5 meter-thick concrete walls for the lower bay and a steel frame roof with precast concrete panel sheathing for the walls of the high bay. [U. S. Nuclear Regulatory Commission, comp, *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250), Washington, DC: U.S. Government Printing Office, (1987): 2-13.] It is designed to withstand only normal building structural loads. Compare this to a modern PWR containment's rated design-basis accident pressure of approximately 65 psig (0.44 MPa) – although actual failure will occur at two to three times this pressure, that is, not below 140 psig (0.95 MPa). The *first* containment in the Soviet Union was constructed for the VVER-1000 Unit-5 at the Novovoronezh Nuclear Power Station in 1980.

[4] Explosions are generally classified by two characteristics or features: by the very nature of the energy contained or by the mechanism of its rapid release – see Appendix II for clarification. Unfortunately, even experts have taken advantage of semantics to exploit the layman's somewhat superficial understanding of nuclear power. See, for example, the somewhat misleading article by William Sweet, "Chornobyl: What Really Happened," *Technology Review* (July 1989): 42–52.

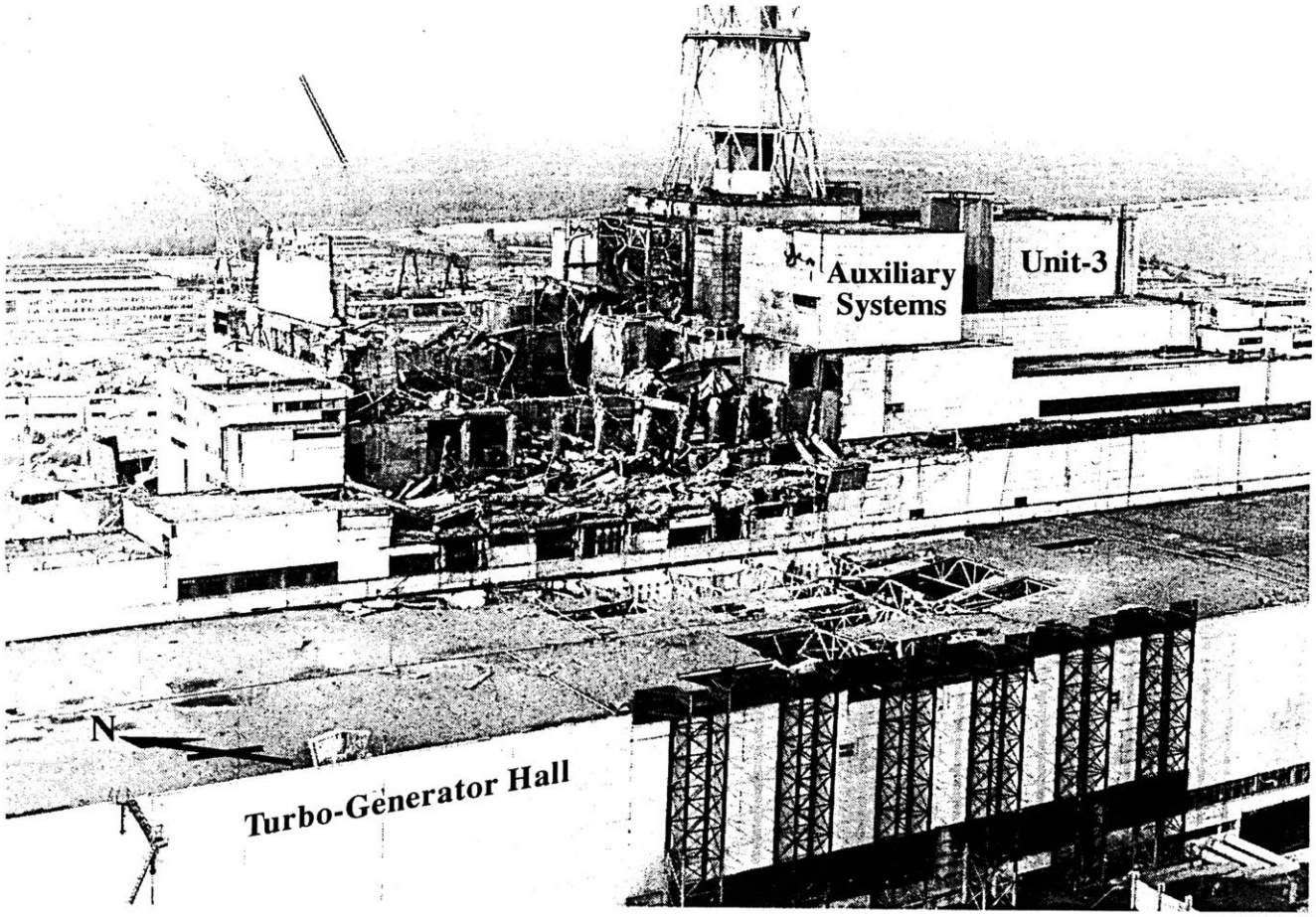
† Medvedev reports that photographic and eyewitness evidence indicates that not less than 10–20% of the reactor core was "blown out," implying 18–35 tonnes of zircaloy, 19–38 tonnes of UO_2 fuel, and 180–360 tonnes of graphite were ejected to outside the building. Note this does not include what fraction of the core was ejected but remained within the reactor building, nor what amount was pulverized and ejected as an aerosol. [Grigori Medvedev, *The Truth About Chernobyl,* New York: Basic Books, Inc., (1991): 58.]

The reactor building itself, especially above the floor of the Central Hall, suffered extensive damage and resulted in the complete destruction of the roof and upper building structures – reducing the height of the building from an initial 71.5 meters to an average 46 meters.[5] (See Figures II.1 & II.2) Other major components of this unit, including the Emergency Core Cooling System (ECCS), deaerator system, steam drums, main coolant pumps, and primary piping were heavily damaged or destroyed. The expolsion's pressure wave significantly displaced those reactor building support columns not completely destroyed – compromising the building's structural integrity and making construction of the sarcophagus extremely difficult. Hot core materials (fuel and graphite) expelled during the explosions started fires in and around the destroyed unit. Particularly heavy damaged was caused by these fires and flying debris to the roof of the "machine hall" that covers Unit-4's two 500 MWe turbo-generators – as a result of which in many places the roof collapsed causing further, wide-spread damage to equipment below.

[5] Г. А. Шароваров, Научный руководитель темы, *Обоснование ядерной безопасности объекта «Укрытие» на основе исследования динамики аварийных процессов: Характеристика объекта «Укрытие» – Его физическая и математическая модель*, Академия Наук Белорусской ССР – Институт Ядерной Энергетики, Минск, Белорусь, (1990) : 36.

Figure II.1

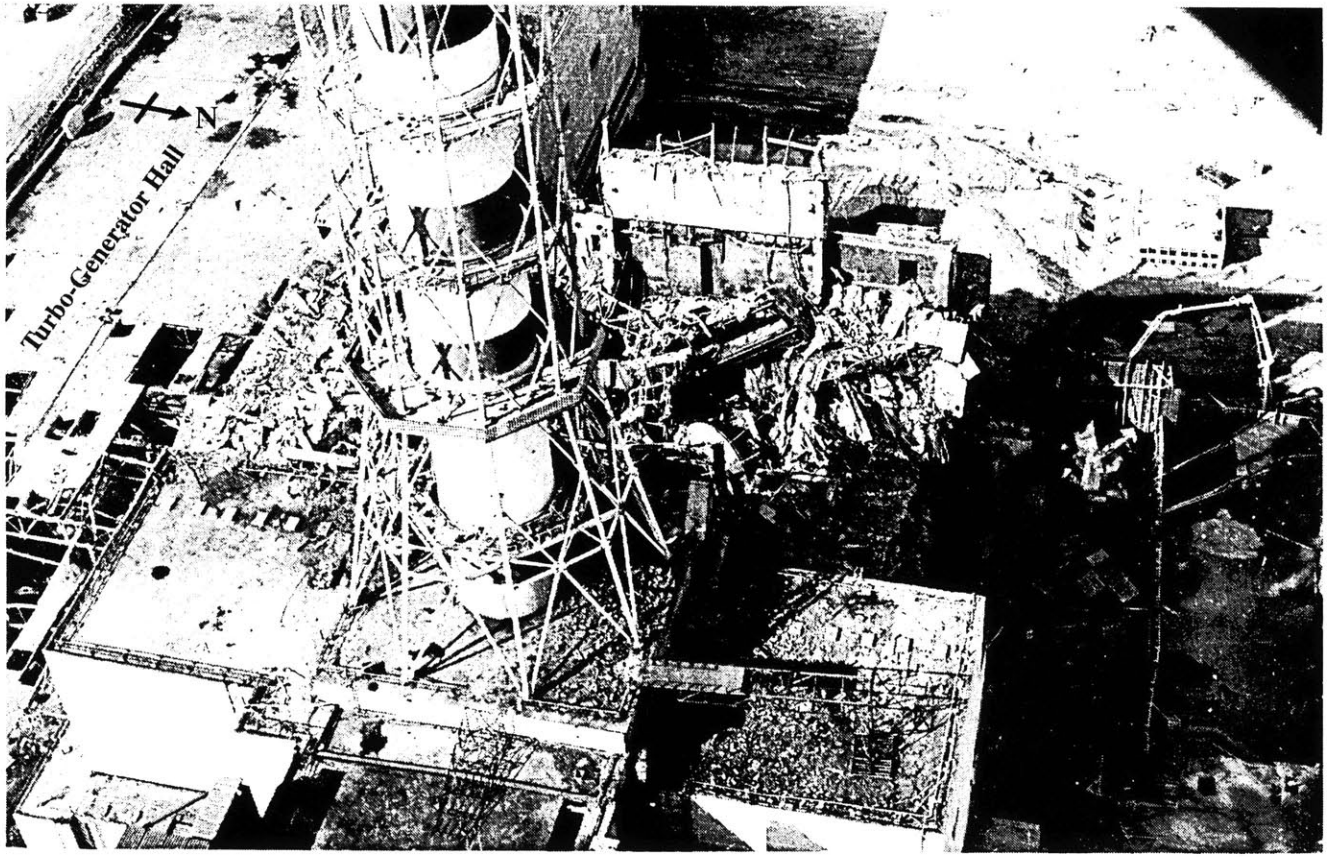
Photograph of the destroyed Chornobyl Unit-4 reactor building in late July or early August 1986 as viewed from the southwest. Note the one meter-thick reinforced concrete structural support members (at the deaerator level) inclined away from vertical.†



† Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

Figure II.2

Photograph of the destroyed Chornobyl Unit-4 reactor building in late July or early August 1986 as viewed from the east-by-northeast and from above Unit-3. Note that much of the core debris have been removed from the south roof of the Auxiliary Building "Block V" while many graphite blocks remain scattered over the northern roof. Note also the construction of the northern Cascade Wall. The large boxes lying in the third tier of the wall are actually metal "cages" used to fill up space over the building debris before concrete was poured on top to fill in that section.†



† Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

II.2 Environmental Contamination from the Fallout of the Accident

In their push for an unrealistic and oftentimes reckless expansion in Ukraine's industrial capacity, and as the result of the subordination of safety and ecological needs to economic demands, Soviet industrial policies have left Ukraine ecologically devasted.† Because of its rich land, favorable climate, and abundant natural resources, Ukraine was the most prized colony of the Russian Empire and of the former Soviet régime. Although Ukraine comprised only 2.8 percent of the territory and 18 percent of the total population of the Soviet Union, it produced 33 percent of the agricultural output, 50 percent of the iron ore, 45 percent of the steel, and 42 percent of the color televisions.[6] Therefore, as far as the Ukrainians were concerned, the Chornobyl accident, besides further contaminating their country's environment, forced the whole issue of external control of the republic's resources into the public arena. Chornobyl brought to the surface many (but far from all) of the injustices and inefficiencies of the Russian-controlled Soviet system; and because of this it has been credibly argued that as a watershed event that forced then General Secretary Gorbachev to accelerate and more fully implement his policy of *glasnost* or "openness," Chornobyl was a major factor that led to the demise of the system and of the Soviet Union.[7]

Before the collapse of the Soviet Union, Ukraine was home to over 1,000 plants for the production of hazardous chemicals while just 7 percent of their production was used in the republic. In 41 out of the 45 largest towns and cities the degree of pollution exceeds levels considered safe by Soviet authorities, themselves lax compared to Western standards. Sixty percent of Ukrainian black earth has been depleted, with an additional 2.5 million acres being lost every year. Twenty thousand small rivers in Ukraine have

---

† For an excellent account and a stunning indictment of the ecological devastation in the former Soviet Union, see Murray Feshbach and Alfred Friendly, Jr., *Ecocide in the USSR*, New York: Basic Books, 1992.

[6] Borys Gudziak, "Easter in Ukraine," *America*, (August 4, 1990): 64.

[7] See Marples, David R., *The Social Impact of the Chernobyl Disaster*, New York: St. Martin Press, 1989; and Marples, David R, *Ukraine Under Perestroika: Ecology, Economics, and the Worker's Revolt*, New York: St. Martin Press, 1991.

been desiccated in recent decades. The per capita water supply in Ukraine is one-tenth that of the Soviet average. For example, in the western Ukrainian city L'viv (with a population of over 850,000) for the last decade tap water has been available only from 6:00 to 9:00 mornings and evenings. In half of the regions of Ukraine the rate of cancer exceeded the Soviet average, in some areas manyfold.[8]

II.2.1. General Extent of the Fallout

The fires, along with the initial explosions, wafted radioactive materials high into the air, much of which were carried away in the form of gases and aerosols by normal air currents. During the "Active Phase" of the accident, the Soviets *officially* estimate a total of about 50 MCi of noble gases (100% is assumed to have been released) and a total of about 50 MCi of other radionuclides (approximately 3.5% of the core inventory) were released to the environment.[9] This greatly exceeded the approximately 17 Ci of Iodine and 2 MCi of noble gases released to the environment as a result of the Three Mile Island accident, or the roughly 1 MCi total activity released during the Windscale accident.*

---

[8] See Volodymyr Boreyko, "The Environment: Pollution Plagues Large Areas of Ukraine," *The Ukrainian Weekly*, Vol. LXI, No. 6, (Sunday, Fegruary 7, 1993); and David R. Marples, "Environmental Problems in Ukraine," *The Ukrainian Weekly*, Vol. LXI, No. 34, (Sunday, August 22, 1993).

[9] Р. М. Алексахин et al, *Радиоэкологические последствия чернобыльской аварии*, серия "Радиоэкологические аспекты ядерной энергетики," под ред. И. И. Крышева, Москва: Ядерное Общество СССР, (1991): 14. Actually here, as in Vienna in August 1986, the Soviets claim only 50 MCi of other radionuclides were released. This can only be true, however, if one considers just the relatively long-lived isotopes. Based on newly available data, if one takes into account only the isotopes of the three volatile elements iodine, cesium, and tellurium with half-lives greater than one day (which would have affected at least those people living within the 30-km exclusion zone), a rough estimate of *at least* 185 MCi can be made (See Chapter VI). Because of the complex nature of release rate over the 9–10 days of the Active Phase, more vigorous studies are needed to estimate the dose acquired by people in the zone before they were evacuated.

The first information on radioactive contamination was obtained by Goskomgidromet (State Hydrometeorology Committee) for the USSR Council of Ministers on May 3, 1986. Air, water, and ground samples collected during 27 April – 2 May showed that 30% of the total activity was attributed to I-131. Other isotopes detected in these samples included La-140, Ru-103, Ru-106, Zr-95, Nb-95, Te-132, I-132, Cs-137, Ce-141, Ce-144, Np-239, and Sr-89.

* The Windscale accident in Great Britain, although neither reactivity excursion-induced nor explosive in nature (which, at Chornobyl, resulted in tremendous damage to the reactor building that provided a virtually unobstructed release path), nevertheless was quite similar to the Chornobyl accident in a number of aspects. The burning of its graphite and uranium core (which lasted about two days) and lack of a containment system permitted fission products to escape from the reactor's stack to the environment. "The stack filter removed much of the particulate iodine (20,000 – 50,000 Ci), but gaseous iodine (20,000 Ci) was released from the stack along with about 7.5% of the tellurium and 0.03 % of the strontium in the core." Achilles G. Adamantiades, Chaim Braun, John E. Kenton, and Frank J. Rahn, *A Guide to Nuclear*

As a consequence of these releases, within a few months after the accident over 400 hectares of pine forest (part of the infamous "red" forest, located approximately 1.5 – 2 kilometers southwest of the station, so christened because of its distinct discoloration as seen from the air) died, were plowed under, covered with fresh soil, and sprayed with a dust-suppressing solution.[10] The 1,438 square kilometers of agricultural land within the 30 km exclusion zone has been declared unfit for any type of agricultural activity. Of this total, 864 km^2 are located in Belarus (Homel oblast) and 574 km^2 are in Ukraine (Kyjiv oblast). (See Figures II.5 & II.6 ahead.) In addition, between the three countries of Belarus, Russia, and Ukraine, 69 square kilometers of tillage and pasture land are contaminated with over 80 Curies of Cs-137 per km^2, 601 square kilometers are contaminated with 40 to 80 Curies per km^2, and a total of 16,670 square kilometers of agricultural land are contaminated with over 5 Curies per km^2.[11] Table II.1[12] summarizes total Cs-137 contamination in Ukraine, Belarus, and Russia, Tables II.2[13] and II.3[14] outline the extent

---

Power Technology: A Resource for Decision Making, New York: John Wiley & Sons, 1984:737. Compare this to Chornobyl's release (questionable) of 100% noble gases, 15% tellurium-132, 4% strontium-89 & -90 as presented by the Soviets at Vienna.

[10] В. Г. Асмолов et al, *Авария на Чернобыльской АЭС: год спустя.* Soviet Report at the International Conference on Nuclear Safety, IAEA, Vienna, September 28 – October 2, 1987, pg. 42. Pine trees are among the most susceptible plants because radiation "thickens" the sap – effectively clogging capillaries and choking off nutrients.

[11] Р. М. Алексахин et al., 136–37 (Table 5-1). Of the 30 km exclusion zone's 2,827 km^2 total area, 1,389 km^2 were not used for agricultural purposes before the accident. In regions with contamination density over 40 Ci/km^2 the use of lands for agricultural production was prohibited. On lands with less contamination, agricultural production is permitted with some "limitations and special rules." (Begichev, S. N., A. A. Borovoj, E. V. Burlakov, A. Ju. Gagarinsky, V. F. Demin, I. L. Khodakovsky, and A. A. Khrulev, "Radioactive Releases Due to the Chernobyl Accident" (preprint), Presented at the International Seminar *Fission Product Transport Processes In Reactor Accidents,* Dubrovnik, Yugoslavia (May 22–26, 1989): 18–19.) Begichev, et al., also claim that for a contamination between 5 and 15 Ci/km^2 the total area amounts to 21,000 km^2 which is inconsistent with that given by P. M. Алексахин et al.

In order to have an idea of how little *mass* (of Cs-137 for example) is required to contaminate the land, the Soviet standard for considering land "exclusionary and designated for evacuation" is if the contamination density of Cs-137 is greater than 15 Curies per square kilometer. This activity planar density equated to a mass planar density is 0.17 (≈ 1/6) gram per square kilometer.

[12] Philip R. Pryde, *Environmental Management in the Soviet Union,* pg 47 as summarized from Израэль, but corrected slighty in Ю. В. Сивинцева и В. А. Качалова, 148.

[13] Ю. В. Сивинцева и В. А. Качалова, 212–214. This section of the book also contains useful data on milk, meat, and fruit & vegetable production in contaminated areas. The Soviets use the following system to characterize the level of soil contamination:

Region (1) < 15 Ci/km^2 Cs-137 and < 3 Ci/km^2 Sr-90 – Food from lands contaminated to this level contain less than the Soviet Maximum Permissible Concentration (MPC) of these radioisotopes.

of Cs-137 contamination to agricultural land for these three countries, while Figures II.3 and II.4 present the data graphically.

Within the 30-km exclusion zone there are now located between six hundred and eight hundred *mohyl'nyky* (little graves) – "temporary" trenches into which approximately 100 kCi of waste was dumped as a result of accident mitigation and clean-up efforts. Several engineered disposal sites in the zone contain 200 to 220 kCi of waste, while a disposal site near the station contains approximately 120 kCi of what is classified as high-level waste – with surface dose rates of more than one Roentgen per hour. The 22 km^2 cooling pond contains some 16 kCi of activity in a layer of silt at the bottom. Apparently, water from the pressure suppression pool was pumped into the cooling pond along with a large amount of radiactive debris.[15]

Region (2) 15 – 40 Ci/km^2 Cs-137 and 3 – 10 Ci/km^2 Sr-90 – If special "agricultural amelioration measures" are taken, the level of contamination in foods may be reduced 2–3 times bringing them within the MPC.

Region (3) > 40 Ci/km^2 Cs-137 and > 10 Ci/km^2 Sr-90 – Land contaminated to this level can only be used (and this is to a limited extent) to raise non-comestible agricultural products.

The scientific basis for such a differentiation was obtained from the study of migration dynamics of radioisotopes from the soil into agricultural products obtained during clean-up and research efforts in the wake of the nuclear accident in the South Urals in 1957. Land is considered "exclusionary and designated for evacuation" if contaminated as follows: >15 Ci/km^2 (>0.17 gm/km^2) Cs-137, >3 Ci/km^2 (>0.021 gm/km^2) Sr-90, and >0.1 Ci/km^2 (>1.6 gm/km^2) Pu-239.

[14] Ibid., 254. The data is incomplete and inconsistent even with earlier data presented in the book.

[15] "Radwaste Measurements In And Around Chernobyl," *Nuclear News*, Vol. 36, No. 9 (July 1993):18

Table II.1
Extent of Cs-137 Contamination in Belarus, Russia, and Ukraine

Country	Total Area Contaminated (1000's ha)				Of Which, Outside the Zone (1000's ha)			
	Contamination Range (Ci/km^2)				Contamination Range (Ci/km^2)			
	1–5	5–15	15–40	>40	1–5	5–15	15–40	>40
Belarus	29,920	10,170	4,210	2,150	29,920	9,830	3,640	1,160
Ukraine†	34,000	1,990	820	640	34,000	540	350	200
Russia	39,280	5,450	2,130	310	39,280	5,760	2,060	310
Totals	**103,200**	**17,610**	**7,160**	**3,100**	**103,200**	**16,130**	**6,050**	**1,670**

† At the end of 1990, *Goskomgidromet* revised the extent of contamination in Ukraine as follows: territory with Cs-137 contamination greater than 1 Ci/km^2 = 38,200 km^2 (outside the exclusion zone = 36,000 km^2); territory with Sr-90 contamination greater than 1 Ci/km^2 = 2,600 km^2 (outside the exclusion zone = 800 km^2). [Ю. В. Сивинцева и В. А. Качалова, 250.] Sadly, for their own people only the following table was published in an April 1990 edition of *Pravda* – just prior to the 4th anniversary of the accident,

	5–15 Ci/km^2 (km^2)	15–40 Ci/km^2 (km^2)	>40 Ci/km^2 (km^2)
Belarus	10160	4210	2150
Ukraine	1960	820	640
Russia	5760	2060	310

Figure II.3
Cs-137 Contamination in Belarus, Russia, and Ukraine

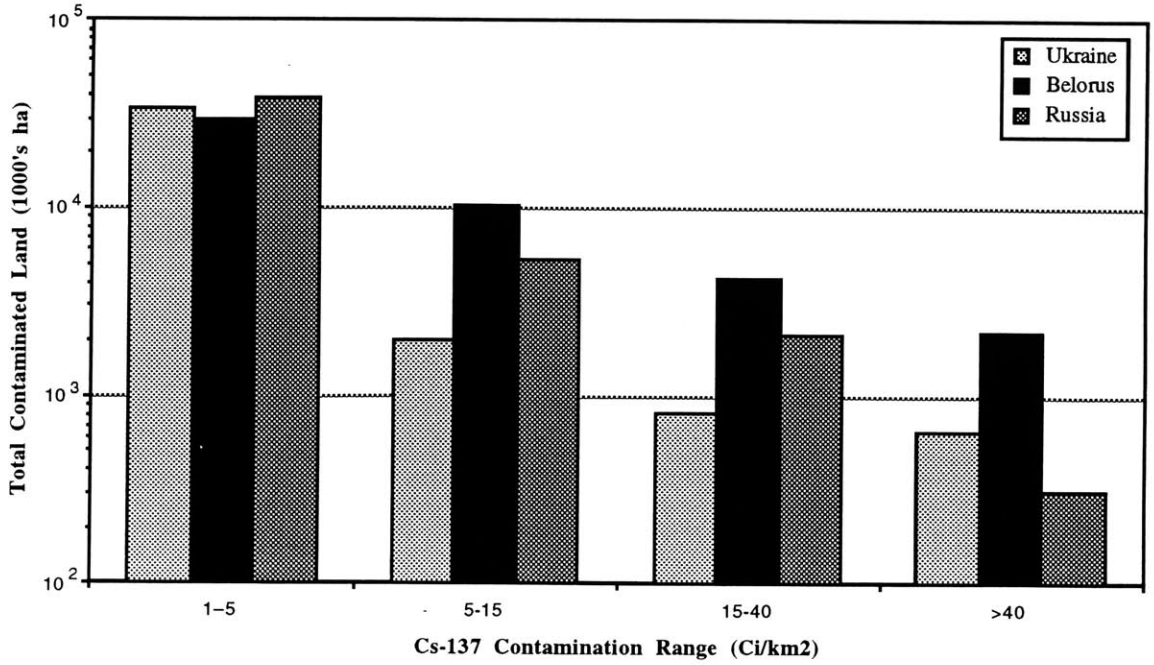


Table II.2

Agricultural Land in Belarus, Russia, and Ukraine (by Oblast)
Contaminated with Cs-137 as a Result of the Chornobyl Accident
(as of January 1, 1991)

Country / Oblast	Total Agricultural Land (1000's ha)					Tillage Land (1000's ha)				
	Contamination Range (Ci/km^2)					Contamination Range (Ci/km^2)				
	1–5	5–15	15–40	40–80	>80	1–5	5–15	15–40	40–80	>80
UKRAINE	**3737.15**	**174.07**	**27.10**	**7.50**	**6.60**	**3341.82**	**87.26**	**19.70**	**5.50**	**5.30**
Kyjiv	211.40	36.10	10.60	4.10	4.60	149.50	12.00	10.40	4.10	4.60
Zhytomyr	130.00	99.80	16.40	3.40	2.00	93.00	57.20	9.20	1.40	0.70
Chernihiv	51.00	6.60	0.10	0	0	26.40	4.80	0.10	0	0
Rivne	196.40	11.80	0	0	0	126.50	4.60	0	0	0
Cherkasy	72.70	6.40	0	0	0	66.20	2.50	0	0	0
Vinnytsja	74.50	0.10	0	0	0	70.70	0.10	0	0	0
Volyn	0.10	0	0	0	0	0	0	0	0	0
Dnipropetrovsk	1.00	0	0	0	0	0.70	0	0	0	0
Ivano-Frankivsk	1.00	0	0	0	0	1.00	0	0	0	0
Kirovohrad	1746.99	0	0	0	0	1752.02	0	0	0	0
Crimea	298.12	0	0	0	0	233.59	0	0	0	0
Odesa	223.40	0	0	0	0	199.73	0	0	0	0
L'viv	419.61	11.77	0	0	0	326.10	4.56	0	0	0
Sumy	2.43	0	0	0	0	1.98	0	0	0	0
Ternopil	6.60	0	0	0	0	6.50	0	0	0	0
Kmel'nyts'kyj	0.70	0	0	0	0	0.70	0	0	0	0
Chernivtsi	301.20	1.50	0	0	0	297.20	1.50	0	0	0
BELORUS	**1007.16**	**479.82**	**228.85**	**35.63**	**0.21**	**567.31**	**288.50**	**132.80**	**21.50**	**0.10**
Homel	623.00	326.20	169.70	35.53	0.21	343.20	189.70	96.40	21.40	0.10
Mohiljow	229.30	141.20	58.70	0.10	0	153.00	94.50	36.20	0.10	0
Brest	61.20	7.90	0.45	0	0	16.90	2.00	0.20	0	0
Hrodna	52.36	0.50	0	0	0	29.20	0.04	0	0	0
Minsk	41.30	4.02	0	0	0	25.01	2.26	0	0	0
RUSSIA	**1338.50**	**547.80**	**142.10**	**17.10**	**0.20**	**1025.72**	**437.30**	**98.60**	**7.10**	**0.20**
Brjansk	320.80	184.10	95.00	16.80	0.20	234.50	135.60	53.70	6.90	0.20
Kaluga	93.20	59.30	5.30	0.20	0	78.20	56.70	5.30	0.20	0
Orël	778.40	21.50	0	0	0	595.80	16.30	0	0	0
Tula	146.10	282.90	41.80	0.10	0	117.22	228.70	39.60	0	0
TOTAL Russia, Belarus, Ukraine	**6082.81**	**1201.69**	**398.05**	**60.23**	**7.01**	**4934.85**	**813.06**	**251.10**	**34.10**	**5.60**

Table II.2 (con't)

Agricultural Land in Ukraine, Belarus, and Russia (by Oblast)
Contaminated with Cs-137 as a Result of the Chornobyl Accident
(as of January 1, 1991)

Country / Oblast	Pasture Land (1000's ha)					Agricultural Land Contaminated >1 Ci/km²			
	Contamination Range (Ci/km²)					Total (1000's ha)	Fraction† (%)	Tillage (1000's ha)	Fraction† (%)
	1–5	5–15	15–40	40–80	>80				
UKRAINE	**421.73**	**82.91**	**7.40**	**2.00**	**1.30**	**3952.42**	**15.50**	**3432.58**	**17.30**
Kyjiv	61.60	24.00	0.20	0	0	266.80	17.00	180.60	14.00
Zhytomyr	37.00	42.60	7.20	2.00	1.30	251.60	17.00	161.50	14.00
Chernihiv	24.60	1.70	0	0	0	57.70	3.00	31.30	2.00
Rivne	69.80	7.20	0	0	0	208.20	25.00	131.10	22.00
Cherkasy	6.50	0.20	0	0	0	79.10	6.00	68.70	6.00
Vinnytsja	3.60	0	0	0	0	74.60	4.00	70.80	4.00
Volyn	0.10	0	0	0	0	0.10	0	0	0
Dnipropetrovsk	0.30	0	0	0	0	1.00	0.04	0.70	0.03
Ivano-Frankivsk	0	0	0	0	0	1.00	0.02	1.00	0.03
Kirovohrad	21.97	0	0	0	0	1746.99	90.10	1752.02	100.00
Crimea	74.53	0	0	0	0	298.12	17.10	223.59	19.20
Odesa	23.67	0	0	0	0	223.40	9.10	199.73	9.90
L'viv	93.51	7.21	0	0	0	431.38	25.90	330.66	42.80
Sumy	0.45	0	0	0	0	2.43	0.20	1.98	0.02
Ternopil	0.10	0	0	0	0	6.60	0.70	6.50	0.70
Kmel'nyts'kyj	0	0	0	0	0	0.70	0.05	0.70	0.06
Chernivtsi	4.00	0	0	0	0	302.70	75.10	298.70	98.60
BELORUS	**439.85**	**191.35**	**96.05**	**14.13**	**0**	**1751.67**	**19.60**	**1010.11**	**17.50**
Homel	279.80	136.50	73.30	14.13	0	1154.64	78.60	650.80	77.90
Mohiljow	76.30	46.70	22.50	0	0	429.30	29.40	293.00	27.10
Brest	44.30	5.90	0.25	0	0	67.55	5.10	19.10	2.40
Hrodna	23.16	0.45	0	0	0	52.86	1.40	29.20	3.50
Minsk	16.29	1.79	0	0	0	45.32	2.60	27.21	2.30
RUSSIA	**281.57**	**107.40**	**42.70**	**9.90**	**0**	**2045.70**	**36.80**	**1568.52**	**36.40**
Brjansk	86.30	48.50	41.30	9.80	0	616.90	33.00	430.50	33.00
Kaluga	15.00	2.60	0	0	0	158.00	34.80	140.40	40.10
Orël	152.00	4.70	0	0	0	799.50	40.00	612.10	37.00
Tula	28.27	51.60	1.40	0.10	0	470.90	38.00	395.52	38.50
TOTAL Russia, Belarus, Ukraine	**1143.15**	**381.66**	**146.15**	**26.03**	**1.41**	**7749.79**	**19.30**	**6011.61**	**20.10**

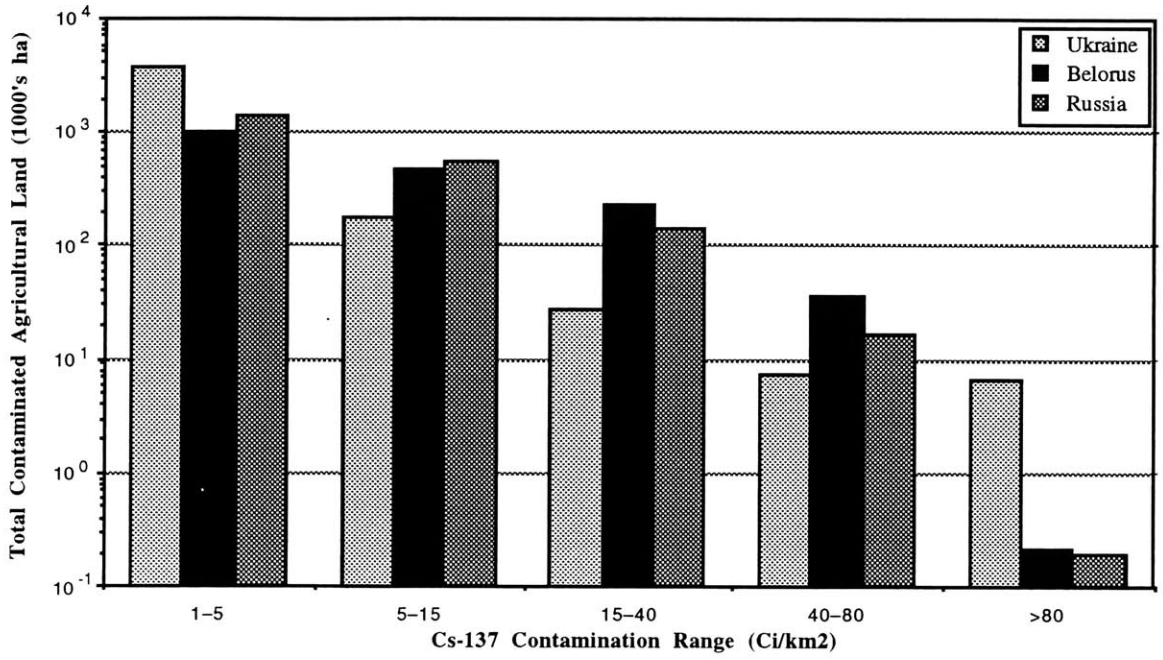
† Fraction of agricultural land contaminated in affected oblasts.

Table II.3
Cs-137 Contamination of Agricultural Land in Ukraine
(as of June 1, 1991)

Oblast	# of Regions Contaminated	Oblast Agroland (1000's ha)	Amount of Contaminated Agricultural Land (1000's ha)					% Total Oblast Agroland
			Cs-137 Contamination Range (Ci/km^2)					
			0.1 – 1.0	1 – 5	5 – 15	> 15	**Total**	
Kyjiv	17	1536	727.0	212.0	29.0	11.0	**979.0**	63
Zhytomyr	9	1526	291.1	267.0	62.0	20.2	**640.3**	42
Chernihiv	6	2036	524.6	47.5	4.7	0.3	**577.1**	28
Rivne	6	852	132.6	144.9	11.5	—	**289.0**	34
Cherkasy	9	1330	421.9	106.7	6.2	0.05	**534.9**	40
Vinnytsja	13	1860	850.0	85.7	0.4	—	**936.1**	50
Volyn	3	987	110.4	15.3	—	—	**125.7**	13
Sumy	2	1639	113.0	12.2	0.3	—	**125.5**	8
Chernivtsi	4	413	74.4	22.7	0.3	—	**97.4**	24
Ternopil	4	970	219.3	12.5	—	—	**231.8**	24
Ivano-Frankivsk	1	508	33.1	5.8	1.0	—	**39.9**	8
TOTAL	**74**	**13,684**	**3,497.4**	**932.3**	**115.4**	**31.6**	**4,576.7**†	**33**

† This amounts to 11% of Ukraine's 415,170 km^2 of agricultural land; but is incomplete and inconsistent (~ 10% difference) compared with Table II.2. The total amount of Ukraine's agricultural land contaminated with greater than 0.1 Ci/km^2 of Cs-137 is at least 74,500 km^2 or approximately 18% of the total agricultural land.

Figure II.4
Cs-137 Contamination of Agricultural Land in Belarus, Russia, and Ukraine



At the beginning of 1990, the number of people living within a 10,300 km^2 area contaminated with over 15 Curies per km^2 (6,400 km^2 in Belarus – including 300 km^2 in the exclusion zone; 2,400 km^2 in Russia; and 1,500 in Ukraine – including 500 km^2 – encompassing approximately 640 settlements) was 230,000.[16] The territory of Ukraine contaminated with greater than 1 Curie per km^2 of Cs-137 amounts to more than 5 million hectares encompassing seventy-four administrative regions (counties) in eleven out of twenty-five oblasts (states) in Ukraine.[17] Included in these regions are approximately 60,000 km^2 of water-basin surface area of the Dnipro, Prypjat, Desna, and other rivers which provide over 32 million residents of Ukraine with water. Moreover, approximately 6,000 km^2 of arable land "seems to be seriously affected and disturbed by decontamination measures in and around the exclusion zone."[18]

In terms of area affected relative to its total territory, Belarus suffered significantly more contamination than Ukraine, where the accident occurred, especially as concerns its agricultural land. Prevailing winds during the first few days after the accident carried fission products and "hot" particles high into the air depositing them over the Belarusian capitol, Minsk, further on over Lithuania, and eventually into Sweden. Contaminated Belarusian land amounts to 46,450 km^2 (or more than 20% of its territory) where 27 cities and 2,666 villages or towns are located, and in which over 2.1 million people live. Table II.4[19] outlines the extent of contamination in Belarus.

---

[16] Ю. А. Израэль, С. М. Вакуловский, В. А. Ветров, В. Н. Петров, Ф. Я. Ровинский, и Е. Д. Стукин, *Радиоактивное загрязнение природных сред*, под редакцией Ю. А. Израэля, Ленинград: Гидрометеоиздат, 1990: 13, 55–56.

[17] Summarized from "Основні дані щодо маштабів та наслідків чорнобильської катастрофи на Україні" in *Новий Шлях*, Vol. LXIII, No. 28 (July 11, 1992), 7; as prepared on June 5, 1992 by Віталій Мельничук and Валерій Косенко and obtained on the basis of data provided by the Ukrainian Chornobyl Ministry and the Ukrainian Parliament's Standing Committee on Chornobyl. This contrasts with that presented in (Ю. В. Сивинцева и В. А. Качалова, 248), "The overall territory contaminated with greater than 1 Ci/km^2 Cs-134 & Cs-137 is 40,000 km^2. Around 2.5 million people in more than 2,000 population centers [of Ukraine] live in contaminated regions.

[18] Zhores Medvedev, *The Legacy of Chernobyl*, New York: W.W. Norton and Company, (1990): 108.

[19] R. G. Ilyazov, S. K. Firsakova, A. G. Karpenko, and M. I. Bordak, "Radiological Problems of Livestock Breeding in the Zone of Radioactive Contamination in the Byelorussian [Belarussian] SSR", International Union of Radioecology, Proceedings of IUR Soviet Branch Seminar on Radioecology and Accident Counter-Measures, Kyjiv, Ukraine, April 27 – May 2, 1991, pg. 1; and Ю. В. Сивинцева и В. А. Качалова, 275.

Table II.4
Cs-137 and Sr-90 Contamination in Belarus

Isotope	Contamination Level (Ci/km^2)	Area Affected (km^2)	# Cities / # Towns or Villages	Population
Cs-137	1 – 5	29,920	14 / 1,352	1,734,000
Cs-137	5 – 15	10,170	8 / 919	267,000
Cs-137	15 – 40	4,210	5 / 325	96,000
Cs-137	> 40	2,150	0 / 70	9,400
Total:		**46,450**	**27 / 2,666**	**2,106,400**
Sr-90	> 11.1	4,780		

Belarusian agricultural land, in particular, suffered extensive contamination. Over 1.7 million hectares, or approximately 20% of the republic's agricultural land, was contaminated – including 106,000 hectares of which are located in the exclusion zone were abandoned in 1986.[20] In the Homel and Mohiljow oblasts alone, 245,000 hectares of agricultural land (where 107 state farms continue to operate) is contaminated with Cs-137 in the range 15–40 Ci/km^2. A significant portion of this land was also contaminated with Sr-90: in the Mohiljow and Homel oblasts, 77,000 and 396,000 hectares respectably are contaminated with greater than 0.3 Ci/km^2 – and significant parts of these lands have contamination levels from 1–3 Ci/km^2.[21] Table II.5[22] summarizes contaminated agricultural lands in Belarus.

Table II.5
Cs-137 Agricultural Land Contamination in Belarus

Contamination Level (Ci/km^2)	Land Area (1000's ha)	Fraction of Agroland (%)
1–5	955.2	55.8
5–15	444.8	26.0
15–40	254.3	14.9
> 40	57.2	3.3
TOTAL	**1711.5**	**100.0**

[20] Ю. В. Сивинцева и В. А. Качалова, 280.
[21] Ibid. Some information is also given on milk and meat contamination in these regions.
[22] Ibid.

During 1986–91, over 484,000 hectares of Belarusian land were declared unfit for agricultural production. As a result, Belarus has lost 85,000 tonnes of meat production and 436,000 tonnes of milk production. In addition, over one million hectares of forest land (18% of the country's forested land) was severely contaminated. Over 194,000 hectares of Belorussian were declared "exclusionary and designated for evacuation;" while 346,000 people in 749 population centers live in areas where the concentration of Cs-137 in milk exceeds the Soviet MPC of 10^{-8} Ci/l.[23]

In the Russian Federation, twelve oblasts were contaminated as a result of the accident. In the four oblasts most affected (Brjansk – see Table II.6[24] below, Tula, Kaluga, Orël), 47,200 km^2 of territory are contaminated by Cs-137 (where 2,272,500 people lived) – including 2,400 km^2 greater than 15 Ci/km^2 where 276 population centers are located and over 110,000 people lived. A small part of this territory was also contaminated with Sr-90. Russian agricultural and forested land suffered significant losses in these areas. About one million hectares of government forest reserve land was contaminated with Cs-137 as follows: 1,100 hectares at greater than 40 Ci/km^2; 28,500 hectares at 15–40 Ci/km^2, and 598,700 hectares at 1–5 Ci/km^2.[25] The Rjazan, Belgorod, Smolensk, Tambovsk, Voronezh, Kursk, Leningrad (St. Petersburg), and Lipetsk oblasts were contaminated in the range of 1–5 Ci/km^2 Cs-137 – generally not exceeding 2–3 Ci/km^2. As a whole, Russian Federation territory contaminated with Cs-137 as a result of the accident can be summarized as follows: (1) 39,280 km^2 at 1–5 Ci/km^2, 5,450 km^2 at 5–15 Ci/km^2, 2,130 km^2 at 15–40 Ci/km^2, and 310 km^2 at greater than 40 Ci/km^2.[26]

---

[23] Ibid., 286–287.

[24] Ibid., 303.

[25] Ibid., 308. Explanations follow of what efforts are being taken to lower the contamination level in foodstuffs from these regions.

[26] Ibid., 300. These figures are given for the end of 1990.

Table II.6
Cs-137 Contamination in the Brjansk oblast of Russia in 1986†

	Contamination Ranges (Ci/km²)			Total
	< 15 (Zone I)	15–40 (Zone II)	> 40 (Zone III)	
Area (km²)	2,720	1,120	107	**3,947**
Population Centers	487	115	11	**613**
Population (1000's)	190.2	88.3	2.4	**280.9**

† On August 14, 1987, after a more refined study of the affected areas, 93 additional population centers were catagorized as Zone II & Zone III; while in September 1988, 55 more were catagorized as Zone II. At the beginning of 1990, 5,500 km² of territory (613 population centers, 287,000 population) was contaminated with > 5 Ci/km² .

On May 4, 1986, the following exposure rates were observed in several oblasts in Russia: Tula oblast – 0.75 mR/hr; Kaluga and Smolensk oblasts – 0.5 mR/hr; Lipetsk oblast – 0.45 mR/hr; Orël oblast – 0.4 mR/hr; Brjansk oblast – 0.35 mR/hr; and the Kursk oblast – 0.25 mR/hr. As radionuclides continued to settle in these areas (from releases during the Active Phase of the accident), the following levels were observed: Brjansk oblast, Krasnogorsk region – 7.5 mR/hr; Kaluga oblast, Khvastovichi region – 1.5 mR/hr; Tula oblast, Plavsk region – 1.2 mR/hr; and the Orël oblast, Bolkhovsk region – 0.75 mR/hr.[27]

During the first weeks after the accident, gamma-field maps were utilized to approximate the total fallout activity for areas close (< 50 km) to the station. In these cases a ratio of 1 mR/hr ≈ 100–200 Ci/km² was used correlate dose rates above the earth surface (as measured by helicopters) and fallout densities.[28] (Table II.7[29] below presents areas of contaminated land as defined by gamma isodoserate lines; while Figures II.5 & II.6 below present various contamination maps.) Based on more detailed measurements taken during 1988[30], the gamma isolines were better defined as 5–15 Ci/km² encompassing

[27] Ibid., 301.
[28] Begichev, et al., 15.
[29] Ibid.
[30] Ibid., 57.

21,000 km^2 and >1 Ci/km^2 encompassing about 100,000 km^2. Investigations conducted during 1986–88 showed that the horizontal migration of radionuclides since the time of the accident was insignificant – radioactive contamination isodoserate lines changed mainly due to radioactive decay and the vertical migration into the soil.[31]

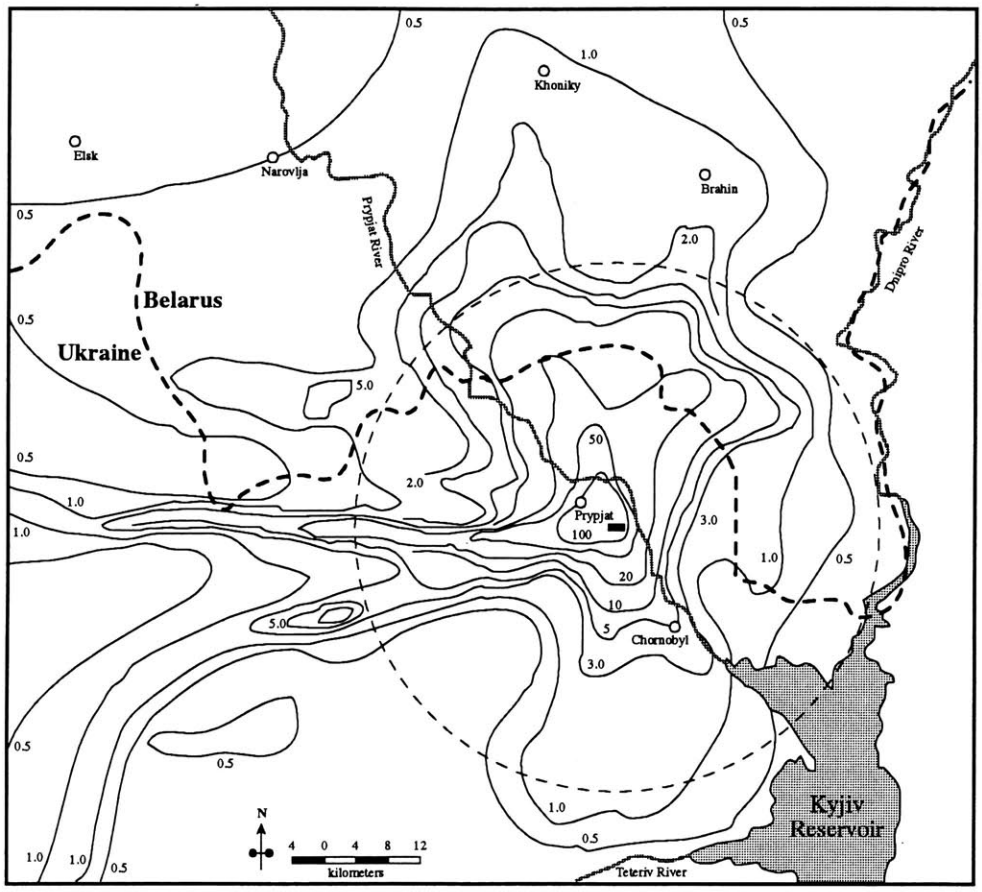
Table II.7
Contaminated Areas Associated with Measured γ Activities

γ-isoline (mR/hr)	Evacuation Designation	Area (km^2) 29 May 1986	Area (km^2) 01 May 1987
>20	complete & immediate	500	8
>10 (15?)	delayed but imperative	1,000	20
>5	advised but voluntary	2,000	70
>1	eligible	10,000	500

[31] Ю. А. Израэл, «Чернобыль: прошлое и прогноз на будущее,» *Правда*, но. 79 (20 марта 1989):4. Also, Ю. А. Израэль, et al, *Радиоактивное загрязнение...*, 69, describes vertical and horizontal migration mechanisms. Up to a wind speed of about 10 m/sec (36 km/hr) there is virtually no horizontal migration; and even at significantly higher wind speed there is neglible transfer of radionuclides. Vertical migration depends heavily on radionuclide chemistry. However, for studies conducted in the exclusion zone to the beginning of the summer of 1987, from 75%–95% of immicible radionuclides remain in the top 3–4 centimeters of top soil; while 5%–26% of the more micible radionuclides have penetrated to between 10 and 20 centimeters.

Figure II.5[32]

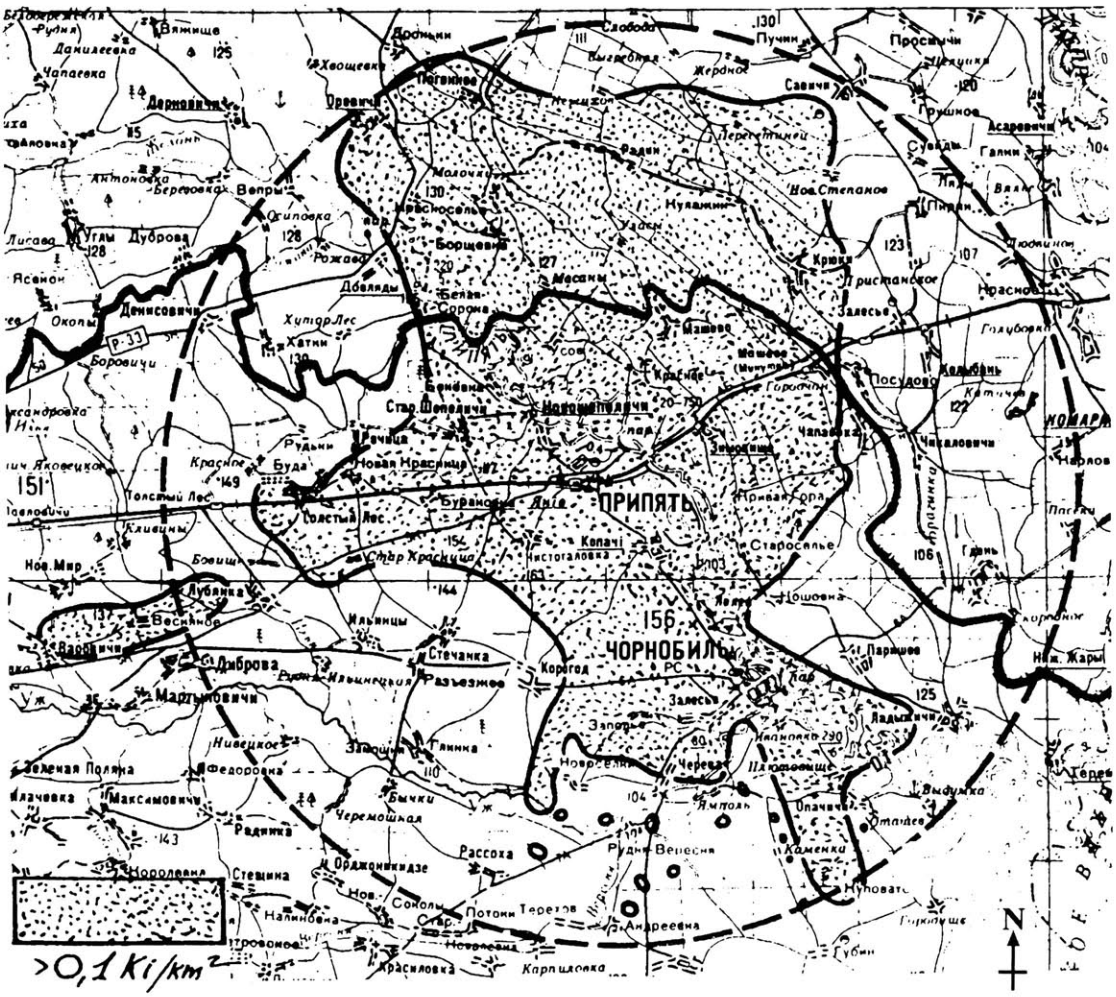
Contamination Map Showing γ-isodoserate lines (mR/hr) on April 29, 1986.



[32] Ю. А. Израэль: Figure II.5 – foldout insert Figure 2.10; Figure II.6 – foldout insert Figure 2.8. See also Chapter 3 "The Environmental Impact" and Chapter 4 "The Impact on Agriculture" in Zhores Medvedev, *The Legacy of Chernobyl.* Although Izrael's book is full of information regarding ecological contamination resulting from the accident, the data presented should be viewed with some skepticism. Yu. A. Izrael, the book's editor, Chairman of the Soviet State Committee on Hydrometerorology and Environmental Protection, and a member of the Government Commission investigating the accident and directing cleanup efforts, has been implicated by the Ukrainian State Prosecutor for taking part in a coverup of the accident's consequences. It is interesting to note that the first contamination map published for the general public did not appear until early 1989 in local Belarusian newspapers. This was hastily followed by a map similar to Figure I.5 on 11 February 1989 in *Pravda.* Ukrainian and other Belarusian newspapers followed suit along with the local Russian newspaper *The Brjansk Worker* in Russia's most affected oblast. In May 1989, after the removal of a "gag rule" by the Soviet Government Commission on Chornobyl, more information and contamination maps were provided to republic, oblast, and regional authorities. In 1990 on the fourth anniversary of the accident, Izrael, defending the policy making secret the extent of contamination, stated, "... the procedure was such that in the event of serious accidents, *this information was privileged* and was being offered to all the organizations dealing with eliminating this accident." (emphasis added) Yurij Izrael, speech to the USSR Supreme Soviet, April 25, 1990 in BBC Monitoring – *Summary of World Broadcasts, Soviet Union*, "Special Supplement, 2; "Debate on Chornobyl," May 5, 1990: SU/0756 C2/1–3.

Figure II.6[33]

Map of Pu-239 and Pu-240 contamination in December 1989 in the area of the 30-km exclusion zone. The shaded region on the map indicates areas contaminated to greater than 0.1 Ci/km^2 (3,700 Bq/m^2) with Pu-239 & Pu-240.



[33] As published in the 20 April 1990 edition of *Izvestia*.

II.2.2. Fallout in Major Cities

Three to four days after the accident (because of a wind shift from the northeast to the south) the release plume drifted over the capital of Ukraine, Kyjiv – located about 105 km south-by-southeast of the station with a population of approximately 2.6 million at the time of the accident. On May 1–2 the average exposure rate (which includes the normal background rate) to individuals on the streets of the city was 1.0 mR/hr – in some places reaching 2.2 mR/hr – about 100 times the pre-accident background exposure rate in Kyjiv of 0.015 – 0.02 mR/hr. Two days later the wind changed direction toward the southwest away from the city, and two days following that it again shifted to the northwest in the opposite direction from Kyjiv. By May 10th the level in Kyjiv was down to 0.32 mR/hr.[34] The average level in Kyjiv varied as shown in Figure II.7[35] In 1988, the average background exposure rate in Kyjiv was 0.02 – 0.03 mR/hr, with certain regions at 0.04 mR/hr; while the integrated average external absorbed dose per person for the first year after the accident *above normal background* was 0.35 Rem, 0.5 Rem six years after the accident, and after 50 years may reach about 1.0 Rem.[36] For comparison, Table II.8 and Figure II.8 present observed maximum exposure rates for various cities.[37]

For Prypjat, located less than three kilometers from the station, the situation quickly deteriorated. By the end of the day on Saturday the 26th (the day of the accident), the average background gamma exposure rate was 14–130 mR/hr, while by early morning on the 27th this had reached 180–500 mR/hr. By the middle of the day on the 27th this had jumped to 400–1000 mR/hr with some locations reaching 1.5 R/hr.[38] This information contrasts significantly with another source: to appreciate the degree of contamination in Prypjat, it is worth quoting at length here the testimony Vladimir N. Shishkin, deputy di-

---

[34] Ю. А. Израэль, et al, *Радиоактивное загрязнение...*, 16.

[35] Ibid., 27, and Ю. В. Сивинцева и В. А. Качалова, 137 (data to create figure).

[36] Ibid., 56. Note the May 1st exposure rate contradicts that for the previous reference. Note also that the additional dose burden over 50 years is approximately 13% of the normal background dose burden over the same period: (50 years) x (8760 hrs/yr) x (0.015 – 0.02 mRad/hr pre-accident background dose rate) = 6.6 – 8.8 Rad.

[37] Table II.8: Ibid., 27 and Ю. В. Сивинцева и В. А. Качалова, 138; Figure II.8: Ibid., 52.

[38] Ю. В. Сивинцева и В. А. Качалова, 126.

rector of *Soyuzelektromontazh* (Union Electric Power Construction Branch) of the USSR Ministry of Electrification and Energy:[39]

> "... the total dose received by each resident of Pripyat and each member of the government commission by 2 P.M. on 27 April was, on average, in the range of 40 to 50 rads... On 27 April, during daylight hours, an hourly dosimetric survey of Prypjat was carried out. Samples of asphalt, air, and roadside dust were collected. An analysis showed that 50 percent of the radioactive particles consisted of Iodine-131. Radioactivity at ground level on the streets was as much as 50 roentgens per hour, and 2 m[eters] above the ground about 1 roentgen per hour."

Table II.8

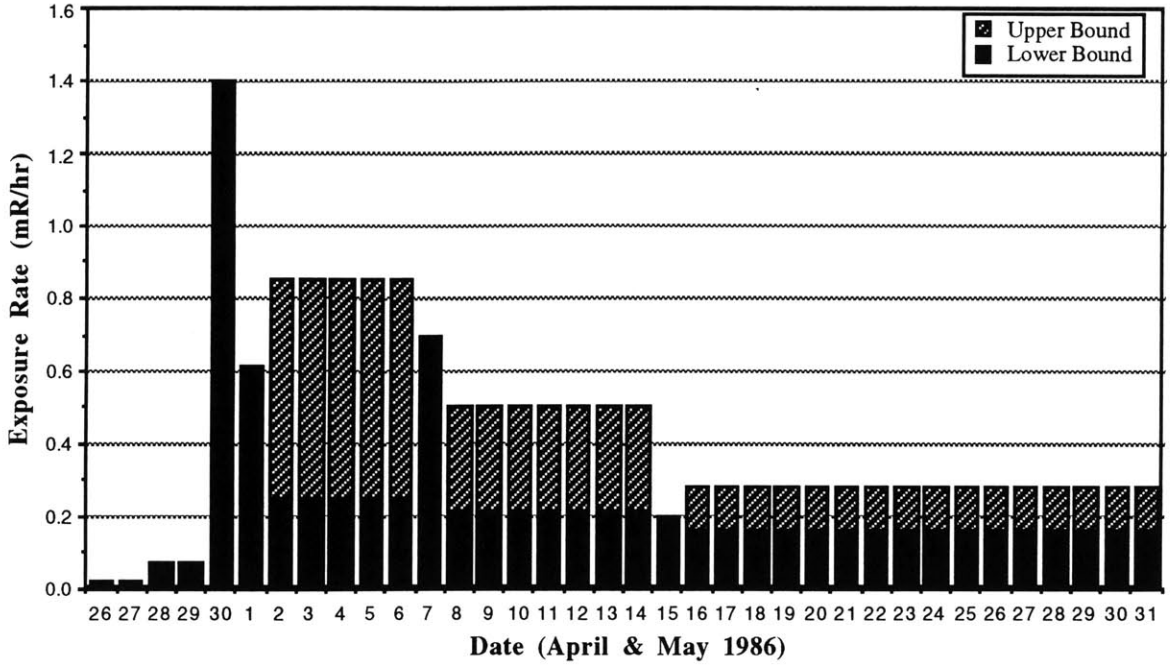
Maximum Observed Exposure Rates in Several Soviet Cities

Location	Exposure Rate (mR/hr)	Distance from Prypjat (km)	Date (maximum observed)
Brest, Belarus	0.06	450	30 April 1986
Homel, Belarus	0.50	130	30 April 1986
Minsk, Belarus	0.50	350	01 May 1986
Chernihiv, Ukraine	0.40	80	30 April 1986
Chernivtsi, Ukraine	0.45	450	02 May 1986
Rivne, Ukraine	0.13	280	29 April 1986
Chornobyl, Ukraine	24.0	15	01 May 1986
Kishinev, Moldova	0.06	490	04 May 1986
Sochi, Georgia	0.2–0.3	1070	12 May 1986
Adler, Georgia	0.12	1100	12 May 1986
Sukhumi, Georgia	0.19	1200	12 May 1986

[39] Grigori Medvedev, 183–184.

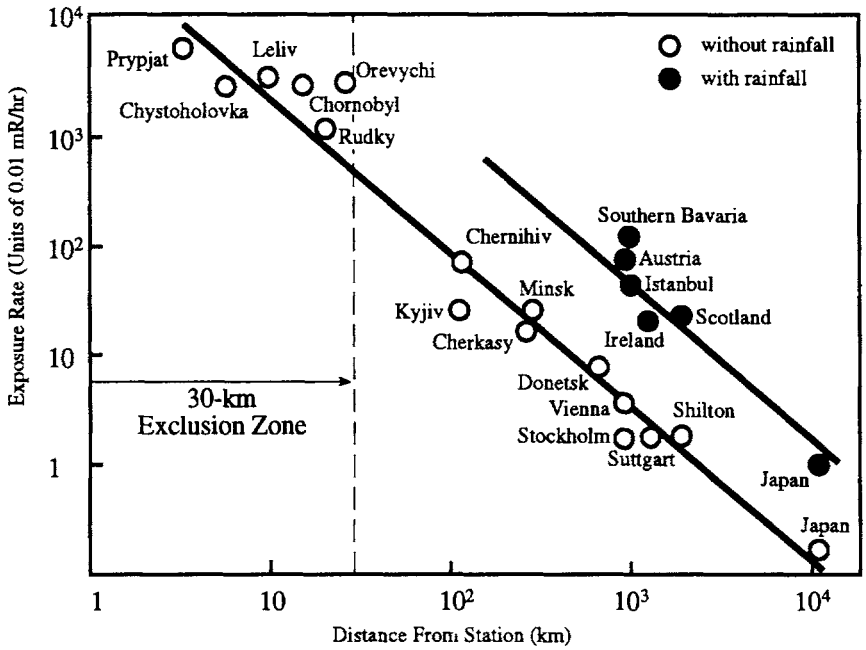
Figure II.7†

Average Outdoor Exposure Rate in Kyjiv During April & May 1986



† For a comparison, the *total* average absorbed dose from the TMI-2 accident for people in the immediate vicinity was 1.5 mRem, with a maximum total absorbed dose of 40–80 mRem primarily from gaseous fission products. The absorbed dose for a typical chest x-ray is in the range of 20–25 mRem.

Figure II.8
Relative External Exposure Rates for Various Points in the Northern Hemisphere†



† The relative external dose rates take into account both radionuclide deposition and air contamination, and are based on measurements taken 7 – 10 days after the accident assuming an average natural background dose rate of 0.010mR/hr. According to data collected in Kyjiv May 2 – 6, 1986, the average background dose rate was 0.25 – 0.85 mR/hr –implying the figure's data point for Kyjiv should reflect a higher dose rate approximately that of southern Bavaria. Израэль et al, 52.

II.2.3. Fallout in Other Countries

The plume of radionuclides released from Chornobyl first crossed the territory of Belarus during April 26th and 27th and continued further on over Poland, Finland, and Sweden in a northwesterly direction. By April 27–29 it had reached Central Europe and was continuing on into Western Europe. Strong rains on April 30th and May 1st increased the fallout over France, southern regions of the Federal Republic of Germany, Switzerland, Austria, Hungary, and Czechoslovakia. The greatest depositions were observed in Austria, Bavria (which averaged up to 1.2 Ci/km^2 of Cs-137), Italy, Norway, and Sweden.[40]

---

[40] Ibid., 49–51. See also Chapter Three for release dynamics and atmospheric transport information. For more detailed information on meteorology during the accident, see section 3.2.2. in Steven McInall, *Atmospheric Transport of Radionuclides Due to the Accident at the Chernobyl Unit-4 Nuclear Power Station*, Master of Science Dissertation, Department of Nuclear Engineering: The Massachusetts Institute of Technology (January 1988).

Unfortunately, more than seven years after the accident, disagreement still persists over how much material was ejected from the core. Although estimates for non-volatile radionuclide releases are in fair agreement at 3.5–4% of the initial core inventory, assessments of volatiles released (such as cesium, iodine, tellurium) vary anywhere from the lows given by the Soviets in Vienna up to 100%. A detailed treatment of this problem is found in Chapter Five "Consequences of the Accident" of this dissertation. Table II.9 below presents the accumulated activity of Cs-137 for various countries in the northern hemisphere excluding the republics of the former Soviet Union.

II.2.4. Contamination of Bodies of Water†

The radionuclides released into the atmosphere by the Chornobyl accident contaminated water systems as a result of both aerosol fallout and wash-down of contamination by rain and melted snow. During the first month after the accident, the main isotopes causing radioactive contamination of water systems were I-131, Ba-140, Zr-95, Nb-95, Ru-103, Ce-141, and Pu-239. Later, as the short-lived isotopes decayed out, Sr-90, Cs-137, and Pu-239 became the main sources. Maximum radionuclide concentrations in the river ecosystem were, of course, observed during the period immediately after the accident, and were mainly the result of aerosol deposition onto the surface of the water. Maximum observed total activity concentrations in local rivers were: Prypjat River (by Chornobyl) – 216 nCi/l; Uzh River – 135 nCi/l; Teteriv River – 135 nCi/l; Dnipro River – 108 nCi/l.[41] Tables II.10 – II.13 below present contamination data for rivers in the Kyjiv Reservoir system, while Figures II.9a & II.9b provide a visual aid for this data.[42]

---

† For more extensive information see Ю. А. Израэль, et al, *Радиоактивное загрязнение...*, Chapter 6 "Radioactive Contamination of Bodies of Water"; and Р. М. Алексахин et al, *Радиоэкологические последствия...*, Chapter 3 "Radioactive Contamination of Water Ecosystems."

[41] Ibid., Chapter 6. At the beginning of 1992, 53 Ci (0.38 gm) of Sr-90 had entered the Prypjat River as a result of rising waters from spring flooding. (Personal conversation with a hydrology specialist, Oleh Vojtsekhovych, from the Ukrainian Chornobyl Ministry. Hryhorij Hotovchyts, Ukraine's Minister for Chornobyl Affairs has said that the Chornobyl plant vicinity still presents a "very serious problem" due notably to the presence of some 800 raioactive saste dumps and the accumulation of 14,000 curies of Sr-90 in the banks of the Prypjat River. [Mark Hibbs and Ann MacLachlan, "Ukrainian Expert Details Doses and Follow-Up from Chornobyl," *Nucleonics Week*, Vol. 33, No. 19, (May 7, 1992): 7.]

[42] Figure II.9a – Израэль, 180; Figure II.9b – Израэль, 196.

Table II.9[43]

Estimated Activities of Cs-137 Accumulated on the Territories of Various Countries in the Northern Hemisphere After the Chornobyl Accident

Country	Area (sq. km.)	Population (1986 estimate)	Total Activity (kCi)
Albania	83,849	3,020,000	10.5
Austria	28,749	7,546,000	29.7
Belgium	30,508	9,868,000	0.5
Bulgaria	114,905	8,990,000	73.0
Canada	9,976,136	25,625,000	6.8
China	9,596,960	1,045,537,000	14.6
Czechoslovakia	127,855	15,542,000	15.9
Finland	337,008	4,931,000	51.4
France	571,530	55,239,000	22.4
Germany, East	123,719	16,692,000	15.7
Germany, West	248,575	60,734,000	43.2
Great Britain	244,045	56,458,000	11.9
Greece	132,468	9,954,000	11.9
Hungary	93,030	10,624,000	21.3
Ireland	70,285	3,624,000	6.8
Israel	20,324	4,208,000	0.1
Italy	301,225	57,226,000	29.7
Japan	377,767	121,402,000	0.7
Kuwait	17,819	1,771,000	0.03
Luxembourg	2,585	367,000	0.1
The Netherlands	40,844	14,536,000	1.8
Norway	324,219	4,165,000	29.7
Poland	312,683	37,546,000	248.6
Rumania	237,500	22,830,000	181.1
Spain	504,781	39,074,000	0.0
Sweden	449,963	8,357,000	91.9
Switzerland	41,287	6,466,000	5.4
Turkey	780,577	51,819,000	48.6
United States (48 cont.)	7,849,145	239,260,000	7.6
Yugoslavia	255,804	23,284,000	164.9
TOTALS	**33,296,145**	**1,966,695,000**	**1145.83**

[43] Adopted from Ю. А. Израэль, et al, *Радиоактивное загрязнение...*, Table 2.5, pg. 53 as referenced in Ch. Hohenemser and Or. Renn, "Chernobyl's Other Legacy," *Environment*, Vol. 30, No. 3 (1988).

Table II.10[44]

Concentrations of Various Radionuclides in the Prypjat River, (nCi/l)*

Date	I-131	Cs-137	Ba-140	Ce-141	Ce-144	Ru-103	Zr-95
May 1	57	6.7	38	11	10	15	11
May 2	120	—	60	—	—	22	42
May 6	22	4.3	4.8	2.4	—	4.6	4.5
June 3	0.9	0.6	—	—	—	0.7	0.3
June 20	—	0.1	—	0.05	0.09	0.1	0.1
July 16	—	0.2	—	0.4	1.0	0.4	1.0
MPC (Soviet)	1.0	15	25	88	12	80	62

* Sample collection at Chornobyl, 14 kilometers south of the station. Also given are (then) Soviet MPCs for each radionuclide. The total β activity in the Prypjat River decreased from a maximum of approximately 100 nCi/l in May 1986 to 1 nCi/l in July 1986, and finally to 0.1 Ci/l in Septermber 1986.

Table II.11[45]

Maximum Concentration of Various Radionuclides in Rivers of the Kyjiv Reservoir Basin, (nCi/l)

River	Date	I-131	Ba-140	Zr-95	Ru-103	Ce-141
Prypjat	May 2	120	60	42	22	—
Teteriv	May 3	54	34	39	19	18
Irpin	May 6	50	30	22	—	—
Desna	April 26	18	14	16	3.3	9.1
Dnipro	May 3	35	19	19	—	9.0

[44] Израэль, 181.

[45] Израэль, 181.

Table II.12[46]

Concentration of γ sources in Rivers of the Kyjiv Reservoir Basin, (nCi/l)†

River	I-131	Cs-137	Cs-134	Ru-106
Prypjat	0.43 ± 0.110	0.49 ± 0.02	0.23 ± 0.06	0.24 ± 0.080
Bravinka	—	—	—	—
Dnipro	0.24 ± 0.025	0.12 ± 0.02	0.06 ± 0.01	0.14 ± 0.015
Uzh	0.63 ± 0.080	0.35 ± 0.15	0.22 ± 0.10	0.19 ± 0.010
Teteriv	0.42 ± 0.150	0.22 ± 0.11	—	0.08 ± 0.015
Irpin	0.22 ± 0.040	0.24 ± 0.07	0.11 ± 0.03	0.10 ± 0.002
Desna	—	0.41 ± 0.03	0.20 ± 0.02	0.16 ± 0.035

† Averaged over June 3 – 11, 1986.

Table II.13[47]

Cs-137 and Sr-90 Concentration Ranges for Rivers of the Kyjiv Reservoir Basin†

River	Sample Location	1986 (pCi/l)		1987 (pCi/l)		1988 (pCi/l)		1989 (pCi/l)	
		Cs-137	Sr-90	Cs-137	Sr-90	Cs-137	Sr-90	Cs-137	Sr-90
Prypjat	Benivka	—	—	8–160	4–73	3–30	4–30	5–29	2–22
Prypjat	Chornobyl	25–6760	10–650	7–185	10–100	9–57	10–112	5–36	6–40
Illja	Rudnja-Illinets'ka	—	69–280	36–890	120–220	28–70	133–230	12–56	62–156
Uzh	Cherevach	63–800	18–57	12–76	17–133	10–43	20–66	6–29	8–33
Dnipro	Nedanchichi	7–173	3–28	9–46	3–54	5–22	3–33	6–18	1–13
Brahynka	Ladyzhchy	48–2000	47–180	18–382	34–180	110–290	54–123	20–157	14–158
Teteriv	Laput'ky	16–750	6–72	6–33	3–18	3–18	3–12	8–11	1–11
Irpin	Demydiv	18–455	4–11	4–24	5–10	1–36	3–9	5–11	2–9
Desna	Ust'e	7–1000	2–43	3–46	1–22	1–20	3–15	6–10	1–13

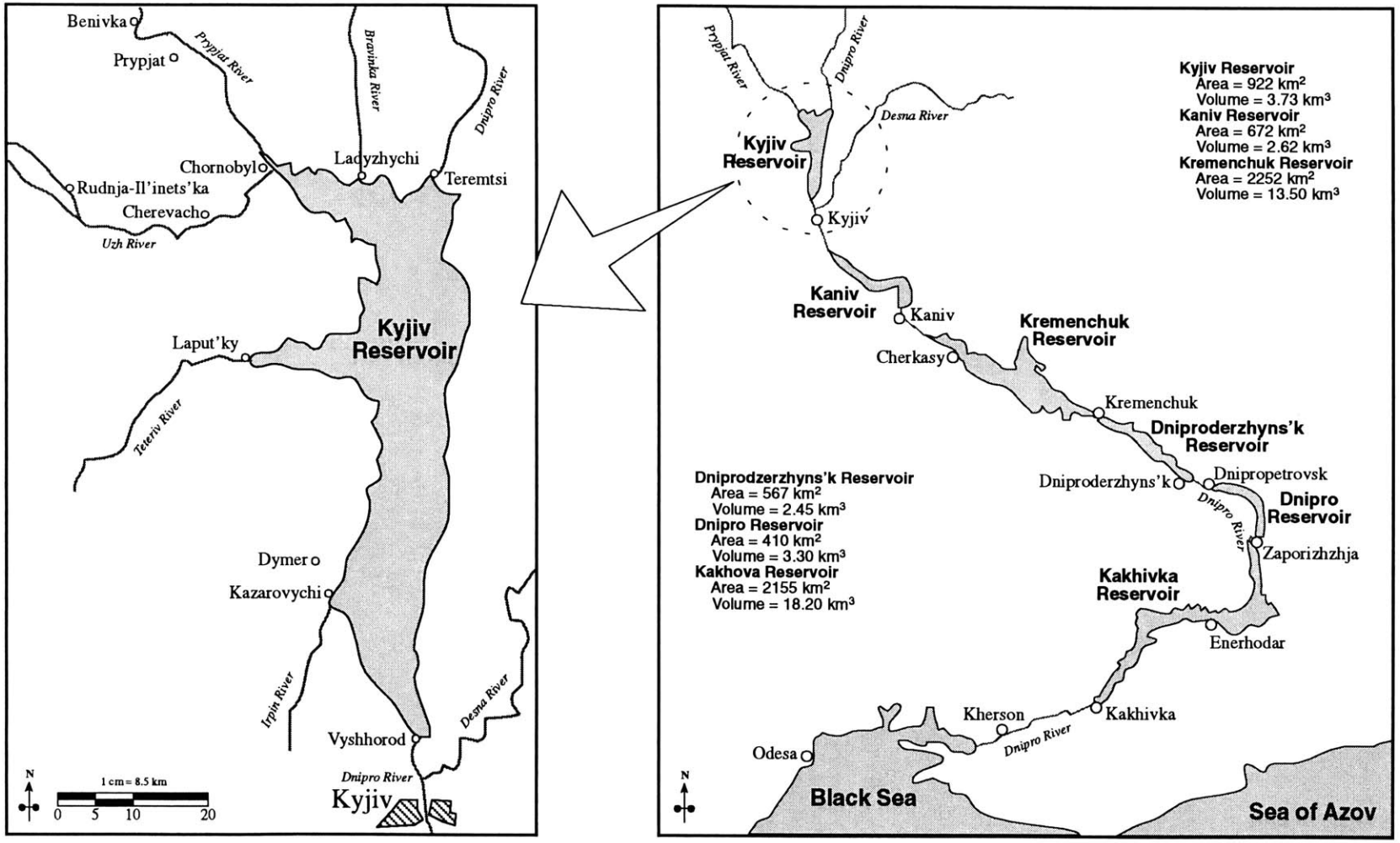
† Note: (then) Soviet MPCs for Cs-137 = 15,000 pCi/l; for Sr-90 = 400 pCi/l.

---

[46] Израэль, 185.

[47] Р. М. Алексахин et al., 48.

Figures II.9a & II.9b
The Kyjiv Reservoir and Its Feed Rivers,
And the Dnipro River Reservoir-Cascade System



The total volume of the Dnipro River Reservoir-Cascade System* is 43.8 km^3 and in 1988 it contained approximately 5500 Ci of Cs-137 in riverbed silts. During the same year, concentrations of Cs-137 in river bed silts of the system were as follows: Kyjiv Reservoir – 4.5 Ci/km^2; Kaniv Reservoir – 1.4 Ci/km^2; Kremenchuk Reservoir – 0.25 Ci/km^2; Dniprodzerzhins'k Reservoir – 0.12 Ci/km^2; Dnipro Reservoir – 0.08 Ci/km^2; Kakhivka Reservoir – 0.07 Ci/km^2.[48] In May 1986 the concentration of Sr-90 in the waters of the Kremenchuk Reservoir was 5 pCi/l; while the total activity that flowed into or was deposited on the Kyjiv reservoir from May 1986 through September 1987 was 1,700 Curies of Cs-137 and 700 Curies Sr-90.[49] The maximum concentration of Cs-137 in the upper layers of the Black Sea was observed in 1986 at 14 pCi/litre – attributed almost entirely to plume fallout. Flow from the Dnipro Cascade into the Black Sea from May 1986 through Sept 1986 contributed only 0.1% of this based on earlier studies of weapons tests fallout. The max observed for the Baltic Sea (Gulf of Finland) during the summer of 1986 of Cs-137 was 10 pCi/litre.[50] Table II.14[51] below presents Cs-137 and Sr-90 contamination data in the Dnipro River Cascade System; while Figures II.10a – II.11b[52] present graphically surface contamination in the Black and Baltic Seas.

---

* Of the Dnipro River's total 2,201 kilometer length (the third longest with the third largest drain-age basin in Europe after the Volga and the Danube), 981 kilometers flow through Ukraine. Its 504,000 km^2 total drainage basin occupies 65% (392,400 km^2) of the land area of Ukraine. Approximately 32,000 rivers and streams flow into it – including eighty-nine whose lengths are longer than 100 kilometers. It has an average surface area (including reservoirs) of over 8,000 km^2 and an average volume of 53.5 km^3. The Black Sea, into which the Danube, Dnipro, Dnister, and Don rivers flow, has a surface area of approximately 422,000 km^2 and a volume of approximately 555,000 km^3. The Azov Sea has an area of over 40,000 km^2 and a volume of 320 km^3.

[48] Израэль, 34.

[49] Ibid., 65.

[50] Ibid., 66.

[51] Р. М. Алексахин et al, *Радиоэкологические последствия...*, 52.

[52] Figure II.10a – Израэль, 211; Figure II.10b – Р. М. Алексахин et al, *Радиоэкологические последствия...*, 52 insert; Figure II.11a – Израэль, 215; Figure II.11b – Израэль, 216.

Table II.14
Cs-137 and Sr-90 Average Concentration for the
Dnipro River Reservoir-Cascade System†

Reservoir	1986 (pCi/l)		1987 (pCi/l)		1988 (pCi/l)		1989 (pCi/l)	
	Cs-137	Sr-90	Cs-137	Sr-90	Cs-137	Sr-90	Cs-137	Sr-90
Kyjiv (Opachichi)	—	28	47	32	24.7	32	12.0	17.5
Kyjiv (Vyshhorod)	—	—	13	15	11.5	21	9.5	10.3
Kaniv	3.0	32	3.3	14	5.3	17.4	7.5	4.8
Kremenchuk	1.3	27	0.8	9.4	1.1	13.6	1.8	6.6
Dniprodzerzhins'k	0.6	22.5	0.5	9.8	1.05	8.4	1.4	7.2
Dnipro	0.5	16	0.5	11	1.1	10.7	0.8	6.5
Kakhivka	0.3	11	0.3	12	0.7	10.5	0.5	8.5

† It is not clear whether these are surface layer or volume-averaged values.

Figure II.10a
Surface Concentrations of Cs-137 in the Black Sea
(June 12 – July 6, 1986)

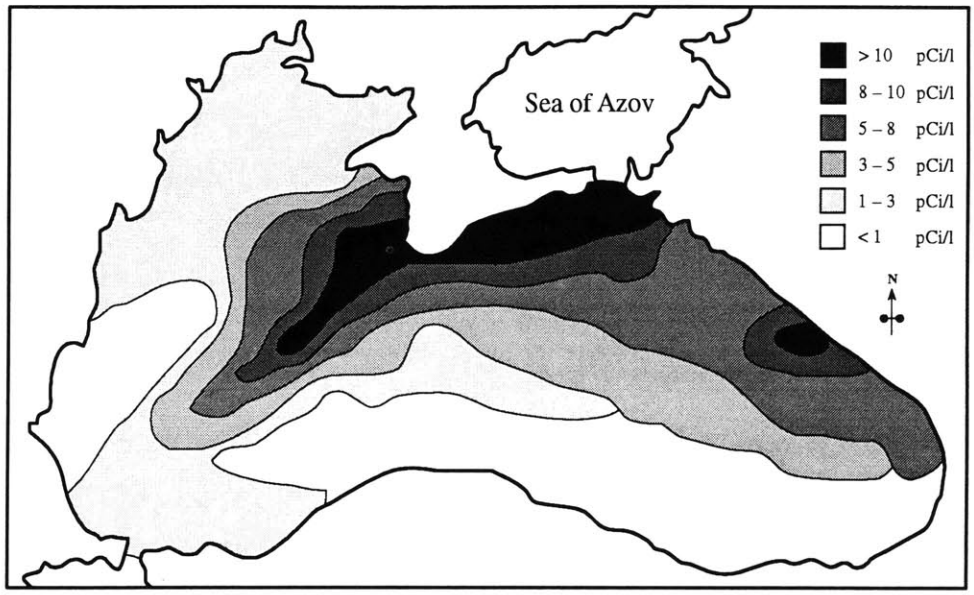
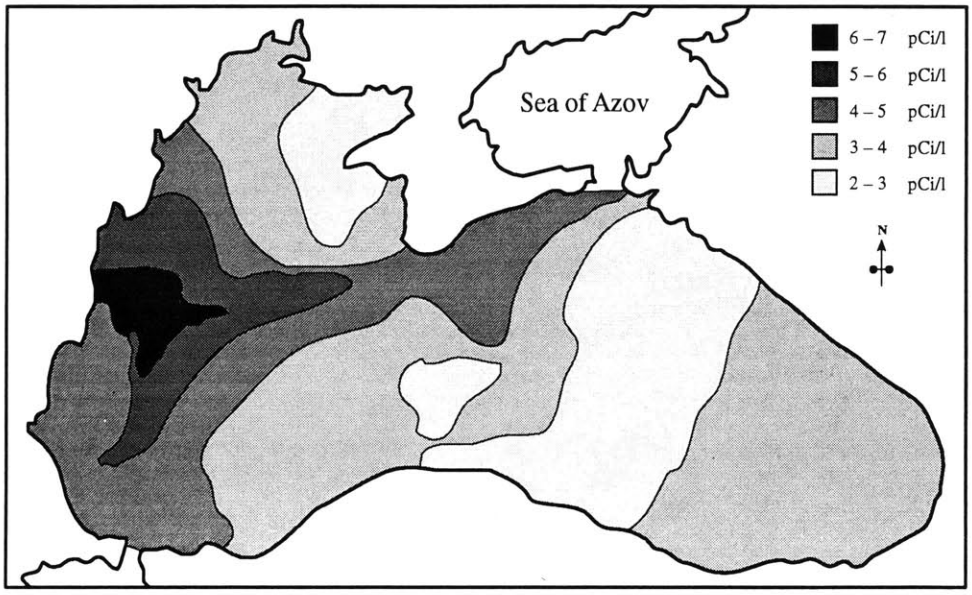
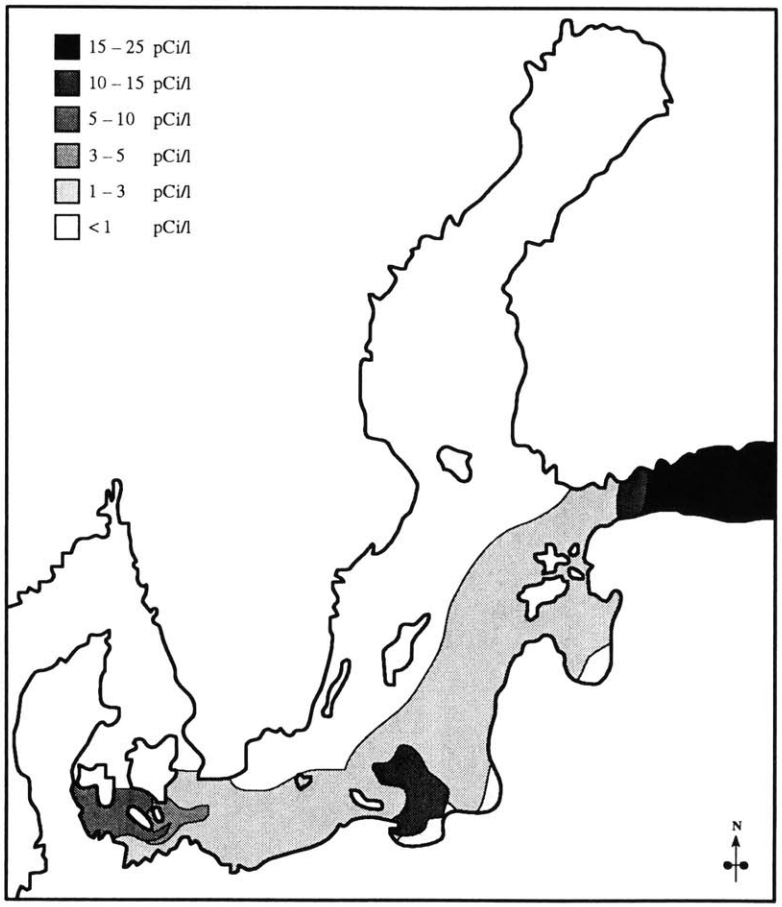


Figure II.10b
Surface Concentrations of Cs-137 in the Black Sea
(October 1986)

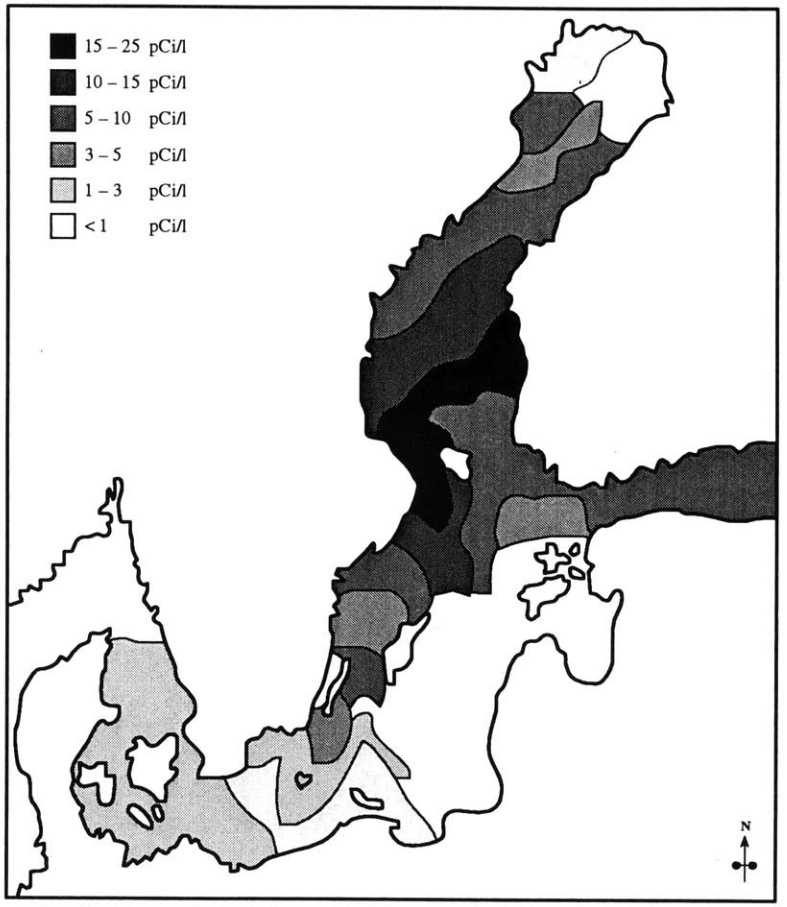


Figures II.11a & II.11b
Surface Concentrations of Cs-137 in the Baltic Sea

June – July 1986



October – November 1986



II.3. Population Resettlement and Cleanup Costs

"Immediate" evacuation of the 49,614 residents of Prypjat and the nearby village of Yaniv began at 1400 on April 27th (36.5 hours after the accident) and was completed without incident approximately three hours later.* After a more accurate appraisal of radiation conditions within the 10-km zone and in certain areas of the central 20-km zone on May 2nd (6.5 days after the accident),[53] a decision was made to evacuate fourteen more villages; but by May 4th (8.5 days after the accident) it was clear that forty-three more villages and towns within the 30-km zone had to be evacuated.[54] Later, when it was realized that a long "tongue" of contamination extended to the west of the station, another seven villages in the Kyjiv oblast and seven villages in the Zhytomyr oblast were evacuated. Altogether, from April 27th through August 16th, 90,784 people were evacuated

* By late afternoon on the 26th of April, the outdoor exposure rate in Pryjat had increased substantially. Exposure rates along city streets were in the range 14–300 mR/hr. At 0700 the following morning on Kurchatov Street (one of the closest to the station) the level was 500 mR/hr, while on other streets it ranged from 180–300 mR/hr. By 1700 the same day (as the evacutation was being completed) the exposure rate in Prypjat ranged from 400–1000 mR/hr, while in certain areas it was 1400–1500 mR/hr. (Ю. В. Сивинцева и В. А. Качалова, 168.) In the middle of the morning of April 26th, groups of women and children "spectators" watching the commotion at the reactor from a bridge about two kilometers from Unit-4 were exposed to rates as high as 17 R/hr.

[53] On May 2nd, a number of central government officials including Prime Minister Nikolai Ryzhkov arrived at the station and were briefed by the Governmental Commission as well as by a number of physicians, scientists, and engineers as to the extent of the accident. On the basis of this information it was only then decided to evacuate the remainder of the 30-km zone. (Ю. В. Сивинцева и В. А. Качалова, 53.)

[54] The Ukrainian goverment has defined evacuation criteria based on contamination levels as follows:

(1) **Exclusion Zone** – territory from which people were evacuated shortly after the accident.

(2) **Compulsory Evacuation Zone** – territory contaminated to levels of 15 Ci/km^2 or greater with Cs-137, or 3 Ci/km^2 or greater with Sr-90, or 0.1 Ci/km^2 or greater with Pu-239; along with territories with soils condusive to a high radionuclide migration rate in the indigenous flaura with contamination levels of 5–15 Ci/km^2 Cs-137, or 0.15–3 Ci/km^2 Sr-90, or 0.01–0.1 Ci/km^2 Pu-239, where the effective absorbed dose may exceed 500 mR over background in one year.

(3) **Guaranteed but Voluntary Evacuation Zone** – territory contaminated to levels of 5–15 Ci/km^2 Cs-137, or 0.15–3 Ci/km^2 Sr-90, or 0.01–0.1 Ci/km^2 Pu-239; along with territories with soils condusive to a high radionuclide migration rate in the indigenous flaura with contamination levels of 1–5 Ci/km^2 Cs-137, or 0.02–0.15 Ci/km^2 Sr-90, or 0.005–0.01 Ci/km^2 Pu-239, where the effective absorbed dose may exceed 100 mR over background in one year.

(4) **Strict (Intensified) Radioecological Control Zone** – territory contaminated to levels of 1–5 Ci/km^2 Cs-137, or 0.02–0.15 Ci/km^2 Sr-90, or 0.005–0.01 Ci/km^2 Pu-239; along with territories with soils condusive to a high radionuclide migration rate in the indigenous flaura with contamination levels of 0.2–1.0 Ci/km^2 Cs-137, where the effective absorbed dose may exceed 100 mR over background in one year.

[Государственная комиссия по чрезвычайным ситуациям, Кабинета Министров СССР – Комитет по ликвидации последствий аварии на Чернобыльской АЭС, *Чернобыль: Информационный бюллетень*, «Закон УССР – О правовом режиме территории, подвергшейся радиоактивному загрязнению в результате чернобыльской катастрофы,» Москва: Энергоатомиздат и Цчииатоминформ (6/1992): 53.]

from seventy-five population centers in Ukraine – 89,489 from the Kyjiv oblast and 935 from the Zhytomyr oblast.[55]

In Belarus, by May 10th, three evacuation zones were established: (1) the "zone of exclusion" (470 km^2) defined by an external exposure rate greater than 20 mR/hr – in which twenty villages were located and 4,400 people lived; (2) the "zone of evacuation" (1,024 km^2) defined by an external exposure rate of 5–20 mR/hr – where eighty-seven population centers were located an 20,300 people lived; and (3) the "zone of permanent control" defined by an exposure rate of 2–5 mR/hr – where one-hundred thirteen population centers were located and 58,300 people lived.[56] On April 30th, the Belarusian Governmental Chornobyl Commission passed a resolution to evacuated children and pregant women from the most highly contaminated areas; and on May 1st they were evacuated from twenty-five population centers. By May 5th, the evacuation of residents from the 30-km exclusion zone had been completed, while by May 7th children and pregnant women were also evacuated from the three southern regions of the Homel oblast bordering Ukraine. During the period of June 3–9, an additional twenty-eight villages and towns from these three regions were evacuated; and by September, another twenty-nine villages were evacuated. In December, twelve towns and villages were evacuated from the Brahinsk region. By the end of 1986, almost 25,000 people from one-hundred seven population centers were evacuated in Belarus.[57]

In Russia, according to a October 5, 1989 decree issued by the Russian Federation's Council of Ministers, thrity-one population centers in the Zlynkovsk, Krasnogorsk, and Novozybkov regions of the Brjansk oblast where 4,725 people lived (January 1, 1990) were designated for "priority" evacuation – almost three and one-half years after the accident. On March 16, 1990, an additional thirteen villages in the Krasnogorsk and Gordejevsk regions of the Brjansk oblast (population 2,080 people) were added to this

---

[55] Ю. В. Сивинцева и В. А. Качалова, 251.
[56] Ibid., 274.
[57] Ibid., 276–277.

evacuation list.[58] The first stage of a 1990–92 plan forsaw the "immediate" evacuation and resettlement of people from sixty-seven population centers (amounting to more than 15,000 residents) located in areas where Cs-137 contamination was over 30 Ci/km^2. As a whole, the plan forsaw the evacuation of 84,200 people; while by 1995 a continuation of the plan forsees evacuating another 26,800.[59] By the end of 1991, residents from only twenty-eight villages and towns had been evacuated. Finance problems, shortage of jobs in areas accepting these people, and the fact that construction of new homes for them had not been completed were blamed.[60]

At the time of the accident, 4,515 population centers (cities, villages, towns) of Belarus, Russia, and Ukraine were located in regions contaminated with over 1 Ci/km^2 where 6,115,000 persons lived – including 1,492,000 children under 14 years of age.[61] The zone of "complete and immediate evacuation" – the so called 10 km "inner" zone – was defined by the 20 mR/hr γ-isoline on 10 May 1986 and has an area of about 1,000 km^2.[62] The 30 km zone, with an area of 2,830 km^2, was defined partly by the boundary of Pu-239 and Pu-240 contamination greater than 0.1 Ci/km^2 and partly by the 5 mR/hr γ-isoline on 10 May 1986.† This "first phase" of the evacuation was completed on May 5th and 6th and accounted for approximately 91,000 people living in seventy-three villages, two towns, and one city (Prypjat).[63] The people evacuated from these regions were resettled "close" to the 30 km exclusion zone in the republic from which they originally came.

The second or so-called "delayed but imperative" zone of evacuation was defined by a 5 mR/hr or greater γ-isoline on 10 May 1986 (in which if people lived for one year they

---

[58] Ibid., 305. It is not clear why Russian authorities waited until three and one-half years after the accident to begin evacuating people from these areas.

[59] Ibid.

[60] Ibid., 306–307.

[61] "Основні дані ...," 7.

[62] Израэль, 17.

† The contours of the exclusion zone were more accurately defined at the end of 1987 by collecting and analyzing ground samples (in contrast to earlier gamma-measurements taken from the air) and establishing the following levels for defining the zone: Cs-137 >15–40 Ci/km^2; Sr-90 >3 Ci/km^2; and Pu-239 >0.1 Ci/km^2 (Ю. В. Сивинцева и В. А. Качалова, 250.)

[63] Zhores Medvedev, 105–106.

would receive an integrated dose of 10 Rem[64]) and by more accurate contamination measurements taken in June 1986. (The 10 Rem dose was defined after the accident by the USSR Ministry of Health as the maximum permitted one-year limit for the general public and the criteria for evacuation.) The territory encompassed by this isoline extends beyond the 30 km zone – up to 75–80 km west of the station in a thin "tongue," and a wider area extending 40–45 km north of the station.[65]

If both the 30-km exclusion zone and this 5 mR/hr γ-isoline are considered together, by January 1, 1987, 115,174 people from one-hundred eighty-eight population centers (91,400 from Ukraine including the city of Prypjat for a total of seventy-six population centers; 23,600 from one-hundred seven settlements in Belarus; and 174 from four settlements in the Brjansk oblast in Russia) were evacuated.[66],[67] Recently, an additional fourteen settelements have been evacuated (mostly by personal innitiative) – twelve in Belarus and two in Russia.[68]

From 1987 through 1990, in accordance with central government policies, an additional 13,000 people were resettled. However, during this period 59,000 more people were resettled independently of the central planners. The total number evacuated and resettled from 1986 through 1991 was 163,000 people. According to the general evacuation plan for 1991, 119,800 people were to be moved from contaminated areas. During the

---

[64] Израэль, 16.

[65] Zhores Medvedev, 105–106.

[66] Ю. В. Сивинцева и В. А. Качалова, 53, 74–75, 79. 44,500 out of 51,000 registered residents of Prypjat were resettled in 53 villages and towns outside the 30-km exclusion zone in the Kyjiv oblast. 2,500 personnel from the USSR Ministry of Internal Affairs (MVD) helped in evacuating people from the inner 10-km zone, while approximately 18,500 took part in general evacuation work and administrative control of the 30-km zone. In addition, approximately 60,000 head of farm animals were evacuated from the zone. It is not clear what happened to these animals. More detailed and extensive information can be found in Ю. В. Сивинцева и В. А. Качалова.

[67] The Soviet report presented in Vienna reports numbers of people evacuated from the following radial bands around the city of Prypjat: Prypjat — 45,000, 3–7 km — 7,000, 7–10 km — 9,000, 10–15 km — 8,200, 15–20 km — 11,600, 20–25 km — 14,9000, 25–30 km — 39,200 [Volume II, Part 7, page 62.]

[68] Израэль, 17, 56. In March 1989 it was reported that twelve more villages would be evacuated in two districts situated close to the exclusion zone because their inhabitants were expected to accumulate 35 Rem per person [*Izvestia*, March 3, 1989]. In February 1989 *Moscow News* reported that in the Narodychi district of the Zhytomyr region in Ukraine (at a distance of between 50 - 90 km from the station) the contamination of the topsoil exceeds 80 Ci/km^2, while external radiation in some parts of the villages was 2 mR/hr (V. Kolinko, "Radioactive Echo," *Moscow News*, 8 (19 Feb 1989):12) – as presented in Zhores Medvedev, 186-87.

first nine months of 1991, 33,000 of these people (or 27.6% of plan – 7,000 from Russia, 15,000 from Ukraine, and 11,000 from Belarus) were resettled. For the total 218,900 planned to be resettled during 1990–1992, by October 1, 1991, 121,000 had actually been resettled. One of the goals of the 1991 plan was to complete the resettlement of people from regions contaminated with more than 40 Ci/km^2 of Cs-137.[69] In 1992-1993 it will be necessary to resettle at least another 85,000 people – although it is not clear whether the Ukrainian and Belarusian governments have the required resources to carry out this resettlement. Of these, 35,000 live in regions of "delayed but imperative evacuation" (Cs-137 contamination greater than 15 Ci/km^2) and 50,000 in regions contaminated from 5 to 15 Ci/km^2 who have expressed a desire for immediate evacuation and have the right to demand so from their governments. In addition, the approximately six million people remaining in contaminated regions are also possible candidates for resettlement.[70]

Direct financial losses as a result of the accident are enormous. The massive cleanup effort and entombment of the destroyed reactor, transportation of equipment and specialized military units from all parts of the former Soviet Union, loss of equipment due to contamination, conscription of workers, health care for victims, loss of agriculturally-rich land, lost electrical power export earnings (at the time of the accident, the Chornobyl station's four 1000 MWe reactors produced approximately eleven percent of Ukraine's electricity), resettlement of people from contaminated areas, the construction of a new city for station workers and others resettled from Prypjat†, etc., have driven official total

---

[69] Ю. В. Сивинцева и В. А. Качалова, 324. The resettlement of people during this period was not without controversy. Apparently, because of demands by the Ukrainian Green World organization, people were resettled from regions only slightly affected by the accident to regions (although not affected by the accident, because of the high content of uranium ores in the ground and the subsequent release of radon gas with its decay) that actually have a higher background radiation rate than the regions from which they were evacuated. (Personal coversation with Borys Samojilovych Prister, Deputy Minister of the Ukrainian Chornobyl Ministry, December 2, 1992.)

[70] Summarized from "Основні дані щодо....

† 21,000 homes and 15,000 apartments were provided for the evacuees. Unfortunately, in their haste to accomodate the 44,000 station workers and their families resettled from Prypjat, the new city of Slavutych (located in the Chernihiv oblast of Ukraine about 48 km east-by-northeast of the station) was itself built almost directly over of a region contaminated by accident fallout.

cost estimates to over $14.4 billion.[71] For example, from 1986 through 1991 $4.5 billion were spent on resettlement alone ($43,000 per person); and to implement the 1992-1993 resettlement program, the (former) Soviet government planned to invest $3.7 billion.[72] In 1991 alone, 10.32 billion rubles as direct capital investment were used to "mitigate the consequences of the accident" and resettle people.[73] Currently, twelve percent of every Ukrainian's currency "coupon" pays for various costs associated with the cleanup and resettlement in the zone and other contaminated areas throughout Ukraine.[74]

II.4. Casualties, Fatalities, and Other Health Effects

To date, forty-two people have died directly as a result of the accident: two Unit-4 workers died immediately either from collapsing structures caused by the initial explosions or from the sudden release of high-temperature, high-pressure steam from Unit-4's damaged primary system, twenty-nine people (mostly fire fighters and station personel present at the station at the time of the accident†) died within three weeks from high radiation doses and burns,†† a helicopter pilot died three years later from complications (infected burns) suffered as a result of what the Soviets have termed "acute radiation sickness," seven firefighters also died later from acute radiation sickness, and there have

---

[71] Paul Quinn-Judge, Soviets Feel Nuclear Protest Heat," *The Christian Science Monitor,* Vol. 80, No. 48 (February 2, 1988): 9. It is estimated that during the period 1986–1991, 650,000 thousand "liquidators" have taken part in mitigating the consequences of the acciden – including more than 340,000 military personnel [Ю. В. Сивинцева и В. А. Качалова, 5.]

[72] "Основні дані ...," 7. Feshback and Friendly estimate economic losses could mount to 200 billion rubles (1986 value), *Ecocide in the USSR*, 3.

[73] Ю. В. Сивинцева и В. А. Качалова, 324. A good accounting of the costs involved is provided here. Unfortunately, because by 1991 the Soviet Union's was well on the way to collapsing, the value of the ruble against the dollar made the planned investment less and less substantial.

[74] Personal coversation with Borys Samojilovych Prister, Deputy Minister of the Ukrainian Chornobyl Ministry, December 2, 1992. See also Janet Wood, "Ukraine Takes On the Burden," *Nuclear Engineering International,* (August 1993): 17, where it appears this doesn't meet half of the funds required.

† At the time of the accident, 176 operating personnel were working at Units 1, 2, & 3 and taking part in the experiment at Unit-4. An additional 268 night-shift construction personnel were working at the site of the future Units 5 & 6, located approximately 1.5 km to the southeast of Unit-4. (Mark Hibbs and Ann MacLachlan, 7.)

†† Out of the fifty-five most severly affected people hospitalized immediately in Moscow, twenty-eight fatalities resulted mainly from thermal burns (40 to 90% of the body). [Edward A. Warman, "Facts and Observations From Vienna Meeting on Chornobyl," lecture given at MIT on September 11, 1986 based on notes compiled by the author at the Vienna conference.]

been three fatal cases of thyroid cancer in children.[75] In addition, 236 people have not died but are suffering from the effects of acute radiation sickness. Of the initial group of 243 people most seriously affected by radiation but who had not died within a few months of the accident (including the seven firefighters who died later), twenty-two received doses ranging from 600 to 1,600 Rems while twenty-three received doses from 400 to 600 Rems.[76] Interesting and quite encouraging is the case of Petro Palamarchuk, head of the startup team for Unit-4, who received a dose of approximately 780 Rems – pushing far forward the previously accepted limit of 600 Rems for human survival from radiation.[77]

The 91,000 evacuees who resided within three to thirty kilometers from the station received an average whole body dose of 16 Rems and an average thyroid does of less than 30 Rems; while the 24,000-person subgroup within three to fifteen kilometers received an average dose of 43 Rems. These large doses reflect the fact that many of these persons were not evacuated until late in the first week following the accident. In contrast, the 45,000 people evacuated from Pripyat (located three kilometers to the northwest of the station) beginning two days after the accident received an average dose of 3.3 Rems.[78] This last figure is disputed in a 1986–1987 study by the Institute of Genetics of the USSR Academy of Sciences (but only published in 1991) that claims the evacuees from Prypjat received and absorbed dose of 11.2 Rem per person. The study also states that the builders of the sarcophagus received an average 34.1 Rem per person (with a range of 5 to 150 Rem), dosimetrists working in and around the station after the accident received and average 32.4 Rem per person, and construction support workers (Drivers,

---

[75] "Probably 42 Deaths Are Attributable to Chernobyl-4...," *Nuclear News*, Vol. 36, No. 15, (December 1993): 75–76.

[76] The Ukrainian Chornobyl Minister, Hryhorij Hotovchyts, has stated that besides the 31 fatalities during the first hours and days after the accident, 145 others got acute radiation sickness and an additional 92 showed symptoms of radiation sickness. Within the first five months after the accident, 1,874 people received doses exceeding 25 rem and 75,000 peole doses between 1 and 4 rem. Doses of over 30 rem were measured in the thyroids of some 150,000 men. (Mark Hibbs and Ann MacLachlan, 7.)

[77] Read, Piers Paul, *Ablaze*, New York: Random House, (1993): 168–170, 328.

[78] Ibid.

doctors, operators, and militia) who worked in the exclusion zone in 1986 received an average in the range of 12 to 23 Rem per person.[79]

According to revised figures for the average individual accumulated dose in areas of "strict control," for the approximately 272,800 persons living in these regions the average whole-body dose was 3.53 Rems (2.67 Rems external, 0.88 Rem internal). Moreover, 80.5% of these people revieved doses below 5.0 Rems for the period in question, 16.2% received doses in the range of 5.0–10.0 Rems, while 0.8% received doses in the range of 15.0–17.3 Rems.[80] (17.3 Rems was the dose limit established after the accident.) Table II.15[81] presents a breakdown of collective doses received in zones of "strict control."

In Belarus, the average accumulated dose to people living in zones of "constant control" (15–40 Ci/km^2 Cs-137 contamination) for the period 1986–89 was 6.5 Rems, for those living in areas with Cs-137 contamination greater than 40 Ci/km^2 the absorbed dose was 10.1 Rems, while for those in other regions the absorbed dose was approximately 4.0 Rems. According to preliminary figures from the Institute of Biophysics of the USSR Ministry of Health, more than 20% of the children living in the southern areas of the Homel oblast recieved an absorbed dose to their thyroid gland of more than 200 Rems, while approximately 4% recieved about 1000 Rems.[82] By March 1991, people living in the most highly contaminated areas of Belarus (nine regions (counties) of the Homel oblast and five regions of the Mohiljow oblast) were examined to determine the absorbed dose in the thyroid gland. Results of these investigations are presented in Table II.15. Work is currently underway in other contaminated regions of Belarus as well as in Russia and Ukraine.

---

[79] Zhores A. Medvedev, "Fifth Anniversary: Perspective from the USSR," *Nuclear Engineering International*, (August 1991): 43.

[80] Ю. В. Сивинцева и В. А. Качалова, 182.

[81] Ibid., 183. Chapter 9 contains a fair amount of interesting health-related information concerning the accident.

[82] Ibid., 288. In Ukraine, out of approximately 144,000 children tested in May 1986, 7% (10,080) of the children recieved an absorbed thyroid dose of more than 200 Rad, and 2% (2,880) recieved more than 500 Rad. Most of these children were from the Polissja region in the Kyjiv oblast and from the Narodychi region in the Zhytomyr oblast. (pg. 262.)

The estimated collective dose (total past and future exposure) to the 280 million person population of the former Soviet Union is approximately 32,654,000 person-Rem.[83] However, extrapolating this figure for the entire territory of the former Soviet Union, which includes people in areas that were scarcely affected, makes little sense. Beyond the bounds of the station, two areas were predominantly affected: Belarus (10,634,000 person-Rem for a population of 10.01 million) and the southwest part of Ukraine (8,066,000 person-Rem for a population of 21.94 million). The central part of Russia was less affected (4,249,000 person-Rem for a population of 29.8 million).[84] The 2.9 million persons residing in southeast Belarus received an "immediate" average external dose of 0.71 Rem. This is about seven times their yearly normal background dose of approximately 0.1 Rem from naturally occurring sources. The 74.5 million persons in the European part of the former Soviet Union received an "immediate" average external dose of 0.11 Rem, which is equivalent to their normal yearly, exposure from natural background.[85]

---

[83] L. A. Ilyin and O. A. Pavlovskyj, "Radiological Consequences of the Chernobyl Accident in the Soviet Union and the Measures Taken to Mitigate Their Impact," report at the *IAEA International Conference on Nuclear Power Performance and Safety*, 28 September – 2 October 1987, Vienna (IAE-CN-48/33) as referenced in Zhores Medvedev, 179.

[84] M. Morrey, J. Brown, J. A. Williams, M. J. Crick, J. R. Simmonds, and M. D. Hill, *A Preliminary Assessment of the Radiological Impact of the Chernobyl Reactor Accident on the Population of the European Community*, United Kingdom: National Radiological Protection Board (1987) as referenced in Zhores Medvedev, 180.

[85] Warman.

Table II.15[86]

Thyroid Gland Absorbed Dose in the Mohiljow and Homel Oblasts of Belarus
(children 0 – 7 years old make up 10% of the population)

Absorbed Dose Interval (Rem)	Homel Oblast (nine regions)		Mohiljow Oblast (five regions)		Homel & Mohiljow Oblasts (fourteen regions)	
	# people	percent	# people	percent	# people	percent
ADULTS						
0–30	239,685	73.93	124,582	87.49	364,267	78.07
30–75	50,207	15.49	14,773	10.36	64,980	13.93
75–200	25,768	7.95	2,703	1.90	28,471	6.10
200–500	7,048	2.17	286	0.20	7,334	1.57
500–1000	1,110	0.34	52	0.04	1,162	0.25
1000–2000	350	0.11	4	0.03	354	0.08
2000–3000	25	0.008			25	0.005
3000–4000	7	0.002			7	0.0015
Total	**324,200**	**100.0**	**142,400**	**100.0**	**466,600**	**100.0**
CHILDREN						
0–30	15,128	46.66	9,637	67.68	24,765	53.08
30–75	8,951	27.61	2,975	20.88	11,926	25.55
75–200	4,924	15.19	1,345	9.45	6,269	13.44
200–500	2,428	7.49	251	1.76	2,679	5.74
500–1000	693	2.14	28	0.20	721	1.55
1000–2000	274	0.85	4	0.03	278	0.60
2000–3000	20	0.06			20	0.04
3000–4000	2	0.006			2	0.004
Total	**32,420**	**100.0**	**14,240**	**100.0**	**46,660**	**100.0**

[86] Ю. В. Сивинцева и В. А. Качалова, 172–173.

Table II.16

Distribution of Absorbed Dose for People Living in Areas of Strict Radiation Control for the Period 26 April 1986 to 1 January 1990

Dose Range (Rem)	Number of People Receiving Corresponding Dose (1000's of People)	(% of Total)	Collective Dose (1000 person-Rem)
0.5–1.0	18.6	6.8	14.00
1.0–2.0	69.3	25.4	10.40
2.0–3.0	63.9	23.4	1.60
3.0–4.0	42.6	15.6	1.49
4.0–5.0	25.3	9.3	1.14
5.0–6.0	15.6	5.7	0.86
6.0–7.0	11.5	4.2	0.75
7.0–8.0	8.2	3.0	0.62
8.0–10.0	9.0	3.3	0.81
10.0–12.5	4.9	1.8	0.55
12.5–15.0	1.8	0.7	0.24
15.0–17.5	1.0	0.4	0.16
> 17.5	1.1	0.4	0.20
Total	**272.8**	**100.0**	**32.82**

Radiation exposures outside the Soviet Union resulted in twice the normal background in most of western Europe for a period of about a week, with ten times background in areas where rainfall occurred. The exposures of individuals residing in western Europe can be expressed as being equivalent to a few days or a few weeks of exposure to naturally occurring radiation – a 52 to 56 week year for 1986.[87] The collective population dose commitment to western Europe is estimated to be 8 million person-Rem;[88] while in the northern hemisphere for the seventy years following the accident (the sum of all indivudal doses) is estimated to be 120 million person-Rem.[89] The integrated internal

[87] Ibid.

[88] M. Morrey, J. Brown, et al., *A Preliminary Assessment...*, as referenced in Zhores Medvedev, 180.

[89] Marvin Goldman, "Chernobyl: A Radiobiological Perspective," *Science*, Vol. 238, No. 4827, (30 October 1987): 622.

lifetime dose to the people of Belarus and Ukraine is thought to be 210 million person-Rem.[90]

The number of latent (additional) fatalities resulting from cancers induced *directly* as a consequence of the accident, however tragic, are much more difficult if not impossible to determine with reasonable accuracy.[91,92] Translating incomplete radiological data (especially Soviet data that is questionable at best)[93] into dose projections for populations of affected countries has been done but with no clear consensus. The stochastic effects of low-level radiation on large populations continues to be debated. To the extent that there is a consensus – albeit a shaky one – between 20,000 and 40,000 cancer-induced deaths resulting from the accident are predicted within the bounds of the former Soviet Union, with substantial numbers outside.[94] But even this figure, apart from not being scientifically confirmable for now, will be hidden in the "noise" of spontaneous cancers for an

---

[90] Richard Wilson, "A Visit to Chernobyl," *Science*, Vol. 236, No. 4809 (26 June 1987): 1638. This is a deliberately pessimistic figure given by Academician L. A. Ilyin (Vice President of the USSR Academy of Medical Sciences) and Professor Pavlowski (Institute of Medical Physics) at the August 1986 Vienna meeting. Western specialists thought this estimate was ten times too high based on measurements of intake of cesium from bomb tests.

[91] For a fairly good introduction to the problems and uncertainties encountered in modeling or estimating possible future cancers resulting from exposures to ionizing radiation, see Harold Denton, "The Causes and Consequences of the Chernobyl Nuclear Accident and Implications for U.S. Regulation of Nuclear Power Plants," presented at the International Energy Seminar *Chernobyl: The Implications for Nuclear Power and the International Nuclear Regime*, sponsored by the International Energy Program of the Johns Hopkins Foreign Policy Institue, Washington, D.C., (July 9, 1986), 14–22.

[92] For a discussion of the renewed concerns about "safe" levels of ionizing radiation, see Len Ackland, "Radiation Risks Revisited," *Technology Review*, Vol. 96, No. 2, (February/March 1993): 56–61.

[93] For example, physicians in Ukraine and Belarus were forbidden to mention radiation in their diagnoses, and medical records for approximately 340,000 soldiers and other workers who took part in clean-up operations are "missing". (For an excellent account see the sections "Coverup and Controversy" and "The Wages of Fear" in Feshbach and Friendly, 150–154.) Moreover, according to Bennet Ramberg, "Learning from Chernobyl," *Foreign Affairs*, Vol. 65, No. 2 (Winter 1986–87): 316, "The Soviets have promised to study intensively the 135,000 evacuees from the exlusionary zone around the plant and to share the information with specialists in the United States and elsewhere." Up until the collapse of the former Soviet Union, virtually nothing was done to address the problem of the evacuees, let alone the "liquidators," and medical data could not be located.

[94] Bennet Ramberg, "Learning from Chernobyl," 314. In a reference the author lists a number of estimates from a low of 210 to a high of one million early cancer-related deaths as a result of the accident. Ramberg goes on to expound on political pressures that may influence scientists' estimates of the the health effects by stating, "political considerations [are] the 'bottom line' in assessing a disaster with as many possible ramifications as Chernobyl." This is in addition to the fact that most scientists are deeply divided on the biological impact of low-level radiation – basing their conjectures upon many different assumptions that are in turn due to an absence of definitive data.

accepted radiation risk coefficient of 2.3×10^{-4} fatal cancers per Rem.[95,96] These cancers, until better methods are developed, may be statistically undetectable; and it is not likely that any epidemiological study could ever detect such a small increment. The best recent estimate is that there would be "an increase of around 1 percent in the incidence of all cancers... expected over the normal lifetime of the people from the contaminated regions and those who had worked on post-accident cleanup."[97]

Until such time that reasonable projections can be made, overgeneralizing conclusions drawn in studies such as the IAEA's *International Chornobyl Project* (ICP), which has been roundly criticized in Belarus, Ukraine, and the West, should be viewed with caution. This study is faulted for drawing specific conclusions that a number of experts claim was limited in scope – it was carried out only four years after the accident (when no specific radiation-related cancers are expected anyway) and because it did not involve the two population groups which were most at risk from radioactive contamination: the approximately 116,000 people who were evacuated from the 30-km exclusion zone and the approximately 240,000 emergency clean-up workers, soldiers, and construction teams ("liquidators")* who carried out the rapid construction the sarcophagus. The study was

---

[95] Goldman, 623.

[96] "Ilya Likhtaroyov, head of the Department of Dosimetry and Radiation Hygiene at the Ukrainian Ministry of Health, confirmed Ukrainian government statements that 6,000 – 8,000 deaths have occurred among the 130,000 – 180,000 individuals who participated in recovery work after the 1986 catastrophe – the so-called liquidators. However, he said during a visit in Bonn last week, the cases of mortality expected in a control population over the same six years 'would not differ greatly' from that number." [Mark Hibbs and Ann Maclachlan, "Ukrainian Expert Details Doses and Follow-up From Chernobyl," *Nucleonics Week*, Vol. 33, No. 18, (May 7, 1992): 6.] This and other statements were made by Ukrainian officials to counter alarmist and baseless claims that one million people would eventually die as a result of the Chornobyl accident – made by the former "liquidator" Vladimir Chernousenko (see Preface). Unfortunately, even western "experts" take advantage of such figures to raise alarmist concerns. For example, David Marples, testifying at a CSCE briefing (Washington D.C., April 26, 1991) on the 31 deaths attributed directly to the explosions and severe radiation exposure and apart from the fact that his basic figures are incorrect, states, "The 31 [direct deaths] figure was never real. It never was a reality. It was alleged there were 28 [29] dead from radiation and 3 from either falling debris or – you know, I think one just got buried by the initial explosion."

[97] *Nuclear News*, (December 1993): 76.

* Although it is true that the ICP should have included in its study people who had been evacuated from the 30-km exclusion zone (some as late as eight and one-half days after the accident), it is unfairly criticized for excluding the "liquidators." Its explicitly stated concern was with assessing the health effects in members of the public living in contaminated regions *at the time of the study* – as the ICP team was requested to do by the then Soviet government. The point made by the study's critics, however, that general conclusions about the effects of the accidents should have been withheld until all affected people were studied, is correct.

also faulted for being inherently biased from the start because Moscow controlled access to data and people as opposed to the republics.[98,99,100,101]

While it is true, however, that these extra deaths would not be detectable in the health statistics for the entire former Soviet Union or for the whole of the northern hemisphere, in the most affected areas of Belarus and Ukraine, a careful follow-up study would almost certainly find future late effects, particularly among younger people, and probably also an increase in leukemia over a shorter period (from two to seven years after the accident).[102] In fact, numerous detectable health effects have surfaced as a result of the accident according to Ukrainian Parliament figures for people in Ukraine: (1) one in four have affected immune systems, (2) blood-related illnesses have increased 2.5–5 times above normal† depending on the level of contamination of the territory of interest,

---

[98] See, for example, (1) Gofman, John W., "Beware the Data Diddlers," *The Bulletin of the Atomic Scientists*, (May 1993): 43; (2) Read, Piers Paul, *Ablaze*, New York: Random House, (1993), 308–319; (3) Marples, David R., "Chornobyl Six Years After: A New Era of Investigation," *The Ukrainian Weekly*, Vol. LX, No. 17 (April 26, 1992): 8–9; and (4) MacLachlan, Ann, "Chernobyl Project Wrapup Marked by Protests From Two Republics," *Nucleonics Week*, Vol. 32, No. 22 (May 30, 1991).

[99] Testifying before the Nuclear Regulations Subcommittee (part of the Senate Committee on the Environment and Public Works) on July 22, 1992, Dr. Fred Mettler, Chairman of the Department of Radiology at the University of New Mexico Medical School and leader of the International Advisory Team that traveled to Ukraine and Belarus in 1990 to study the health impact of the Chornobyl accident and prepare the IAEA's report, conceded that the study "... never examined the populations most endangered by radiation – namely, the [163,000] evacuees and the 650,000 clean-up workers." He further agreed that this study could have been either premature, or too limited in scope [to come to a reasonable conclusion, and] to detect the increases in cancers, leukemias, and birth defects others had observed.

Particularly damaging to the validity of the study's assumptions was the revelation [at the hearing] that "six months after the IAEA study was completed, the federal prosecutor of the USSR disclosed the sale of 47,500 tonnes of contaminated meat, and 2 million tonnes of milk produced between 1986 and 1989 on contaminated territories. A secret memorandum from the Politburo revealed that these products exceeded by several hundredfold the maximum permissible limits for radioactive cesium. Yet the IAEA concluded that 'doses actually received due to the ingestion of contaminated foodstuffs were substantially lower than the prescribed intervention levels... and... foodstuffs may have been restricted unnecessarily.'"

[Alex Kuzma, "Senate Hearing: Information from Ukraine Shows Rise in Cancer, Birth Defects," *The Ukrainian Weekly*, Vol. LX, No. 49 (Sunday, December 6, 1992): 9.]

[100] An informative and well-balanced article is, Steven Dickman, "Chernobyl Effects Not As Bad As Feared,"*Nature*, Vol. 351, (30 May 1991): 335. A similar article, although not as well-balanced is, Felix Eijgenraam, "Chernobyl's Cloud: A Lighter Shade of Gray," *Science*, Vol. 252, (31 May 1991): 1245–1246.

[101] Jeremy Webb, "Chernobyl Findings 'Excessively Optimistic,'"*New Scientist*, Vol. 130, No. 1771, (01 June 1991): 17.

[102] Somewhat surprisingly, "While a significant increase in childhood thyroid cancer due to radiation exposure is now being recorded in Belarus – which took the brunt of the contamination arising from Chernobyl – there is, as yet, no evidence of increased childhood leukaemia rates attributable to the accident." ["Chernobyl: No Leukaemia Yet," *Nuclear Engineering International*, Vol. 38, No. 467, (June 1993): 8.]

† There have been no long-term confirmations of these observations to directly link them to radiation exposure resulting from the Chornobyl accident. Moreover, the words "above normal" as applied in this

(3) endocronic illnesses (especially of the pituitary gland) have increased 2–6 times above normal, (4) oncological (tumor) sicknesses have risen 2–3 times among the approximately 630,000 so-called "liquidators" – those who took part in clean-up operations and construction of the sarcophagus, (5) early termination of pregnancies, stillbirths, birth defects, and developmental anamolies in children have risen 1.7–3 times above normal, (6) genetic defects in people living in the contaminated regions has increased 6–15 times above normal, (7) children in contaminated areas are experiencing a genetic acceleration of the aging process.[103,104] Table II.16 below presents the frequency of oncological

---

context to the former Soviet Union is ambiguous given the poor level of health as compared with other industrial countries. For example, for the first time since World War II, the 1991 deathrate exceeded the birthrate in Ukraine by 39,000 people, and this trend continued in 1992 with approximately 100,000 more deaths than births. [Міністерство статистики України, *Народне господарство України у 1991 році: Статистичний щорічник*, Київ, (1992): 89).]

Feshbach and Friendly conclude that, "By failing to invest effectively in health care and environmental protection, the rulers of the USSR brought the average life expectancy of its citizens down to the level of average life expectancy in Paraguay. From 66.1 years in 1964–65, life expectancy for Soviet men dropped to 62.3 years in 1980-81," (compare to 70.4 in the U.S. at the same time) and, "In Ukraine, according to a September 1988 disclosure, the asphyxia, pneumonia, respiratory-disorder syndrome, and very premature birth that ranked as the principal causes of deaths among newborns were 'directly related to the inadequate skills of the medical personnel in attendance," (pg. 4,7). Two striking sections in their book, "Chernobyl: Costs of Cataclysm" and "Mind Over Matter" (pages 146–150) outline estimates of possible deaths resulting from the accident as well as an increase in alledgedly radiation induced illnesses.

[103] "Основні дані ...," 7.

At a July 22, 1992 Senate Nuclear Regulations Subcommittee hearing, the following evidence was presented pointing to direct medical effects resulting from the Chornobyl accident: reports from the Kyjiv Institute of Endocrinology and Metabolism show that the number of children afflicted with thyroid cancer has increased steadily, from an average of two per year, to seven in 1989, 20 in 1990, 30 in 1991, and over 50 in just the first six months of 1992; 52 cases of thyroid cancer in children were registered in the first three months of 1992, while 1,700 thyroid cancers were registered in Belarus as of January 1992 – in the twenty years prior to the accident only five cases had been reported; genetic malformations among newborns throughout Ukraine had risen from 13,000 in 1985, to more than 14,000 per year between 1987 and 1990. [Alex Kuzma, "Senate Hearing: Information from Ukraine Shows Rise in Cancer, Birth Defects," *The Ukrainian Weekly*, Vol. LX, No. 49 (Sunday, December 6, 1992): 9.]

"According to V. G. Barjakhtar, vice president of the Ukrainian Academy of Sciences, the Ukrainian "liquidators" are already suffering serious health impacts. The Ukrainian Ministry of Helath and various institutes of the Academy studied a representative sample of 500 of the 120,000 1986-87 liquidators living in Ukraine over the period 1989-91, he said. Eighty percent of them have immune system depression and about one-third suffer from "sexual difficulties." About 40% of them have hearing and balance problems and 24% show abnormal blood patterns." [Ann MacLachlan, "The Case of the Missing Liquidators: Why They Weren't Included in the ICP Study," *Nucleonics Week*, Vol. 32, No. 22 (May 30, 1991): 11.]

In addition to health affects in humans, a significant increase in genetic mutations have occurred in livestock and other animals living in affected areas. See, for example, Zhores Medvedev, page 116 and Figure 14 on page 179.

[104] An increase in "anemias and immune system weaknesses" started occuring five to six years after the accident as oppossed to the expected ten years as reported in "Чернобыльский Синдром," *Правда Украины*, Дмитрий Киянский вёл интервю с Ольгой Бобылевой, № 193 (15181), (14-го ноября 1992): 3.

(tumor) diseases occuring in the Zhytomyr oblast of Ukraine as well as comparisons with other regions.[105]

In Belarus, for people living in contaminated areas, an increase of 1.5–2 or more times in the number of spontaneous mutations of chromosomes has been observed; and a statistical analysis has shown that the increase corresponds to an absorbed dose of 30–40 Rads. The number of thyroid gland-related diseases has more than doubled, while cases of childhood anemias has risen from 26.7 per thousand in 1985 to 207.6 per thousand in 1989. Heart disease-related cases have risen from 169 cases in 1983 to 257 in 1988, while the number of cases of diabetes has increased 2–4 times.[106] The incidence of thyroid cancers in Belarus has increased (shown also in Table II.16) where more than half (71) of the 131 cases to mid-1992 were in the Homel oblast.[107]

---

[105] Валерій Нечипоренко, «Життя після Чорнобиля,» *Заложники Чорнобиля*, (Січень 1992): 4.

[106] Ю. В. Сивинцева и В. А. Качалова, 288. Belarusian authorities have reported that 1,700 thyroid cancers in the country as of January 1, 1992, including 55 cases in children between 6 and 12. Of the latter, 52 cases had cropped up in the last three months of 1991. In the 20 years preceding the accident, only five cases had been reported in adults and none in children. [Ann Maclachlan and Laura Pilarski, "WHO study of Chornobyl Health Effects Gets Formal Launch," *Nucleonics Week*, (April 23, 1992): 12.]

In another article, a group from the WHO states that "The Belarus experience 'suggests that the consequences to the human throid, especially in fetuses and young children, of the carcinogenic effects of radioactive fallout are much greater than previously thought.'" [Ann MacLachlan, "Rising Children's Thyroid Cancers Indicate Growing Chornobyl Link," *Nucleonics Week*, Vol. 33, No. 37 (September 10, 1992): 8.]

[107] Gamini Seneviratne, "WHO Says Belarus Cancers May Stem From More Than Chornobyl," *Nucleonics Week*, Vol. 33, No. 51 (December 17, 1992): 12.

Table II.17[108]

Frequency of Oncological Diseases in the Zhytomyr Oblast of Ukraine†
(per 100,000 children ages 1–14 years)
and Cases of Childhood Thyroid Cancers in Belarus

Year	Zhytomyr Oblast	"Contaminated" Regions	Ukraine Average	United States Average	Thyroid Cancers (cases in Belarus)
1986	10.7	11.7			2
1987	12.7	14.2			4
1988	14.7	15.9	9.6		5
1989	14.4	15.5			6
1990	12.2	10.5		3.3	29
1991	?	?			55
1992	?	?			67

† anemias in children have increased as high as twenty-five times that of pre-accident figures, and Zhytomyr has the highest infant mortality rate in Ukraine.

[108] Sources include U.S. Department of Commerce — Economics and Statistics Administration of the Bureau of the Census, *1993 Statistical Abstract of the United States*, 113 Edition, Washington D.C., Table 128, page 93; Valery Nechiporenko, "Life After [the] Chernobyl Catastrophe," *Chernobyl's Hostages*, No. 1 (January 1992):4; Ann MacLachlan, "Rising Children's Thyroid Cancers..., 8.

II.5. Chornobyl's Impact on the Nuclear Power Industry and on the Public's Perception of Nuclear Energy

Before the Chornobyl accident the nuclear power industry in the West was facing an uphill battle for public support and understanding ever since the Three Mile Island accident – this despite the fact that up to Chornobyl, throughout the world the nuclear industry had accumulated well over three thousand years of commercial nuclear power plant operation without significant loss of life to the public due to a nuclear accident.[109] In the West Germany, for example, plans for 45,000 megawatts of installed nuclear capacity were to be scaled down by 1990, and many plants ordered before 1975 have never been built because of falling electricity demands and the success of opponents in licensing hearings. In Sweden, where anti-nuclear sentiments are particularly strong, a referendum held in 1980 voted in favor of stopping the nuclear program and phasing out nuclear power by 2010.[110]

In the wake of the Chornobyl accident, the mood initially moved even more decisively against nuclear power – seriously impacting nuclear power programs in Western European countries. For example, the former Chancellor of Austria, Dr. Fred Sinowatz, announced in 1986 that Austria's only nuclear plant at Zwentendorf (completed in 1978 but never used because a referendum decided against commissioning it) was to be dismantled. According to Sinowatz, the dismantling Zwentendorf was a necessary consequence of Chornobyl, further stating that "the problem of the use of nuclear energy in Austria can be considered as decided and closed."[111,112] Another quick cancellation was announced in the Philippines by former President Corizone Aqino. She stated that her government would mothball an almost completed reactor (620 MWe PWR) being built

---

[109] The *Report of the President's Commission on the Accident at Three Mile Island* estimates that less than one public cancer fatality will result from the radiation doses absorbed by the approximately two million persons living within a 50 mile (80.5 km) radius of TMI Unit-2.

[110] Ivring Spiewak and Alvin M. Weinberg, "Inherently Safe Reactors," *Annual Review of Energy – 1985*, Jack M. Hollander, ed., Annual Review, Inc., Vol. 10 (1985): 431. Actually, it appears that the Swedes came to their decision a bit prematurely, and now it appears they may rescind the decision.

[111] Nigel Hawkes, et al, *Chernobyl: The End of the Nuclear Dream*, London: Vintage Books, (1986): 221.

[112] "Chernobyl Casts A Shadow," *Nuclear Engineering International*, (June 1986): 2–3.

on the Bataan peninsula at a cost of $2.3 billion.[113] In the former Yugoslavia, Chornobyl also had immediate effects (although not officially confirmed as the reason) when government authorities dropped plans to build the country's second nuclear station at Prevlaka. In the Netherlands, where two nuclear plants operate, the government was obliged to abandon plans for a major expansion of nuclear power in the 1990s. An opinion poll held two weeks after the accident showed that seventy percent of those questioned in the Netherlands were opposed to nuclear power. In West Germany, a poll in *Der Spiegel* produced almost identical results, with sixty-nine percent opposed to any new plants, and fifty-four percent believing that the existing plants, which provide one-third of West Germany's electricity, should be phased out.[114] Based on "horror" stories and the general unreliability of Soviet-based designs, the parliament of a new united German Federal Republic voted in 1991 to "turn off" all reactors in the former German Democratic Republic until an investigation into the safety of these reactors could be conducted.[115]

However, though the accident has fueled public and political anti-nuclear sentiment in the United States, compared to the response in European countries, the U.S. reaction to Chornobyl has been more muted – principally due to the fact that radioactive contamination in the U.S. was negligible. Moreover, rather than a setback to the U.S. industry, the accident represented an opportunity to improve public understanding of the safety of U.S. reactors. After the Chornobyl accident, views were expressed as to the irrelevancy of Chornobyl to the outlook for a similar worst case accident happening to reactors operating in the Western World. It was commonly argued that the design of the RBMK was

---

[113] Lee Stokes, UPI Wire Service News Release, (30 June 1986).

[114] Nigel Nawkes, et al, *Chernobyl: The End of the Nuclear Dream*, London: Vintage Books, (1986): 220–222. This contrast somewhat with the results of another public opinion poll in which during the summer of 1991, "... 61% [were] in favor of continued operation of the existing nuclear power plants, and more than half of them (31%) even advocated additional stations be built. The proportion wishing to abandon nuclear power dropped to 29% after 34% in 1989 and 38% in 1986 immediately after Chernobyl." ("World Nuclear Status Report 1991 – Germany," *Nuclear Europe WorldScan – ENS World Yearbook 1992*, No. 7/8, (August 1992): 50.

[115] Colette Lewiner, "Editorial," *Nuclear Europe WorldScan – ENS World Yearbook 1992*, No. 7/8, (August 1992): 6.

simply too different from the more prevalent types of reactor designs in the West to draw meaningful inferences from the Chornobyl accident regarding the safety of western reactors.[116] Additionally, based on the results of studies and reviews by international inspection teams from the IAEA[117] and independent assessments by experts from the nuclear industry in the West as access to Soviet nuclear power installations became more commonplace,[†] it has become apparent that earlier presumptions that safety regulation in the former USSR might not have been as stringent as in other nations, and that a deficient safety culture existed (and continues to exist) in the Soviet nuclear power industry, were justified.[118]

As time has passed, reaction to the accident has naturally subsided (with a less-than-expected impact on orders and future plans),[119] and attention has subsequently focused more upon the safety and reliability of Soviet and Soviet-built reactors in the CIS and in Eastern Europe. In particular, Soviet reactors have come under increasing criticism concerning their safety standards and design deficiencies prompting numerous articles, stud-

---

[116] See, for example, *Report of the U.S. Department of Energy's Team Analyses of the Chernobyl-4 Atomic Energy Station Accident Sequence*, (DOE/NE-0076; DE87 003614) Washington, D.C.: U.S. Department of Energy, (November 1986).

[117] See INSAG-7, "General remarks on the lack of safety culture," 21–22; and a number of short articles appearing in *Nucleonics Week* since 1989.

[†] Since coming to power in early 1985, former General Secretary Michail Gorbachev attempted to make his policy of *glasnost* (openness) a hallmark of his regime. Yet, when the accident occurred, the Soviets initially repressed news about it. When this reticence proved counter-productive both at home and abroad, the Soviets launced a relatively informative – and quite effective – public relations campaign. However, this campaign, rather than focusing on the obvious design deficiencies of the RBMK-1000, actually led to a cover up of the causes of the accident (see Chapter I), and focused attention on the expected horrors of fallout from a nuclear war (thus strenghtening the Soviet position on nuclear disarmament) and on the human errors which ostensibly caused the accident. The success of this *semi-glasnost* in containing the negative repercussions created by Chornobyl apparently strengthened the position of those Soviet leaders who believed that qualified openness mods foreign and domestic public opinion more effectively than secrecy. Moreover, the success of this campaign is evidenced by the fact that not until seven years after the accident was the Soviet portrayal of the accident as being caused by human error overturned by INSAG-7, and that the extent of the contamination and its effect on humans is only now being uncovered.

[118] For a stinging indicment of the political and social atmosphere in which Soviet science was conducted, see Sergei P. Kapitza, "Lessons of Chernobyl: The Cultural Causes of the Meltdown," *Foreign Affairs*, Vol 72, No. 3, (Summer 1993).

[119] See Richard Masters, "Chernobyl Has Less-Than-Expected Impact on Orders and Future Plans," *Nuclear Engineering International*, (June 1987).

ies, visits by experts, and reviews of safety practices.[120] It is as yet unclear, given the economic and political instabilities currently being faced especially by the former Soviet republics, in what form safety improvements will be implemented and how much aid will be allotted to help these struggling nuclear programs.

[120] See, for example, the following articles: Maurice Strong, "40 Chernobyls Waiting to Happen," *The New York Times*, Vol. CXLI, No. 48913 (Sunday, March 22, 1992): E15; John Shanahan, "Cuba's Potential Chernobyls," *The Wall Street Journal*, (August 5, 1992): A14; "Chernobyls-in-Waiting," *The Economist*, Vol. 324, No. 7772 (August 15, 1992): 18; "Eastern Europe's Nuclear Reactors: Too Little...," *The Economist*, Bol. 324, No. 7772 (August 15, 1992): 56.

CHAPTER III

THE RBMK AND THE CHORNOBYL NUCLEAR POWER STATION: HISTORICO-POLITICAL & TECHNICAL DEVELOPMENT AND DESCRIPTION

"Chernobyl exploded because of human errors, such as operators shutting down automatic safety systems to conduct unauthorized power tests. Such errors won't be repeated, but there is nothing fundamentally wrong with the design of the Chernobyl plant or Soviet engineering."

– Boris Y. Shcherbina, (Former) Deputy Chairman of the USSR Council of Ministers[1]

"Regarding the RBMK-1000: It's worth reiterating to the public that a similar reactor type will not be constructed in our country, that its selection and significant implementation in the national economy was a mistake..."

– Kurchatov Institute's newspaper, *Soviet Physicist* Editorial comment, 20 January 1990

At the August 1986 meeting of experts in Vienna sponsored by the IAEA, Soviets experts were quite keen about faulting "an extremely unlikely combination of procedural violations and operating conditions tolerated by personnel of the power unit [as] the original cause of the accident,"[2] as if to say, "the operators managed to destroy the reactor, and the reactor in turn allowed them to."[3] However, with INSAG-7's reappraisal of the causes of the accident, it is now clear that the inadequate design of the reactor and incomplete training of the operators played the major role in causing the accident.[4] Two

[1] Youseff M. Ibrahim, "Soviet View On Lessons From Chernobyl Points Up Obstacles the West Now Faces," *The Wall Street Journal*, (October 2, 1986): 30.

[2] U.S.S.R, State Committee on the Utilization of Atomic Energy (comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Part I: General Material*, report presented at the International Atomic Energy Agency Expert's Meeting, August 25–29, 1986, Vienna: 34.

[3] Youseff M. Ibrahim, 30.

[4] An unpublished report by the Kurchatov Institute released about two months after the Vienna Meeting states that, "... the original cause of the accident was an very unlikely combination of procedural violations and operating conditions permitted by the personnel of the power unit, *along with the manifestation of deficiencies in the design of the reactor and the control rods.*" (Italicized words are those deleted from the official version.) The report further states that, "... *it is sufficiently clear that the only version [of the causes of the accident] that does contradict the data on hand is that version having to do with the con-*

questions naturally arise: why were such reactors were developed for major exploitation in the Soviet Union, and what charmed Soviet leaders into proudly calling the RBMK the "Soviet national reactor?" To comprehend the Soviet leader's rationalism for taking such a course, one must first understand the character of their energy development program from its inception.

III.1. Soviet Nuclear Energy and the Development of the RBMK

III.1.1. Political and Economic Backdrop

For most of its history, the Soviet Union has paid a great deal of attention (many would argue an inordinate amount) to the expansion of power production in the country. Great significance was attributed to the states's electrification to support the material and technical base of communism as envisioned by Lenin. His view's on electrification are reflected in his bold statement, "Communism is Soviet power plus the electrification of the whole country."[5] This indicates what importance he placed not only upon transforming the Soviet Union into a modern industrialized nation, but also, in turn, manipulating this economic-industrial base to effect social transformations he perceived were necessary to build a communist paradise on earth. Consequently, it is no surprise that within a week *after* the Chornobyl accident, an illustration appeared on the first page of *Pravda* (Figure III.1) placing electrification in its "rightfully distinguished" position.[6]

---

trol rod followers." «Исследование причин аварии на ЧАЭС,» Отчёт ИАЭ им. И. В. Курчатова, инв. Но. 34/716186 дсп от 30 X 86, as cited in Государственный Комитет СССР по надзору за безопасным ведением работ в промышленности и атомной энергетике, *О Причинах и обстоятельствах аварии на 4-ом блоке чернобыльской АЭС Апреля 1986 г.*, Доклад Комессии Госпроматомнадзора СССР, Москва (1991): 6–7.

[5] From a speech at the Eighth All-Russia Congress of Soviets on the "Work of the Council of Peoples' Commissars," December 22, 1920. This naturally evokes a tongue-in-cheek question: Does Lenin imply that Communism minus electrification of the whole country is (was!) Soviet power?

[6] Paul R. Josephson deserves great credit for picking up on this in "The Historical Roots of the Chernobyl' Disaster," *Soviet Union / Union Sovietique*, Vol. 13, No. 3 (1986): 291 with the graphic "Утро трудового дня," taken from the front page of *Pravda*, 123 (24745), (May 3, 1986):1. In his article Josephson does an excellent job of placing the Chernobyl accident in the historical context of the development of the Soviet nuclear (military and commercial) industry. He focuses not upon the direct technical causes of the accident but on the more important (in my opinion) Soviet ideological and philosophical links between the accident and Soviet attitudes toward science, technology, and safety, and especially upon what Gloria Duffy has termed Soviet nuclear "positivism."

Figure III.1

Pravda Graphic Glorifying Electrification, Labor, and the Communist Party One Week After the Chornobyl Accident.

пролетарии всех стран, соединяйтесь!

тическая партия Советского Союза

ПРАВДА

ан Центрального Комитета КПСС

1745) ● Суббота, 3 мая 1986 года ● Цена 4 коп.

РАБОЧИЙ РИТМ МАЯ

Утро трудового дня.

Гравюра В. Садина (г. Слуцк).

Составы в пути

Ударную вахту несут железнодорожники Брянска. С рейса, во время которого машинист В. Сурин и помощник В. Фетисов провели электровоз в шесть тысяч тонн из ста

Но трио труда метет уже километров от них сотних километров от полюса холода труда полюса результатов процент мигушет холода по труда метет уже километров от них сотних километров от полюса холода зультатов процент мигушет труда метет уже труда полюса результатов процент мигушет холода по труда метет уже километров от

Вахта у мартенов

Читайте к
Прин
истории –
лежит нар
Детям
него края
Послу
жизнь

Р
бу

Москва:

Больше четве
суте Москву, а
тельно дольше -
чинкой улицы
Помню, в восте
все. и широкий
ной площади,
Кремля, и моск
Воробьевых гор
улицы и перту
дворы, разной
тельно дольше -
чинкой улицы
Помню, в восте
все. и широкий
ной площади,
Кремля, и моск
Воробьевых гор
улицы и перту
дворы, разной
тельно дольше -
чинкой улицы
Помню, в восте
все. и широкий
ной площади,
Кремля, и моск
Воробьевых гор
улицы и перту
дворы, разной
тельно дольше -
чинкой улицы
Помню, в восте
все. и широкий
ной площади,
Кремля, и моск
Воробьевых гор
улицы и перту
дворы, разной
тельно дольше -
чинкой улицы
Помню, в восте
все. и широкий
ной площади,
Кремля, и моск
Воробьевых гор
улицы и перту
дворы, разной
тельно дольше -
чинкой улицы
Помню, в восте
все. и широкий

The Soviets considered economic reasons to be the determining factors in their drive for an increased share for nuclear power in the country's energy balance. Although the Soviet Union was a country extremely rich in natural resources, the pattern of energy supply and use presented numerous paradoxes. First, the Soviet's utilization of natural resources per unit of output was higher than the average for industrial countries, whereas its consumption of energy on the same comparison was considerably lower. Second, the Soviet Union before the Second World War exhibited a rate of growth of energy consumption exceeding that of the total national product, but subsequently achieved an energy rate lower than, or at best equal to, the national product. Third, the Soviet Union was the world's largest oil exporter – thanks to the great increases in oil prices in the wake of the 1973 Arab oil embargo, oil exports (worth six billion dollars in 1978) constituted half of all Soviet hard-currency earnings – although domestic oil consumption per capita was much lower than in the industrial countries to which it sold oil.

However, probably the most important practical factors influencing the push for nuclear power development were site considerations, extraction difficulties, transport costs, and even environmental problems associated with fossil fuel power production. "Despite the abundance and low cost of resources in the East [of the country], transport costs g[a]ve a strong economic advantage to nuclear power west of the Urals. The uneven distribution of water resources (important both as a power resource and for cooling thermal stations) shape[d] Soviet energy policy in distinctive ways, such as the long-standing fascination with big projects of the interbasin [Siberian] diversion of water and the great interest derived there from peaceful nuclear explosives. The regional problem ha[d] a heavy influence on the direction of the Soviet innovation effort – it provide[d] a special motivation for innovation in long-distance transmission of electric power and for novel transport modes for other kinds of fuel."[7] The Soviets reasoned that because nuclear fuel

[7] Robert W. Campbell, *Soviet Energy Technologies*, Indiana University Press, (1980): 246. It was recognized by the Soviets that fossil fuel resources had become increasingly difficult and expensive to exploit. The shift in production geographically had been to the north and east – into not easily accessible Siberia. Moreover, emphasis and investment in basic research for "softer" alternate energy forms and

is compact, easily transportable, and needs to be replaced only infrequently, nuclear plants were highly suited to an economic infrastructure like that in the former Soviet Union where fuel sources were remote from fuel users. Uncertainties concerning future fossil fuel production spurred heavy reliance on nuclear power to provide the requisite increase in planned and real generating capacity. Another factor that swayed the argument in favor of nuclear power is that in private, Soviets involved in gas and oil production criticized somewhat successfully exploitation techniques which boosted short-term productivity but decreased total resources recoverable from operating fossil fuel fields.

A final argument for the strong support of nuclear power development (although one not readily admitted by the Soviets) had to do with their attitudes toward large and "exotic" technologies.[8] The Soviets were the inheritors of the technocratic progressivism so characteristic of the economic policies of capitalist societies in the pre-limits of growth, pre-environmental consciousness years. This reasoning stems in part from Soviet ideology that has characteristically reflected a boundless faith in technology and the beneficial effects of technological developments on the welfare of mankind. In energy development, the Soviet goal was higher production with little consideration of the opportunity costs of a particular avenue of development. Soviet nuclear energy policy in particular is driven by a desire to demonstrate conspicuous technological achievements in a large-scale program that the Soviet Union itself regards as necessary to its role as a world superpower. A successful nuclear power program is seen as a means of enhancing the prestige of the country and providing visible evidence of the superiority of socialism. Even three years after the Chornobyl accident the Soviets found it difficult to shake their underdog's naive faith in the automatic merits of newer, bigger, and more complex tech-

---

strategies (such as solar and wind power and an emphasis on home energy conservation) fell far below that of most western countries.

[8] To be fair, one must also admit that the United States is at times also guilty of "technical chauvinism" regarding complex and exotic technologies. Kuchment and Bernstein ("Chernobyl and Challenger: Trading Disasters," draft of paper published in April 1987 IEEE *Spectrum*) have argued that despite their vastly different societies and a large difference in relevant technolgical levels, the Chornobyl and Challenger accidents had some surprisingly symmetrical aspects.

nologies.[9] They had a cavalier attitude toward safety, siting nuclear power plants relatively close to population centers for convenience in transmission and eliminating from their plant designs the redundant core cooling systems and the costly protective containment structures built around reactor cores in the West. Josephson has concluded that, "Soviet ideology and philosophy not only support[ed] but also handicap[ped] the achievements of an impressive technological base. Since the founding of the Soviet state, party leaders and ideologues... believed that technology is the key to economic development and Soviet success. They... argued that technological innovation is always desirable, and that technology is infallible, a symbol of national achievement, and the highest level of culture, with mass production its outstanding form. Large-scale, expensive technologies which require highly centralized and extensive networks of support [were] seen as safe and desirable, as solutions for social and economic problems."[10]

[9] See for example the section "The Soviet Pro-Nuclear Power Camp" in Chapter 7 "The Nuclear Power Debate" in David Marples, *The Social Impact of the Chernobyl Disaster*, New York: St. Martin Press, (1989): 257–262.

[10] Paul Josephson, 275.

III.1.2. A Brief History of the Soviet[11] Nuclear Energy Program and Development of the RBMK

> *The system of legal, economic, and sociopolitical correlations that existed prior to the accident and still exists in the field of nuclear power has no legal basis, and did not and does not meet the requirements of ensuring the safe utilization of nuclear power in the USSR.*
>
> – A major conclusion of the Shteinberg Commission of the Soviet State Committee for Nuclear Oversight (GosAtomNadzor) that reassessed the causes of the Chornobyl accident.[12]

The development of nuclear power as a large-scale provider of electrical energy enjoyed significant support from the government as part of the drive to fulfill Lenin's dream of electrifying the entire country. It's advent was heralded on June 27, 1954 by the startup of the 5 MWe (30 MWt) Obninsk experimental prototype – a graphite-moderated light water-cooled reactor and the brain-child of the father of Soviet nuclear power, Vladimir I. Kurchatov. The Obninsk reactor was the precursor to the "high-power channel-type reactors with graphite moderation and boiling-water cooling" (RBMK) which evolved from a series of test reactors built during the late 1950s and early 1960s. The Obninsk reactor design, refined for the most part only in scale, was utilized in the Siberian and Belojarsk reactors;* and the experience gained with these reactors was then readily transferred to the

---

[11] Although Ukraine declared its independence on August 24, 1991 and formally became independent as a consequence of the dissolution of the Soviet Union on December 4, 1991, except for decisions implemented by the Ukrainian Supreme *Rada* (Parliament) regarding its own nuclear power program since that time, this discussion focuses on the (former) Soviet Union's nuclear energy program.

Several sources on the history of the Soviet nuclear energy program are the following:

(1) Robert W. Campbell, *Soviet Energy Technologies*, Indiana University Press, 1980.

(2) Gloria Duffy, *Soviet Nuclear Energy: Domestic and International Policies*, Rand Corporation, December 1979.

(3) Leslie Dienes and Theodore Shabad, *The Soviet Energy System: Resource Use and Policies*, Washington D.C.: V.H. Winston & Sons, 1979.

(4) Paul R. Josephson, "The Historical Roots of the Chernobyl' Disaster," *Soviet Union / Union Sovietique*, Vol. 13, No. 3 (1986): 291.

(5) Paul R. Josephson, "Atomic Culture and Atomic Energy in the USSR," draft paper at the Massachusetts Institute of Technology, Summer 1987.

(6) Marples, David R, *Chernobyl and Nuclear Power in the USSR*, New York: St. Martin Press, 1986.

(7) Дементьев, Б. А., *Ядерные энергетические реакторы: Учебник для вузов*, Москва: Энергоатомиздат (1990).

[12] INSAG-7, 87.

* The Siberian nuclear power station consisted of six 100 MWe predecessors to the present day RBMKs. The two units at the Belojarsk station (100 and 200 MWe) demonstrated to Soviet planners the practicality of steam superheating in a water-cooled graphite-moderated reactor. The steam outlet pressure

design of Bilibino natural circulation-cooling, graphite-moderated reactor. The Soviet BK-50 reactor (startup in 1965) was used for water chemistry research and the development boiling water-based designs such as the RBMK.[13]

The father of the next generation of graphite-moderdated, boiling water-cooled reactors – the RBMK-1000 – was Alexander P. Alexandrov.† The first commercial large-scale, first generation RBMK: the 1000 MWe St. Petersburg Unit-1 at the Sosnovy Bor station, achieved full power operation in January 1974. (After the Leningrad and Kursk stations in Russia, the Chornobyl Station in Ukraine was the third nuclear power plant with RBMK reactors.) Because of the degree of standardization invloved in RBMK-1000 units, few changes were necessary for the introduction in May 1977 of the next generation RBMK-1500 MWe (4800 MWt) at the Ignalina station in Lithuania. Modifications included changes in fuel assembly design and the coolant circulation circuit.[14] An interesting design variant is a 2400 MWe RBMK with a parallelepiped core (7m × 7m × 24m!) and steam superheating (Figure III.2[15]) – although no units of this type went into operation; and there were even reports of development teams working on a 4800 MWe RBMK design.[16] Table III.1 below presents basic data and implementation schedules for

---

was approximately 9 MPa at a temperature of 500–510°C.

[13] Сивинцева, Ю. В., В. А. Качалова общие редакторы, *Чернобыль: Пять трудных лет: Сборник материалов о работах по ликвидации последствий аварии на Чернобыльской АЭС в 1986–1990 гг*, Москва: ИЗДАТ (1992): 19.

† The Kurchatov Institute of Atomic Energy in Moscow was appointed as the principal scientific research and management center for the RBMK-1000, the chief architect-engineering firm was the Scientific Research and Construction Institute of Power Engineering (NIKIET) under the USSR Ministry of Medium Machine Building (*MinSredMash*), while the USSR Ministry of Power was eventually to be responsible for its operation. It is not surprising that the construction of RBMK stations were under the direct control of *MinSredMash* because it is this Ministry that also oversaw the design and construction of Soviet nuclear weapons. (In Ukraine before the collapse of the Soviet Union, for example, the other four VVER stations were under the direction of the Ukrainian Ministry of Energy and Electrification which was in turn subordinate to its all-union counterpart.) The core design of the graphite-moderated, boiling water-cooled reactors, although having a positive void coefficient, was suited for the production of plutonium both because of the low fuel-to-moderator ratio and its capacity for on-line refueling. The latter is essential for withdrawing low-burnup assemblies that contain relatively greater amounts of the fissile Pu-239.

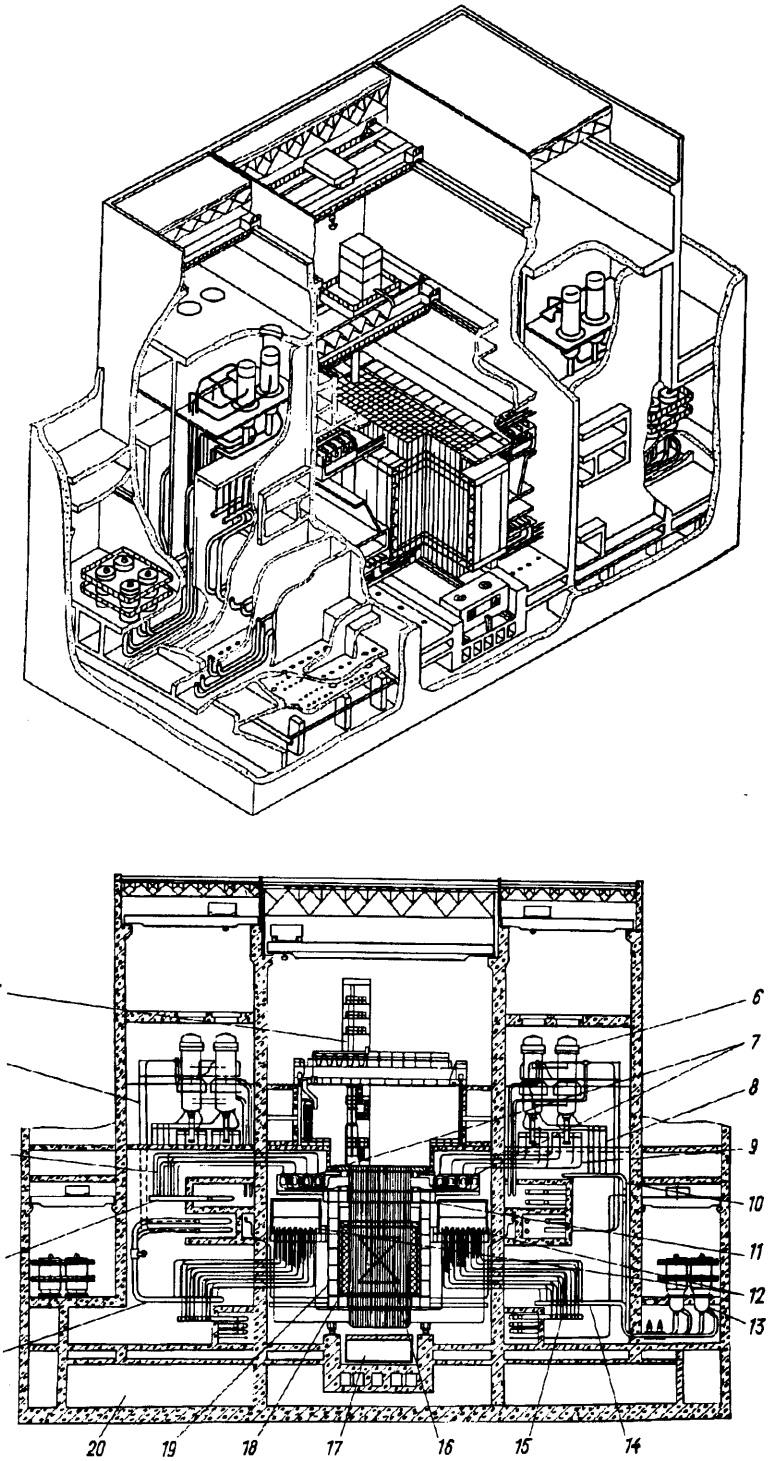
[14] "Background Notes: Chernobyl Nuclear Power Plant," *USSR Technology Update*, Vol. I, No. 7 (May 7, 1986): 3. In order to get 50% more power the new design uses "ribbons" on the fuel rods to improve heat transfer characteristics and bigger pumps to overcome a larger two-phase flow pressure drop. The reactor is thus run at a higher power level, with a higher core design average void fraction.

[15] Н. А. Доллежаль, И. Я. Емельянов, *Канальный ядерный энергетический реактор*, Москва: Атомиздат (1980): 199–201.

[16] Г. Львов, "Чернобыль: Анатомия Взрыва," *Наука и Жизнь*, Издательство «Правда»: Москва, Россия, (12/1989): 10.

Figure III.2

The 2400 MWe RBMK



1. Saturated Steam Collector 2. Superheated Steam Collector 3. Superheated Steam Piping 4. Saturated Steam Piping 5. Refueling Machine 6. Steam Separator 7. Dispensing Header Assemblies 8. Feedwater Piping 9. Two-Phase Coolant Piping 10. Dearator Collectors 11. Upper Biological Shield 12. Group Dispensing Headers 13. Main Circulating Pump 14. Pressure Header 15. Feedwater Header 16. Graphite Pile 17. Sub-Reactor Repair Machinery 18. Lower Biological Shield 19. Lateral Biological Shields 20. Pressure Suppression Pool.

RBMK prototypes while Table III.2 shows the design evolution of RBMKs while. From December 1973 through February 1986 (two months prior to the Chornobyl accident), one RBMK-1500 and fourteen RBMK-1000 reactors at five power plants were constructed and connected to the USSR's commercial power grid. Table III.3 presents construction schedules for these and similar large-scale RBMKs,[17] while Table III.4 compares the basic design characteristics of the RBMK-1000 and RBMK-1500.

Table III.1[18]
USSR RBMK-Prototype Basic Data

1	2	3	4	5	6	7	8
Unit	Power (MWt/MWe)	Start of Operation	Fuel Channels (equilibrium)	Average Enrichment (%)	Burnup (MW•d/kg)	Specific Power (MWt/t U)	Fuel Cladding Material
Obninsk 1	30 / 5	1954	998	5.0	?	54.6	Stainless Steel
Siberian 1	? / >100	1958	?	?	?	4.3	Aluminum
Siberian 2	? / >100	1958	?	?	?	4.3	Aluminum
Siberian 3	? / >100	1958	?	?	?	4.3	Aluminum
Siberian 4	? / >100	1958	?	?	?	4.3	Aluminum
Siberian 5	? / >100	1958	?	?	?	4.3	Aluminum
Siberian 6	? / >100	1958	?	?	?	4.3	Aluminum
Belojarsk 1	286 / 100	9/1963	998	1.8	4.0	11.3	Stainless Steel
Belojarsk 2	530 / 200	10/1967	998	3.0	14.6	16.7	Stainless Steel
Bilibino 1	62	1974	273	3 / 3.3	?	?	Stainless Steel
Bilibino 2	62	1975	273	3 / 3.3	?	?	Stainless Steel
Bilibino 3	62	1975	273	3 / 3.3	?	?	Stainless Steel
Bilibino 4	62	1976	273	3 / 3.3	?	?	Stainless Steel

[17] See Table II-V, INSAG-7, 130, for performance data (electricity output and load factors) for RBMK plants during 1986-1990.

[18] U.S. Nuclear Regulatory Commission, comp, *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250), Washington D.C.: U.S. Government Printing Office, (1987): 2-2; and Доллежаль, 9.

Table III.2[19]
Design Evolution of Channel-Type Uranium-Graphite Reactors

Parameter	Belojarsk 1	Belojarsk 2	Bilibino* 1–4	RBMK 1000	RBMK 1500	RBMKP 2400
Reactor Power (MWt / MWe) Gross efficiency (%)	286 / 100 35	530 / 200 37.7	62 / 12 19.4	3200 / 1000 31.8	4800 / 1500 31.3	6500 / 2400 36.9
Steam Parameters before turbine: Pressure (MPa) Temperature (°C)	9.0 500	9.0 500	6.4 104	6.5 280	6.5 280	6.5 450
Turbine Power (# x MWe)	1 x 100	1 x 100	?	1 x 500	1 x 750	1 x 1200
Core Dimensions Diameter (m) Length x Width (m) Height (m)	7.2 – 6	7.2 – 6	4.2 – 3	11.8 – 7	11.8 – 7	– 25 x 7 7
Full Fuel Load (t UO_2)	?	48	?	190.3	189	?
Fuel Channels (inc. superheated)	998 (266)	998 (266)	273	1693 / 1661**	1661	2880 (960)
Control Channels	?	100	?	179 / 211**	235	?
Average Enrichment (%)	1.8	3.0	3.0 / 3.3	1.8 / 2.0 / 2.4†	2.0 / 2.4	2.4 (3.0)
Average Burnup (GWd/t U)	4.0	14.6	18.0 (max)	18.5 / 20**	18.1 / 21.0	27 (25)
Fuel Rod Cladding Material	Stainless Steel	Stainless Steel	Stainless Steel	Zircaloy	Zircaloy	Zircaloy (Stainless Steel)

* There are four identical natural circulation-cooling 62 MWt reactors in a row within the same building at the Bilibino Station. The fuel is metallic in the form of a tube (for internal and external cooling) in which uranium metal is contained within a magnesium matrix and covered in stainless steel cladding. The total electrical power produced by these four is 48 MWt, while at the same time producing 78 MWt of process (steam) heat. A second series of the Bilibino reactor at 140 MWt were being planned.

** 1st generation / 2nd generation.

† 1st generation / 2nd generation / post-Chornobyl technical fix.

[19] Доллежаль, 9.

Table III.3[20]
USSR RBMK-Series Construction and Startup Schedules

1		2	3	4	5	6	7		
							Startup Period [refer to column #'s]		
Unit		Power (MWe)	Construction Start	Physical Startup	Connected to Grid	Achieved Full Power	3 —> 5 (months)	4 —> 5 (days)	5 —> 6 (days/months)
Leningrad	1	1000	03/70	12/09/73	21/12/73	01/11/74	46	100	316 / 10.4
	2	1000	06/70	06/05/75	11/07/75	11/02/76	61	66	215 / 7.1
	3	1000	12/73	17/09/79	07/12/79	29/06/80	73	81	204 / 6.7
	4	1000	02/75	29/12/80	09/02/81	29/08/81	72	42	201 / 6.6
						average:	**63**	**72**	**234 / 7.7**
Kursk	1	1000	06/72	25/10/76	19/12/76	12/10/77	55	55	297 / 9.8
	2	1000	01/73	16/12/78	28/01/79	17/08/79	73	43	201 / 6.6
	3	1000	04/78	09/08/83	17/10/83	30/03/84	67	69	164 / 5.4
	4	1000	05/81	30/10/85	02/12/85	05/02/86	53	33	65 / 2.1
	5	1000	12/85	??	??	??	–	–	–
	6	1000	08/86	–	–	–	–	–	–
						average:	**62**	**50**	**182 / 6.0**
Chornobyl	1	1000	06/72	02/08/77	26/09/77	24/05/79	64	55	240 / 7.9
	2	1000	02/73	17/11/78	21/12/78	31/05/79	71	34	161 / 5.3
	3	1000	05/77	02/06/81	10/11/81	06/06/82	55	161	208 / 6.8
	4	1000	04/79*	05/11/83*	21/12/83	25/05/84*	57	46	155 / 5.1
	5	1000	1981	(04/87)	–	–	–	–	–
	6	1000	1983	(04/87)	–	–	–	–	–
						average:	**62**	**74**	**191 / 6.3**
Smolensk	1	1000	10/75	10/09/82	09/12/82	29/09/83	87	90	294 / 9.7
	2	1000	06/76	09/04/85	31/05/85	25/01/86*	108	52	239 / 7.9
	3	1000	05/84	??	??/06/90	??	??	??	??
	4	1000	10/84	–	–	–	–	–	–
						average:	**98**	**71**	**267 / 8.8**
Ignalina	1	1500	05/77	04/10/83	31/12/83	15/05/85	80	88	150 / 4.9
	2	1500	12/78	26/12/86	20/08/87	29/01/88*	105	237	162 / 5.3
	3	1500	06/85	(08/88)	–	–	–	–	–
	4	1500	??	(08/88)	–	–	–	–	–
						average:	**93**	**163**	**156 / 5.1**
					Overall	**Average:**	**70**	**78**	**205 / 6.7**

* No official data is available. Dates in parentheses indicated planned implementation.

[20] Ю. С. Панитков et al, *Отчёт о научно-исследовательской работе: Восстановление динамики разрушения 4-го блока ЧАЭС на основе физического и математического моделирования: Разработка физической модели чернобыльской катастрофы.* Минск, Беларусь: Академия Наук Беларуси, (1991): 7; and other sources.

Table III.4
Comparison of RBMK-1000 and RBMK-1500 Basic Design Characteristics

Parameter	RBMK-1000	RBMK-1500
Thermal Power	3140 MWt	4400 MWt
Gross Electrical Power	1000 MWe	1500 MWe
Gross (Thermal) Efficiency	31.8 %	34.1 %
Net Electrical Power	925 MWe	1380 MWe
Net Efficiency	29.5 %	31.4 %
Coolant Flow Rate (tonnes/hr)	37,500–42,000	29,000–32,000
Average Linear Power	31.5 kWt/m	48.5 kWt/m
Average Power Density	4.2 MWt/m^3	6.3 MWt/m^3
Maximum Fuel Exposure	22.3 MWt-d/kg U	21.6 MWt-d/kg
Power of Max. Channel	3.25 MWt	4.91 MWt
Fuel Temperature Coefficient (at full power & average burnup)	-1.20 e-05	-1.02 e-05
Void Coefficient ($\Delta k/\%a = \Delta\rho/\Delta\alpha$) (at full power & average burnup)	2.0 e-04	1.0 e-04
Approximate Core Average Void (assuming no sub-cooled boiling)	25 %	40 %
Core Outlet Quality	14.5 %	29.0 %
Main Coolant Pump Δp	1.61 MPa	2.00 MPa
Steam Drums Steam Production Rate	1450 t/hr	2200 t/hr
Steam Drums Exit Pressure	6.86 MPa	7.00 MPa
Turbogenerator Power	2 x 500 MWe	2 x 750 MWe

It was at the same time that when the St. Petersburg (Sosnovyj Bor) Station was put into operation, the Soviet Union's nuclear power program was gaining significant momentum in other areas of development and inplementation.† In the 1960's the pace of construction was fairly slow but accelerated dramatically during the 1970's (in the early 1970's the Soviets embarked upon an ambitious power program aimed at commissioning approximately 15,000 MWe of installed capacity by the end of 1980), especially toward the end of the decade.[21,22] At the conclusion of the 9th Five-Year Plan (1971–1975) the

† Soviet planners expected to rely heavily on nuclear electricity to provide the growing percentage of their electrical needs for the future. In the ensuing quarter century, the Soviets assigned a large priority to all forms of nuclear research and the development of all major forms of nuclear power generation as a necessary part of maintaining its role as a superpower. For example, development of the water-moderated water-cooled reactors (VVER) was proceeding at nearly the same time as the RBMK with the first two VVERs, rated at 210 and 365 MWe, installed at the Novovoronezh power plant in 1964 and 1969.

[21] Achilles G. Adamantiades, Chaim Braun, John E. Kenton, and Frank J. Rahn, *A Guide to Nuclear*

Soviet Union had installed 6200 MWe of nuclear generating capacity, which represented about 3% of the total Soviet electrical generating capacity available at that time. During this period, two 440 MWe VVERs entered operation at the Novovoronezh plant – initiating series production of these reactors. The first 1000 MWe RBMK reactors were installed in 1973 and 1975 at the St. Petersburg plant and at Kursk; and "the rate of growth of nuclear power was greater in the first half of the 1970's than either thermal (fossil fuel-based) or hydroelectric power."[23] During the 10th Five-Year Plan (1976–1980), VVER-440, VVER-1000, RBMK-1000, and RBMK-1500 nuclear reactors were ordered – in parallel with series production of 1,000 and 1,500 megawatt turbines.[24] Production of the VVER pressure vessels and major components occurred primarily at the Izhora Plant Association near St. Petersburg. Most VVER-440 reactors were, until the collapse of communism in Eastern Europe, built in Czechoslovakia. VVER-1000 components were to be built (according to plan) at the Atommash plant in Volgodonsk at the ambitious rate of eight per year by 1990.† Also during the late 1970's, the Soviets concentrated efforts on more efficient use of uranium and thorium. Research was conducted on fast breeder

---

Power Technology: A Resource for Decision Making, New York: John Wiley & Sons, (1984): 19–20.

[22] U.S. Central Intelligence Agency, *USSR Energy Atlas*, U.S. Government Printing Office: Washington, D.C., (1985): 52.

[23] Leslie Dienes and Theodore Shabad, *The Soviet Energy System: Resource Use and Policies*, V.H. Winston & Sons: Washington D.C., (1979): 151.

[24] "A Brief History of Soviet Nuclear Power," *USSR Technology Update*, Vol. I, No. 12 (July 16, 1986): 3.

† The enormous 'all-nuclear' association of factories known as Atommash, situated near the city of Volgodonsk, was to be an independent and self-sustaining nuclear power machine fabrication complex using electricity generated by its own nuclear reactors. In the end it proved to be a technological nightmare. In 1983, just two years after opening, it was discovered that the complex was built too close to a reservoir. As a result, an entire wall collapsed because the foundation of the main foundry was built improperly. In addition, the complex has had a history of producing poor quality parts and late deliveries – including to the Chornobyl station. Atommash was scheduled to build eight reactor pressure vessels per year by 1985, but only managed to deliver its fourth in August 1985. Nigel Hawkes, et al, *Chernobyl: The End of the Nuclear Dream*, Vintage Books: New York, (1986): 92–93.

Interestingly enough, the failure of the Atommash plant was reflected in the decision to select the RBMK as the design choice for the Chornobyl Station: "Instead of being able to build a power facility around the new pressurized water reactors (VVER) from the discredited Atommash assembly line, the experts in charge at the site of the Chernobyl nuclear energy plant fell back on the less-advanced channel-type uranium graphite reactors (RBMK)." Ze'ev Wolfson, "Some Environmental and Social Aspects of Nuclear Power Development in the USSR," as quoted in Feshbach and Friendly, 130.

reactors, and in 1973 a pilot 350 MWe breeder was put into operation in Kazakhstan. Accelerated development of breeder reactors was a feature of the 1978–80 period.[25]

The Soviets were particularly interested in the use of nuclear power for the provision of thermal energy for residential and industial use. The first combined heat and power nuclear plant (ATET)† became operational in the town of Bilibino in northeastern Siberia in 1974 with a rated capacity of 48 MWt. The Soviets were likewise interested in small block-type nuclear power plants for regions located long distances from the existing power networks. In 1961, for example, a large-block transportable nuclear power plant was developed in the Soviet Union called the TES-3 which had a 1.5 megawatt water-moderated, water-cooled reactor and has seen wide use as a research facility.[26] There has even been a proposal to construct a 6 MW floating nuclear power station to provide electricity for oil and gas exploration in the far north and east of Siberia.[27] The 750 kWt ARBUS nuclear plant, with organic moderator and coolant, was also constucted in the seventies.[28]

Up until the Chornobyl accident, the former Soviet Union was world's third largest producer of nuclear-generated electricity. In 1985 Soviet nuclear power plants produced approximately 167.4 million megawatt-hours of electricity with an installed capacity of 28,400 MWe from 36 reactors; while in 1988, 216 million megawatt-hours of nuclear-generated electricity was produced with an installed capacity of 33,400 MWe from 41 reactors.[29] These figures seem to indicate that the Soviet nuclear energy program was steadily growing – even in the aftermath of the Chornobyl accident[30] and the steadily

---

[25] "Soviet Nuclear Power Plants," *USSR Technology Update*, Vol. 1, No. 12, (July 16, 1986): 7.

† Nuclear combined heat and electrical power plants in the former Soviet Union are referred to as ATETs (Атомный Теплоэлектроцентр), while nuclear power plants providing exclusively electrical power are known as AESs (Атомная Электрическая Станция), and nuclear power plants which provide only heat are known by the acronym AST (Атомная Станция Теплоснабжения).

[26] "A Brief History of Soviet Nuclear Power," op. cit.

[27] V. M. Abramov, et al, "Utilization of Floating Nuclear Power Plants in Northern Regions," *Atomic Energy*, Vol. 51, No. 2, (August 1981): 83–87.

[28] "Soviet Nuclear Power Plants," 7.

[29] Векслер, Л. М., В. К. Попов, "Авария на Чернобыльской АЭС и её уроки (1986 – 1990)," (Москва, Россия: припринт Института атомной энергии им. И. В. Курчатова), 1990.

[30] The Soviets, at the IAEA sponsored meeting in Vienna in August 1986 resolutely defended their

crumbling Soviet economy after three years of *perestroika*. In reality, this was due more to the momentum of "the great atomic program" built up at an almost breakneck pace as demanded by the Tenth (1976-1980), Eleventh (1981-1985), and Twelfth (1986-1990) Five-Year Plans (FYP).[31] The rate of growth of nuclear energy after 1986 actually declined drastically: the Thirteenth FYP (1991-1995) called for a growth of less than 15,000 MWe of installed capacity, that is, less than earlier forecasted 41,000 MWe by almost three times. Tables III.5 and III.6 summarize the growth of installed electrical generating capacity and electricity production in the former USSR; while Figures III.3 – III.5 present this information graphically.

Prior to the Chornobyl accident, the Ministry of Medium Machine Building (*MinSredMash*) was responsible for design and construction of nuclear power plants, while the operation of these plants was the responsibility of the Soviet Ministry of Energy and Electrification (*MinEnergo*). These two ministries were subordinate to different structures within the Soviet Council of Ministers. The USSR State Committee of Hydrometeorology and Environmental Control (*GosGidromet*), responsible for radiation monitoring, and the USSR State Committe for Nuclear Oversight (*GosAtomNadzor*), responsible for nuclear safety, also acted in parallel. After Chornobyl the USSR Ministry of Nuclear Energy Industry (*MinAtomEnergoProm* – commonly referred to as MAPI) was formed. Subsequently, MAPI was dissolved and its functions reassigned to *MinSredMash* – which itself was renamed the Ministry of Nuclear Power and Industry, and on January 29, 1992 (by degree of Russian President Boris Yeltsin) again renamed the Russian Ministry of

---

nuclear power program and even went so far as to assert that there would be no let up in the growth of nuclear power. Interestingly, but hardly unusual for the Soviets, the entire responsibility was apportioned among Chornobyl's officials and government ministires – while no blame fell on party officials or party policy; see Serge Schmemann, "Chernobyl Answers: New Questions," *The New York Times*, (July 21, 1986): A3.

[31] The program for nuclear power development for the Eleventh FYP anticipated a rise in output from 167 GWe-hr attained in 1985 (10.8% of total electricity generated) to 390 GWe-hr in 1990 (21% of total electricity generated) and as high as 35.2% in the European part of the USSR – to be achieved primarily by bringing into service VVER-1000s (Soviet version of the western pressurized water reator.) Brian Gordan, U.S. Industry Report Details Repercussions from Chernobyl," *Nucleonics Week*, Vol. 28, No. 19 (May 7, 1987): 7.

Atomic Energy (*MinAtom*). MinAtom (whose counterpart in the United States is the Department of Energy) is responsible for, among other things, the research, development, testing, and production of nuclear warheads. As such, it supervises the entire chain of production – from uranium ore mining through the fabrication of warheads – and is responsible for the production of all nuclear materials, uranium enrichment, production reactors, nuclear waste management.[32]

Table III.5
USSR Electrical Energy Generation Data[33]

Year	Installed Capacity (million kWt)				Production (billion kWt•hrs)				
	Nuclear	Fossil	Hydro	TOTAL	Nuclear	Fossil	Hydro	TOTAL	PLAN
1970	1.0	133.8	31.4	166.2	3.7	613.0	124.4	741.1	830
1975	4.7	172.3	40.5	217.5	20.2	892.4	126.0	1038.6	1065
1980	12.5	201.9	52.3	266.7	72.9	1036.9	183.9	1293.7	1380
1985	28.1	225.3	61.7	315.1	167.4	1162.3	214.5	1544.2	1555
1989	37.4	244.2	64.4	346.0	213.5	1284.9	223.6	1722.0	1795

[32] Thomas B. Cochran and Robert Standish Norris, *Russian/Soviet Nuclear Warhead Production*, Washington D.C.: Natural Resources Defense Council, (8 September 1993): 24–25.

[33] As compiled from "CMEA Countries Cooperate in Nuclear Power Development," *USSR Technology Update*, Vol. I, No. 12 (July 16, 1986): 1; U.S. Central Intelligence Agency, *USSR Energy Atlas*, U.S. Government Printing Office: Washington, D.C., (1985): 47; Gloria Duffy, *Soviet Nuclear Energy: Domestic and International Policies*, A report prepared for the U.S. Department of Energy (R-2362-DOE), Santa Monica: The Rand Corporation, (December 1979): 40–45; Министерство Энергетики и Электрификации СССР – Центр научно-технигеской информации по энергетике и электрификации, *Электроэнергетика в СССР и за рубежом: Краткий статистический обзор*, (1991); and personal conversations with people at the Ukrainian Ministry of Energy and Electrification, March 1993.

Figure III.3
USSR Electricity Generation

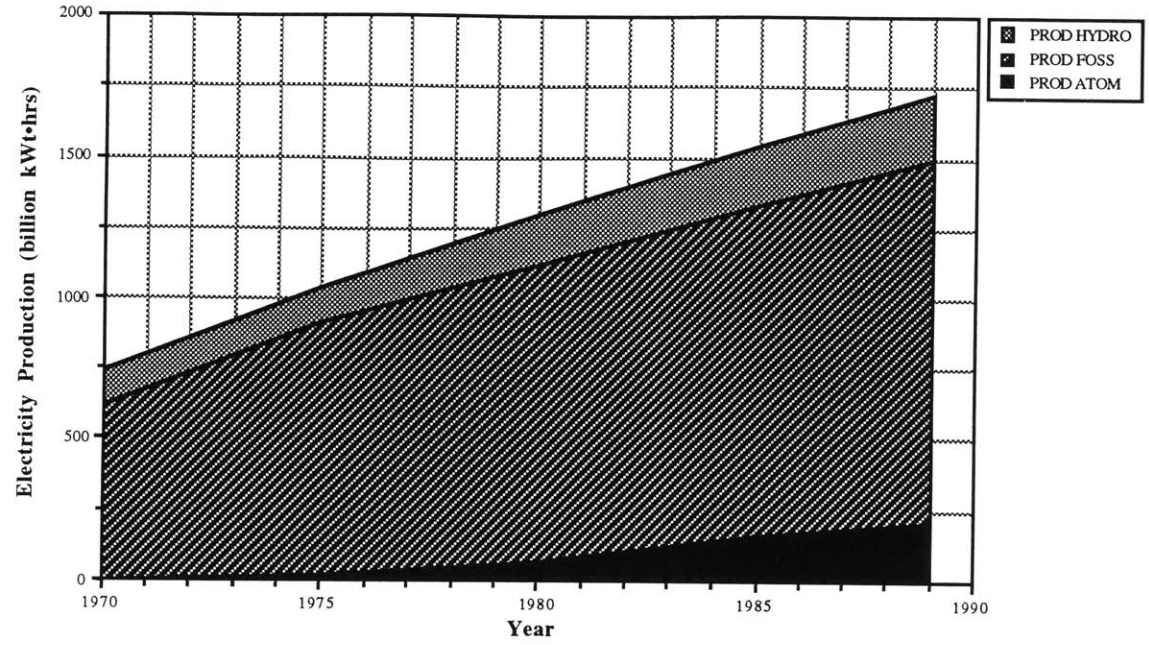


Figure III.4
USSR Installed Electrical Generating Capacity

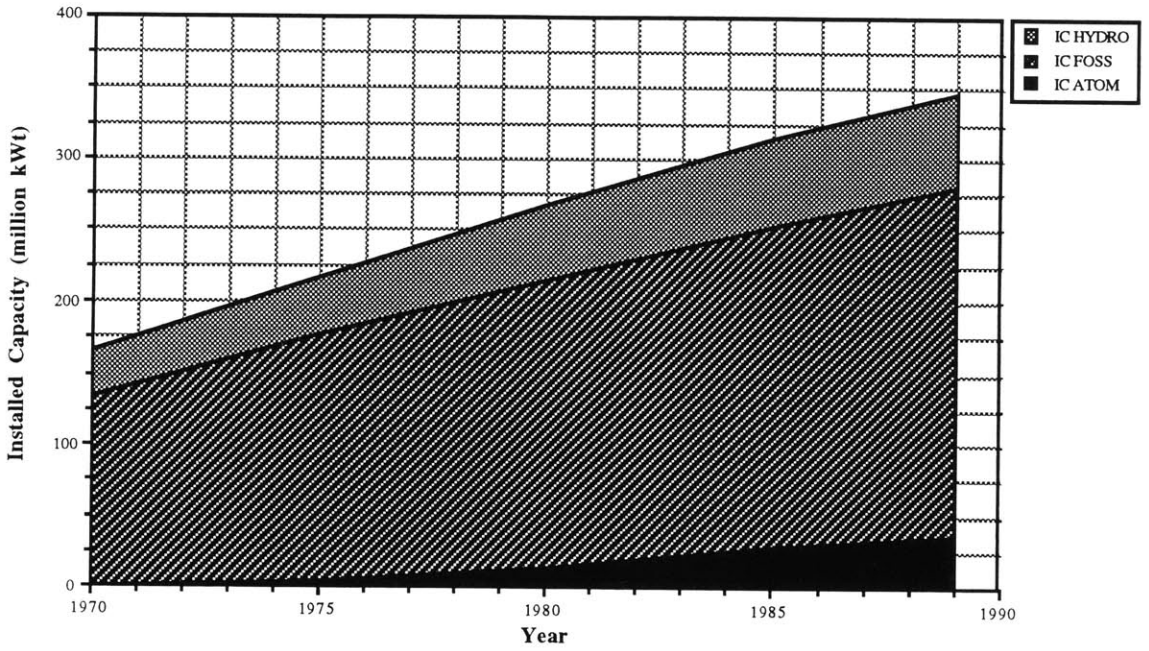
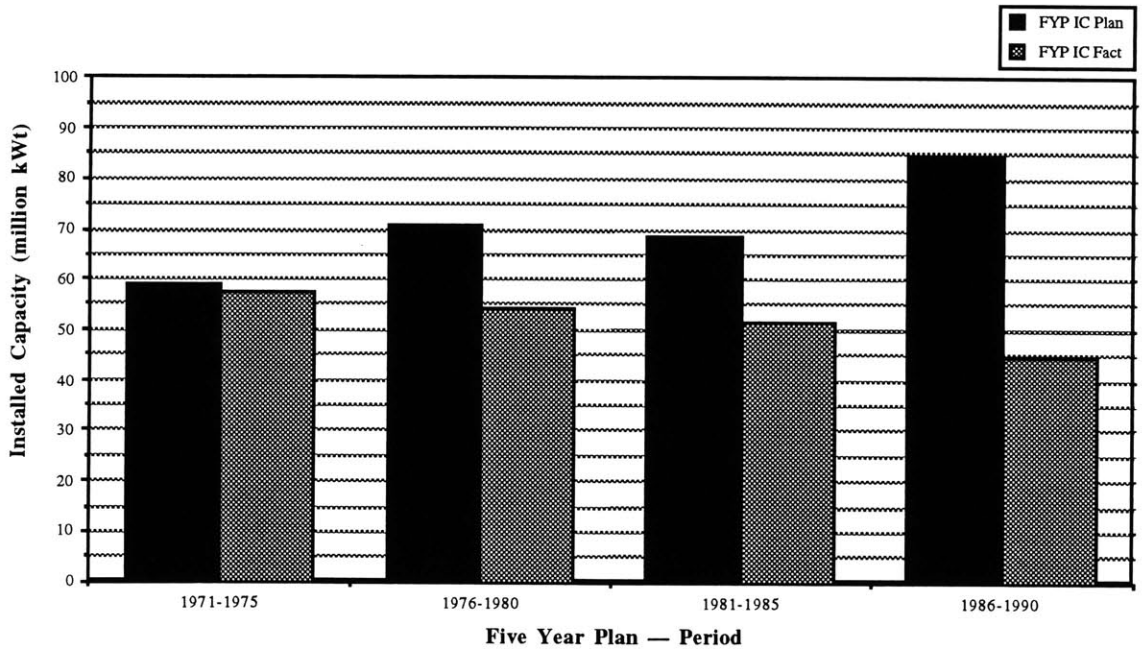


Table III.6
Five-Year Plan Electrical Generating Capacity Fulfillment Data[34]

Five-Year Plan	Installed Capacity (million kWt)		
	Plan	Actual	Actual/Plan (%)
1971–1975	58.9	57.6	97.8
1976–1980	71.0	54.0	76.1
1981–1985	68.9	51.6	74.9
1986–1990	84.9	44.7	52.7

Figure III.5
USSR Five-Year Plan Fulfillment for
Installed Electrical Generating Capacity



The former Soviet Union was the only Communist country with a reactor development program; and although fifteen countries have appeared in the wake of the dissolution with Russia, Ukraine, Armenia, Lithuania, and Kazakhstan having nuclear reactors on their territories, only Russia currently has a reactor development program. As to fur-

[34] Ibid.

ther development, Ukraine's position is yet unclear because its parliament and government are working out an energy policy for the country. Until Chornobyl, the Soviets had been focused primarily upon the economic performance of its reactors. Since the accident and up to the collapse of the Soviet Union their priorities have appeared to be ambiguous. Active development of new Chornobyl-type reactor designs has ceased,[35] but several RBMK-1000s were in mid or late stages of construction through the end of the late 1980s – early 1990s and Russia decided to complete construction by 1994 of its Kursk-5 unit.[36]

III.1.3. Advantages and Disadvantages of the RBMK

There were a number of important factors considered in the development and design work that favored what the Soviets regarded as their "national" reactor – the RBMK – and why it was chosen to provide the larger share of the nuclear program in the Soviet Union. Uranium-graphite reactors systems cooled by boiling light water are the simplest and most technologically accessible for a country with a moderate economic base and technological infrastructure. (It was also for this reason, among others, that such a reactor was used to produce plutonium both for military purposes and for experimental fast breeder reactors.)† Although the RBMK has a more complex structure than the typical vessel reactor,[37] similar designs were not without precedent in fossil-fueled plants, and

---

[35] In 1988 the decision was made not to build any new RBMKs [*Argumenty i Fakty*, 15 (1988): 8.] There appears to be talk, however, of further development of the RBMK design concept as witnessed by studies carried out to see how the positive void coefficient of reactivity might be reduced or eliminated. Two general approaches being studied are to increase the fuel enrichment to increase neutron absorption on coolant voiding (although this will also increase local peaking factors), and to effectively reduce the lattice pitch to give an undermoderated condition by removing the corners of the graphite blocks through which the fuel channels penetrate. [E. O. Adamov, "The Soviet RBMK: Where Do We Go From Here?" *Nuclear Engineering International*, Vol. 6, (June 1990): 33–36.

[36] Ann MacLachlan, "Russia Okays Plans to Proceed With Major Nuclear Construction," *Nucleonics Week*, Vol. 34, No. 3, (January 21, 1993).

† Interestingly, both Enrico Fermi for the United States and Vladimir Kurchatov for the Soviet Union designed their reactors based on uranium-graphite reactor physics priniciples.

[37] The U.S. DOE concludes, for example, "Soviet RBMK-1000 boiling water type reactors have an unusually complicated steam-generating system, from the point of view of construction and assembly." [U.S. Department of Energy, Department of Energy's Team's Analyses of Soviet Designed VVERs, Washington D.C.: U.S. DOE, DOE/NE-0086 Analysis Appendix H, (1986): H-4. This echoes an assessment of the RBMK system's major drawbacks as, "... complex and bulky coolant circulation circuits and a large number of auxiliary systems," in a Soviet textbook on the construction of nuclear power plants, [V. Dubrovskyj (editor), *Construction of Nuclear Power Plants*, Moscow: Mir Publishers, (1981): 92.]

the absence of complex and expensive steam generators proved to be a distinct advantage. Moreover, the industrial and technological base needed to mass produce large pressure vessels for the VVER design had not yet matured in the 1960s and early 1970s. Besides not requiring a huge outer structure surrounding the reactor core (such as the pressure vessel for a typical LWR or pre-stressed concrete vessel for gas reactors), the graphite channel reactor allows for more flexibility in reactor design and fuel composition. Because of the lack of restrictions on core size,* the use of standard structural elements was possible in the construction of the RBMK units. Its modular construction allows for fabrication of major reactor components at existing manufacturing plants, and relatively simple transport and assembly at the plant site. Further, the RBMK can be refueled without interruption of reactor operation (on-line refueling and hence a very high plant capacity factor), allows nuclear superheating of steam and channel-by-channel maintenance, has a flexible fuel cycle control (easily adapted to variations in the fuel market conditions), and has relatively high burnup. The fact that this reactor can be controlled by controlling the flow rate for each channel separately and that reactor operation permits channel-by-channel maintenance implies that the thermal equipment has high thermodynamic reliability, each channel's integrity and operational parameters can be monitored separately, and damaged channels can be replaced while operating. Another major advantage from the Soviet point of view is that RBMK reactors use lower enrichment uranium and produce more plutonium (ostensibly for breeder reactors) than water cooled, water moderated reactors. The RBMK reactors can also be used for the production of U-233 from Th-232.

Zhores Medvedev concludes, "It was not because of economic efficiency, safety, or institutional support that the RBMK was later given priority. In the late 1950s and the 1960s is was simply easier for Soviet industry to construct its less sophisticated design... There were also nationalistic reasons for giving priorities to the RBMK system: it was the only entirely Soviet system. Other designs would have entailed copying or imitating Western models." [Zhores Medvedev, *The Legacy of Chernobyl*, New York: W.W. Norton and Company, (1990): 230.]

* The RBMK was originally heralded by Soviet designers as a modular system that could be built up to large sizes – the RBMK was the world's first 1000-MWe reactor, and the Ignalina reactors that have operated up to 1500 MWe are still the world's largest, while designs for 2400-MWe and even 4800-MWe RBMKs exist.

Although the RBMK has several important and rather significant advantages compared to its LWR counterparts, some of the features of the RBMK that were intended to make it more efficient actually introduce equally significant disadvantages that are even identified as design faults.† For example, the over-moderated core was designed to give the neutron economy needed to operate with low fuel enrichment, but it was precisely this feature that gave the reactor a positive void coefficient over a wide range of operating conditions and a positive power coefficient at low power. Although the RBMK can be considered a "modular" system that can be built up to large sizes, this results in a loosely coupled core that is difficult to control – particularly at low power levels. (There is a high sensitivity of the neutron field to reactivity disturbances of various kinds necessitating a complex control system for stabilizing the distribution of energy generation in the core.††) Additionally, the large dimensions of the core of an RBMK-1000 and RBMK-1500 (diameter 11.8 m, height 7.0 m – compared to the core of a typical 1300 MWe PWR with core diameter of 3.4 m and height 4.3 m) and large core load of UO_2 (190.3 tonnes compared to 103.9 tonnes for a 1300 MWe PWR)* give rise to the potential for local critical masses within the core.** A localized excursion would be much more damaging

† Although a rather large number of design faults can be identified in the RBMK-1000, four are of particular concern: (1) the sensitivity of the neutron field to reactivity perturbations leading to control difficulties and requiring complicated control systems, (2) a relatively small and weak containment around the core itself (identified by the Soviets as the ALS or Accident Limitation System, (3) a positive void coefficient of reactivity that increases as power is decreased and that was said to have a full power value of 0.02 $\Delta k/k/k/\Delta\alpha$ (where $\Delta\alpha$ is the change in void fraction), and (4) a control rod follower design fault that actually increases reactivity at the bottom of the core upon insertion from a completely withdrawn position.

†† The first generation RBMK-1000 was considered to have stability problems and was difficult to control, particulaly at low power levels. The approach to resolving these problems was to place increased reliance on automatic control systems, to adopt a higher fuel enrichment (1.8% to 2.0%) and slightly lower graphite moderator density (1.7 to 1.65 gm/cm^3) in order to decrease the positive void coefficient.

* For example, the French Belleville-1 PWR has a Thermal Power of 3817 MW(t), Gross Power 1330 MW(e), Net Power 1275 MW(e), Active Core Height 4.25 m, Active Core Diameter 3.37 m. The German Gundremmingen B BWR has a Thermal Power of 3840 MW(t), Gross Power 1300 MW(e), Net Power 1240 MW(e), Active Core Height 3.71 m, Active Core Diameter 4.82 m.

** In particular, because of the creation of "local" critical masses, the first fuel loading give rise to a problem in which the control rod system alone is not sufficient to hold the core (as a whole) subcritical for the initial fuel loading. To compensate, it was necessary to load one supplemental absorber rod for every six fueld channels. These were slowly withdrawn and replaced with fuel assemblies as fuel burnup increased.

because the same power would be concentrated over a smaller volume and thus has the propensity to propogate to other regions of the core.

The graphite followers attached to the bottom of the control rods were designed to improve neutron economy while in the core and to maximize reactivity change on control rod insertion. But because the followers and control rods fit rather closely in the guide channels, their movement was damped by the surrounding water, giving a desperately slow insertion time of 20 seconds. Moreover as identified after the accident, there can be no justification for the fatal design error of a control rod follower whose length did not match the full height of the reactor core. This left a water gap top and bottom which caused what is now referred to as a "positive scram" effect that exacerbated the accident.

Structural design deficiencies of the RBMK also present significant safety problems. Besides the complexity of the inlet-outlet piping system for the heat-transfer agent of each channel and the large amount of thermal energy accumulated in the metal structures, fuel elements and graphite-block structure of the reactor, RBMK reactors have a limited capability to accommodate the structural (stress and strain) effects of thermal transients – namely in the zirconium-to-stainless steel transition welds at the inlet and outlet to the fuel pressure channels in the core. It is not precluded that a severe accident could occur at the fourteen operating or planned RBMKs in Russia and Lithuania (Sosnovyj Bor, Kursk, Smolensk, and Ignalina Stations). The design-basis accident for an RBMK-1000 is the rupture of a maximum of two "technological" or fueled-coolant channels in the reactor core, where in the event of such accident the ECCS and pressure suppression system (bubbler pool underneath the reactor) are designed to contain the associated over-pressurization of the thin stainless steel shell that surrounds the core. If more than two of the 1661 technological channels fail, it is postulated that the 2500 tonne-equivalent Upper Biological Shield would be lifted upwards – shearing more of the channels and eventually leading to a catastrophic failure: the shearing of the channels and subsequent pressur-

ization of the reactor cavity may eventually lead to releases outside the reactor building.[38]

Despite certain design improvements implemented by the Russians for some of their RBMKs, each reactor remains without an adequate containment.[39] RBMK-type reactors use local area compartmentalization to accommodate the effects of breaks of the primary coolant pressure boundary. This concept relies on the pressure containing capability of each room, cell, or vault to contain material released in the event of an accident. Only the newer "2nd generation" RBMK-1000s – such as Chornobyl Units 3 & 4 – use a steam suppression/bubbler pond confinement system – as opposed to containment structures that can withstand internal pressure such as are used in LWRs in the west. (Chornobyl Units 1 & 2 in Ukraine, as well as Sosnovyj Bor [Leningrad] Units 1 & 2 and Kursk Units 1 & 2 in Russia do not have pressure suppression pools.)[40] The "compartments" are not designed to accommodate more than one primary coolant pressure boundary breach based on failure of the largest pipe in the compartment. For this reason alone an accurate appraisal of the Chornobyl accident is essential for probabilistic safety analyses of operating RBMKs, major backfit and upgrade plans for these reactors, emergency response and evacuation procedures, or to assess whether RBMKs should operate in the future.[41]

Particular attention must be drawn to the zirconium-to-stainless steel transition welds for *each* of the 1661 "technological" (fueled) channels in *all* RBMK-1000 and RBMK-

---

[38] There is already a precedent for coolant channel ruptures in the aging fleet of operating RBMKs in the CIS: Sosnovyj Bor (Leningrad) Station Unit-1 in 1975, Chornobyl Unit-1 in 1982, Chornobyl Unit-4 in 1986, and Sosnovyj Bor Unit-4 in 1992.

[39] There are studies currently underway to design a pressure containment system to mitigate against the rupture of one of the forty-four (twenty-two per loop) group-distribution header which distributes coolant water to approximately forty of the reactors 1661 coolant channels. If implemented (difficult at best considering Russia's current economic plight), this would certainly decrease the probability of a catastrophic failure – although the upper part of the reactor would still remain without effective containment. See International Atomic Energy Agency, *Safety Assessment of Proposed Improvements to RBMK Nuclear Power Plants*, Vienna: IAEA, IAEA-TECDOC-694, (March 1993).

[40] "... there are six first generation RBMK[-1000] units which have *no reinforced leaktight compartments and no special structures to localize radioactive releases*. The main aim in these units must [, therefore,] be to reduce the probability of large diameter pipe breaks up to a point where such incidents might be termed hypothetical." [emphasis added], INSAG-7, 125.

[41] Interestingly, the IAEA concluded, based on the results of ASSET (Assessment of Safety Significant Event Team) safety analysis of a number of RBMK stations that, "no operational issues have been identified whtat would preclude current continued operation of the four RBMK sites [Kursk, Ignalina, Sosnovyj Bor, Smolensk] reviewed." However, it is clear as stated in the mission's goals, that the analysis examined plant events that occurred over the past five to ten years – and not the very design of the RBMK.

1500 reactors. If we consider only the six units without pressure suppression systems, this amounts to approximately 20,000 possible break locations in these reactors. As is constantly pointed out by the Russians, the newer generation models (including Chornobyl Unit-4) have pressure suppression systems ostensibly to mitigate against one to two such breaks. Unfortunately, they conveniently neglect to mention that the pressure suppression system was of no consequence in the Chornobyl accident. It is precisely the fuel channel transition welds within the core that are considered to be the weakest points in the main coolant circuit and the most likely to fail according to safety analyses.[42] The Russians have estimated that the probability of the rupture of two channels is on the order of 10^{-8} per reactor reactor-year and that the existing steam dump system for the reactor space is designed to cope with the steam discharge from such a simultaneous break of two channels. It is unclear whether this probability applies to *all* fuel channels in *all* existing reactors, or that the probability must then be multiplied by the total number of pairs of fuel channels – which would bring the probability for failure up to the order of 10^{-5} per reactor reactor-year. Given the precedence of such channel breaks (see above), the seriousness of such events and their impact on core safety analyses cannot be underestimated.

[42] "The [transition] weld is designed to handle temperature changes up to 15°C per hour. Many metallurgical experts consider this weld to be the weakest point in the RBMK primary system." (NUREG-1250, 3-32.)

III.2. Nuclear Energy in Ukraine

III.2.1. Chornobyl's Impact in Ukraine and the Former Soviet Union[43]

Although for the first few years after the accident remained a "success" story in the controlled Soviet press – the dissenting voices muffled by a barrage of propaganda and scientific explanations of the accident and improvements made to the RBMK reactor design – in the first five years after the accident no new reactors went into operation, two operating reactors were closed, and construction halted on thirty-nine reactors targeted by demonstrators – on eleven of them, work was eventually cancelled outright.[44] Ukrainians also entered the fray – but with surprising ferocity. Within a few years the strongest and most surprising opposition to the accident was coming from within Ukraine – mistakenly considered by Russian leaders (in a distant and somewhat aloof Moscow) to be a relatively docile and obedient communist stronghold. The Ukrainians decided, therefore, to have their own say about Chornobyl, about the ambitious nuclear power program building that was under way in Ukraine,† and about the general harm inflicted upon the Ukrainian environment by an oftentimes reckless Soviet industrial development.[45]

Taking advantage of the strong impulse the accident imparted to Gorbachev's policy of *glasnost* or "openness," within two years after Chornobyl, Ukraine's nuclear power program as well as other industrial projects came under virtual siege from fledgling environmental groups.[46] Soon after, the accident was used more as springboard for other na-

---

[43] See also, Alexander R. Sich, "Continuing Repercussions from Chernobyl' in Soviet Ukraine: A Summary of Technical, Policy, and Public Responses to the Chernobyl' Accident in Ukraine and the USSR," presented at the *Fourth Annual Ivy League Graduate Student's Conference in Russian and Soviet Studies*, Yale University, April 7–8, 1989; and Marples, David R, *Chernobyl and Nuclear Power in the USSR*, New York: St. Martin Press, 1986.

[44] Feshbach and Friendly, 134–35 as quoted from Michael Dobbs, "Chernobyl: Symbol of Soviet Failure," *Washington Post* (26 April 1991): A1, A38; and "Powerless," *The Economist* (13 April 1991): 67–68.]

† Ukraine, the most densely populated republic and representing 2.7 percent of the total land area of the former Soviet Union, at the time of the accident had within its borders 25 percent of the USSR's nuclear power plants representing 34 percent of nuclear power capacity in the Soviet Union. This, however, must be kept in perspective considering France (slightly smaller than Ukraine) has approximately twenty-five times the number of reactors per person per unit area than Ukraine.

[45] See Feshbach and Friendly chapter 2 "Birth of the Future" and chapter 7 "... Plus Electrification."

[46] "Chernobyl's fallout... helped to melt away much – but far from all – of the secrecy that authorities had long used to hide a vast range of health and environmental dangers." Feshbach and Friendly, 12.

tional grievances against the Russian-controlled Soviet Government and the eventually successful drive for independence, than against nuclear power per say.[47,48] Chornobyl, for the first time since Ukraine's incorporation into the Soviet Union, created a powerful issue over which Ukrainians saw the advantages of local control over central planning by a "foreign" Moscow. Before the demise of the Soviet Union, Ukrainians won a small number of significant victories against central planners in Moscow, partly because of the more tolerant conditions under *glasnost*, and partly because in the Soviet Union as a whole a major campaign for ecological protection was mounted. For example, in their campaign against nuclear power in Ukraine, the Executive Committee of the Ukrainian Helsinki Union in November 1988 issued a statement and petition demanding, among other things, the gradual but complete elimination of the nuclear power option with Ukraine.[49] Since then the Ukrainian *Rada* (Parliament) voted to impose a moratorium on the construction of any more units effective to the end of 1994, and to close down the station by the end of 1993.† However, these decisions have since been rescinded when during the fall of 1993 Ukraine's Parliament revisited nuclear power issues under pressure from Russian attempts to "squeeze" Ukraine by demanding world market prices for its oil and gas – compounding Ukraine's already rapidly deteriorating economic condition.[50] In October 1993 Ukraine's struggling nuclear energy program received an impor-

---

[47] See, for example, Feshbach and Friendly, 22, 123, 230.

[48] See Chapter Three "Ukraine: The Pivotal Nation" and in particular this chapter's section 'After Chernobyl' in Nadia Diuk and Adrian Karatnytsky, *New Nations Rising: The Fall of the Soviets and the Challenge of Independence*, New York: John Wiley & Sons, (1993): 71–107.

[49] "For the Record" Ukrainian Helsinki Union's Statement and Petition on Nuclear Plants," *The Ukrainian Weekly*, Vol. LVI, No. 51, (Sunday, December 15, 1988): 10.

† In the wake of the turbo-generator fire in October 1991 at Unit-2, the Ukrainian Parliament voted in late 1991 to close the Chornobyl Station for good at the end of 1993, bringing forward by two years the Chornobyl shutdown deadline it had set in 1990 when Ukraine was still part of the Soviet Union.

[50] "Ukraine Faces Russian Oil and Gas Squeeze," *The Ukrainian Weekly*, Vol. LXI, No. 9, (Sunday, February 28, 1993): 3. These actions are interpreted by many as attempts to undermine Ukraine's fledgling independence in a broader program for Russia to reconstitute the former Soviet Union – even in the wake of the failed coup by communist hardliners and Russian ultranationalists in September 1993. See, for example, William Odom, "Yelstin's Deal With the Devil," *The Washington Post*, (October 23, 1993); John P. Hannah, "The (Russian) Empire Strikes Back," *The New York Times*, (October 27, 1993); "A New Russian Empire?" *Congressional Record: Proceedings and Debates of the 103d Congress, First Session*, SENATE, Vol. 139, No. 154, (Friday, November 5, 1993); Marta Kolomayets, "Ky[j]iv Condemns Russia's Attempts to Diplomatically Isolate Ukraine," *The Ukrainian Weekly*, Vol. LXI, No. 50, (December 12, 1993): 1.

tant impetus when its parliament voted to prolong the operation of the Chornobyl Station, and to lift a moratoruim on the construction of new nuclear units imposed in the wake of the Chornobyl accident.[51,52] Table III.7 and the preceding text present a summary of changes in the Soviet and Ukrainian nuclear power programs in the wake of Chornobyl.

Ukraine

(1) In April 1987, Chornobyl Units 5 & 6, both third generation RBMK-1000 and partially completed (80% and 15% respectably) at the time of the accident, were offcially abandoned.

(2) In October 1987, construction work was halted on the nuclear power and heating co-generation plant (ATET – VVER-1000) near Kyjiv. The plant is to be replaced by a fossil-fueled station.

(3) In November 1987 it was announced that work on the Odesa nuclear power and heating plant (ATET – VVER-1000) – which was at an "advanced stage of construction," had been stopped as a result of public protest.

(4) In February 1988, the Chyhyryn nuclear power plant project was put on review by a special investigative panel and in July of the same year was officially abandoned.

(5) In July 1988 it was announced that a new site would be sought for the nuclear power and heating plant that was to be built near the eastern Ukrainian city of Kharkiv.

(6) Work on the Crimean nuclear plant (2 x AES – VVER-1000) was halted by parlimentary decree pending a special commission's investigation. One of the major public concerns was that the plant is located in a known seismic region.

(7) In mid 1990 the Ukrainian Parliament imposed a moratorium on the construction of new units effective to the end of 1994. It also voted to shutdown the remaining operating RBMK-1000 units at the Chornobyl Station by the same date. However, the decision to close the Chornobyl Station was conditioned upon the availability of replacement power.

(8) In October 1991, in the wake of a major fire that destroyed one of Chornobyl Unit-2's generators, Ukraine's Parliament voted to accelerate shutdown of the Chornobyl Station (originally planned at the end of 1994) to the end of 1993.

---

[51] "Ukraine to Keep Chernobyl in Operation," *The New York Times*, Vol. CXLIII, No. 49,492 (Friday, October 22, 1993): A8; Ann MacLachlan, "Power Shortfall Plus Political Chaos: Good News for Chernobyl," *Nucleonics Week*, Vol. 34, No. 37, (September 16, 1993): 4. Ukraine's decision to prolong the operations of the Chornobyl Station, although necessary from the point of view of energy shortages, apparently contradicts its stated intention to become energy independent from Russia. Russia is the original designer of the RBMK series of the reactors as well as the only country that manufactures and services then, that enriches and fabricates their fuel, and prepares engineers to run them. With the continued operation of Chornobyl, Ukraine will remain strongly dependent on Russia for RBMK support. Operation of Ukraine's VVER plants holds more promise since the design is quite close to western PWRs. Moreover, Russia's monopoly on fuel manufacturing for these reactors is eroding with Westinghouse, Franatome, and Siemens development of their own designs of VVER-440/1000 reactor fuels. ["Westinghouse Contracts At Temelin: Signed And Sealed at Last," *Nuclear Engineering International*, (July 1993):2]

[52] Interestingly, Ukraine's second most senior nuclear regulator, Georgyi Kopchinsky, resigned as *DerzhAtomNahljad's* first deputy minister in protest over the Ukrainian Parliament's October 20, 1993 decision to keep the Chornobyl nuclear station operating indefinitely. [Ann MacLachlan, "Ukrainian Regulator Resigns to Protest Chernobyl Decision," *Nucleonics Week*, Vol. 34, No. 39, (December 9, 1993): 11.

Table III.7[53]
The Ukrainian S.S.R. Nuclear Power Program, 1988–2000
(all figures in MWe gross)

Station	1993 Capacity	Projected Capacity (pre-Chornobyl)	Projected Capacity (post-Chornobyl)
Chornobyl [ATET]	2,000	6,000	3,000 (0 > 1993)
Rivne[VVER]	1,832	3,832	3,832
South Ukraine [VVER]	3,000	6,000	3,000 (4,000?)
Zaporizhzhja [VVER]	5,000	6,000	6,000
Khmel'nyts'kyj [VVER]	1,000	4,000	2,000
Crimea [VVER]	0	2,000	under review
Chyhyryn [VVER]	0	4,000 (?)	abandoned
Odesa [ATET]	0	2,000	abandoned
Kharkiv [ATET]	0	2,000	abandoned
Kyjiv [ATET]	0	2,000	abandoned
Totals	**12,832**	**37,832**	**14,832 – 15,832?**

The Soviet Union

(1) In early 1986, work on the Armenian nuclear plant (Units 3 & 4) was stopped temporarily, ostensibly for modernization. Later, the Armenian authorities shut down work on these reactors and declared that the republic will seek alternative energy sources in the future. The two operating units were to be shutdown in 1991 because the station is located in a region noted for seismic activity. All four reactor at the plant are VVER-440 AESs.

(2) Work on the Georgian and Azerbaijan stations will not be completed because both are located in zones of known seismic activity.

(3) In October 1987 it was reported that the planned AES RBMK-1500 plant being built at Kostroma in central Russia had been converted to a VVER-1000 station for "economic reasons."

(4) In late August 1988 it was announced that construction of the third and fourth units of the AES RBMK-1000 plant at Ignalina, Lithuania was suspended. Unit-2 was shut down in September of the same year because of a fire in the control power cables. By mid-September the Initiation Group for the Support of *Perestroika* in Lithuania had collected 287,000 signatures on a petition demanding that the plant be investigated by an international commission.

(5) In January 1988 construction of the Krasnodar station was abandoned (after a capital outlay of more than 14 million rubles) due to "intense public protest."

(6) The construction of a co-generation nuclear power and heating plant (ATET) near the city of Minsk, Belarus was halted in September 1988 following citizens' fears about the operation of such a station located 22 miles from the city center. It is to be replaced with a natural gas-based plant.

(7) Four reactors scheduled for 1989 completion have been postponed: Kursk-5 (RBMK-1000), Kalinin-3 (VVER-1000), Rostov-1 (VVER-1000), and Ignalina-3 (RBMK-1000). This amounted to an approximately 57 percent reduction of the originally planned total for 1989.

---

[53] Adapted from David Maples, "Ukraine's Nuclear Power Program Attacked by Academicians, Writers," *The Ukrainian Weekly*, Vol. LVI, No. 9, (February 28, 1988):11; David Marples, "Nuclear Power, Ecology, and the Patriotic Opposition in the Ukrainian SSR: An Analysis of a Post-Chernobyl' Trend," *SOVSET NEWS*, Vol. 5, No. 1, (January 10, 1989).

III.2.2. Ukrainian Nuclear Energy: Facts and Figures

A number of sources outline fairly well Ukraine's nuclear power development – both as an integral part of the former Soviet Union as well as its few years as an independent state.[54,55,56,57] It is not the intent here to present a thorough history of nuclear power in Ukraine, but rather by means of basic facts, data, and an account of the latest developments, to summarize briefly the current position of Ukraine's nuclear energy industry.

Almost eight years after the accident, Ukraine finds itself at an impasse regarding its critically important nuclear energy industry. On the one hand, its existing plants have been hampered by a series of mishaps that have seen almost all reactors removed from service for short periods over the past several years. On the other hand, the political and economic disputes with Russia have led to an energy conundrum and an apparent acceptance that Ukraine cannot yet do without nuclear energy,[58] which currently accounts for approximatley 30 percent of it total electrical output. Moreover, as a ubiquitous backdrop to this question is the ongoing debate of how to deal effectively with the effects of the Chornobyl accident in the midst of a transition to a market-based economy, as well as the impact of the accident on public opinion.[59] As an extreme example of public pressure, protests directed against the construction of a 2500 MWe hydro station on the South Buh River – ostensibly because of concerns over what effects a large dam would have on the local ecosystem. Ulterior motives, however, were clear in that the hydro power station would have eased a cooling water shortage at the nearby South Ukraine Nuclear Power Station – thus allowing Unit-4 (currently 75% complete) to go into service. The hydro

---

[54] Marko Bojcun and Viktor Haynes, *The Chernobyl Disaster*, London: The Hogarth Press, 1988.

[55] David R. Marples, *Chernobyl and Nuclear Power in the USSR*, New York: St. Martin Press, 1986.

[56] David R. Marples, *The Social Impact of the Chernobyl Disaster*, New York: St. Martin Press, 1989.

[57] Zhores Medvedev, *The Legacy of Chernobyl*, New York: W.W. Norton and Company, 1990.

[58] Nikolai Shteinberg, Head of *DerzhAtomNahljad*, Ukraine's State Committee for Nuclear Oversight, has stated categorically, "Ukrainian independence is impossible without nuclear energy." Personal conversation with the author, March 1993.

[59] Chornobyl's impact is also evident in its effect on Ukraine's nuclear power industry as a whole. See, for example, Pearl Marshall, "Marshall: Nuclear Plant Morale is Poor in Ukraine, Blooming in Russia," *Nucleonics Week*, Vol. 33, No. 20, (May 14, 1992): 3.

station had to be abandoned, and as a result construction work on Unit-4 was postponed until the water shortage problem is resolved.[60]

There are currently fourteen nuclear power reactors with a total installed capacity of approximately 12,800 MWe (gross) located at five separate stations. Besides the 30% of total electricity generation provided by nuclear power, fossil stations provide about 66% while hydropower stations about 4%. (Figures III.6 – III.10 and Tables III.7 – III.8 at the end of this section summarize basic data on the reactors at these stations as well as providing general information on electrical power production in Ukraine; while Appendix III.C provides more detailed information on nuclear power reactors in the CIS.) The Ukrainian government took over responsibility for the control and operation of the nuclear stations from the former Soviet Ministry of Nuclear Power and Industry (MAPI) in November 1991. At first the Ukrainian stations were formed into a consortium, *UkrAtomEnergoProm*, with Volodymyr Fuks (General Director of the South Ukraine Station) as chairman of the board and Mykhajlo Umanets (former General Director of the Chornobyl Station) as president. The governing council of *UkrAtomEnergoProm* asked Ukraine's president, Leonid Kravchuk, to transfer to the consortium control of all research and development institute previously affiliated with the Ministry for Medium Machine Building (*MinSredMash*), as well as extraction and ore processing enterprises associated with Ukraine's rather substantial uranium supplies located about the town of *Zhovti Vody*. *UkrAtomEnergoProm* has also sought contractual agreements with organizations in Russia for services needed to keep Ukrainian plants in operation. Ukraine is dependent on Russia for nuclear fuel and there have been problems over the acceptance by Russia of spent fuel from the Ukrainian reactors,[61] which was due to be sent to Krasnoyarsk.

---

[60] "Datafile: Ex-USSR — Ukraine," *Nuclear Engineering International*, (August 1992): 39.

[61] "Ukraine and Russia Are At Odds Over Spent Fuel," *Nuclear News*, (March 1992): 52; "Russia Has Again Stopped Taking Ukraine's Spent Fuel," *Nuclear News*, (June 1992): 104. Russia has since agreed again to accept Ukraine's spent fuel. In general, a decline in the rate of spent fuel processing in Russia is a consequence of transportation problems and a Russian nuclear waster law that prohibits importing nuclear waste into Russia. There has been a holdup in the shipment of spent fuel from Ukraine, Czechia, Slovakia, (formerly) East Germany, and Hungary awaiting legal clarification whether spent fuel should be regarded as "regular" nuclear waster. Ukraine has no large-capacity spent-fuel storage facilities

At the time of this writing Ukraine was struggling through a severe economic crises brought on by its independence in August 1991 from the Soviet Union, as a consequence of the transition to a market-based economic system, as well as renewed economic pressures and territorial threats from Russia.[62] Since its independence the government was changed three times (three Prime Ministers were forced to resign), and the parliament was forced to agree to early elections in late 1993 – approximately one and one-half years before the old parliament's (elected in March 1990 while still under the communist régime) tenure was to expire. Additionally, as part of the reform process Ukraine is drafting a new constitution – which precludes all but a temporary energy policy to define current trends and determine future strategies.[63] Unfortunately, an action widely interpreted as a step backward from market-based reforms, President Kravchuk (formerly Ukraine's chief communist ideologue) decreed strict currency controls including hard currency sales – an action that may lead to a complete loss of credibility with western economic analysts and world banking organizations involved with supporting reforms in the former Soviet Union.[64] Moreover, sharp disagreements with Russia regarding oil and gas supplies[65] and problems involved with the previously mentioned transfer of spent nuclear fuel to Russia

---

and limited storage capacity at its operating plants. If Russia were to stop accepting spent fuel, Ukraine would be left with only 1.5–2 years of storage capacity.

[62] Jon Auerbach, "Russia Tightening its Grip on Former Republics," *The Boston Globe*, Vol. 244, No. 159 (December 6, 1993): 1.

[63] For a discussion of possible future energy strategies for Ukraine, see, "Енергетичну кризу можна обминути," *Голос України*, (26-го вересня 1992), and "Як забезпечити державу електроенергією?" *Вечірній Київ*, (вівторок, 22-го вересня 1992).

[64] "Shifting Back to Communist Era, Ukraine Bars Hard Currency Sale," *The New York Times*, (Thursday, November 4, 1993): A1.

[65] See the four page survey on Ukraine by Chrystia Freeland and Edward Balls, "Financial Times Survey: Ukraine," *The Financial Times of London*, (Wednesday, January 27, 1993): 9–12; "Ukraine Faces Russian Oil and Gas Squeeze," *The Ukrainian Weekly*, Vol. LXI, No. 9, (Sunday, February 28, 1993): 3; and David R. Marples, "Newly Independent Ukraine Faces New Energy Crisis," *The Ukrainian Weekly*, Vol. LX, No. 5, (Sunday, February 2, 1992).

It appears that the Russians are dictating conditions for the sale of energy resources to Ukraine, thus breaching protocol in agreements between CIS member states and despite the fact that the Tjumen oil industry in Russia has been developed with significant human and material resources from Ukraine. On the other hand, it should be recognized that Russian President Boris Yeltsin is under pressure from the International Monetary Fund (IMF) to raise Russian oil prices to the world level – although some have argued this gives Russia an excuse for pressuring Ukraine for other concessions as, for example, the contentious issue of nuclear weapons. Whatever the opinion held, the steady rise in oil and gas prices has imposed serious financial burdens upon Ukraine – a country rich in natural uranium and some coal reserves but virtually no indigenous oil reserves.

for final deposition have not only sharpened the debate surrounding nuclear power in Ukraine, but have also left Ukraine in a state of flux and at times paralyzed when trying to define a nuclear energy policy. This was particularly the case during 1992–1993 when a new ministry-level State Committee on Nuclear Power was created in January 1993, apparently to represent the interests of power station operators. The new committee's standing in relation to the State Committee on Nuclear and Radiation Safety (*DerzhAtom-Nahljad*) – the regulatory and oversight body set up after the collapse of the Soviet Union and headed by Nikolai Shteinberg† – was not made clear from the onset. At about the same time, the former nuclear power station consortium *UkrAtomEnergoProm* (which was, at its inception, placed in charge of esstentially the entire nuclear industry in Ukraine on the level of a government ministry), was relegated to only an advisory position.

French and German regulators have made concrete offers of aid to improve safety at Ukraine's operating plants; and at the time of this writing, Ukraine and the IAEA began negotiations toward a bilateral nuclear power safety agreement.[66] Ukraine's aim is to use this help to establish safety analyses reports for the plants as a basis for decisions on issuing licenses for continued operation. (However, western European experts are growing ever more disenchanted with efforts by eastern European nations to keep unsafe plants running rather than preparing them for shutdown.[67]) Under the former USSR Ministry of

---

† Interestingly, Nikolai Shteinberg was chairman of a commission of the former Soviet Nuclear Oversight Committee (*GosAtomNadzor*) that reinvestigated the causes of the Chornobyl accident. The document his commission produced, О причинах и обстоятельствах аварии на 4-ом блоке чернобыльской АЭС апреля 1986 г. (*On the Reasons and Circumstances of the Accident at the 4th Unit of the Chornobyl NPS on April 26, 1986*) was seminal in the IAEA also reinvestigating the causes of the accident. This eventually led to the publication in January 1993 of INSAG-7 The Chornobyl Accident: Updating of INSAG-1 that shifted the blame away from the operators and onto the design of the RBMK, the lack of proper training for RBMK reactor operators, and generally low level of "safety culture" in the former Soviet nuclear power industry. (See Chapter I)

[66] Mark Hibbs, "Ukraine, IAEA Commence Safeguards Negotiations," *Nucleonics Week*, Vol. 34, No. 40, (October 7, 1993): 11. Unfortunately, as mentioned in the article and as the over-arching problem with virtually all important negotiations Ukraine has with the West, the issue is made more complex by the presence of ex-Soviet nuclear warheads in Ukraine. Fortunately, On November 19, 1993, Ukraine's Parliament overwhelmingly ratified the START-I disarmament treaty as its first formal commitment to eventual complete nuclear disarmament. [Ron Popeski, "Ukraine Ratifies Atom Pact," *The Boston Globe*, (Friday, November 19, 1993): 2.]

[67] Ann MacLachlan, "Disenchantment Settles Over Eastern Nuclear Safety Aid," *Nucleonics Week*, Vol. 34, No. 49, (December 9, 1993): 1.

Atomic Energy there was no licensing of nuclear plants as it is understood in the West, but rather supervision of their operational safety by a national nuclear safety committee (*GosAtomNadzor*) based in Moscow, with regional inspectorate branches. While the Russian Federation has inherited most of the R&D expertise and nuclear organizations of the former Soviet Union, Ukraine finds itself with a relatively large number of operating nuclear reactors (as of January 1, 1994, fourteen reactors at five stations) and relatively little scientific support for safety activities. The loosely organized plant operating consortium *UkrAtomEnergoProm* had agreements with central support offices in Moscow, but the Ukrainian regulators are battling to build a competent and effective safety authority from practically nothing.[68]

[68] Ann LacLachlan, "French and German Regulators to Aid Ukrainian Nuclear Safety," *Nucleonics Week*, (August 27, 1992): 9–11.

Figure III.6
Map of Ukraine and Locations of Nuclear Power Stations

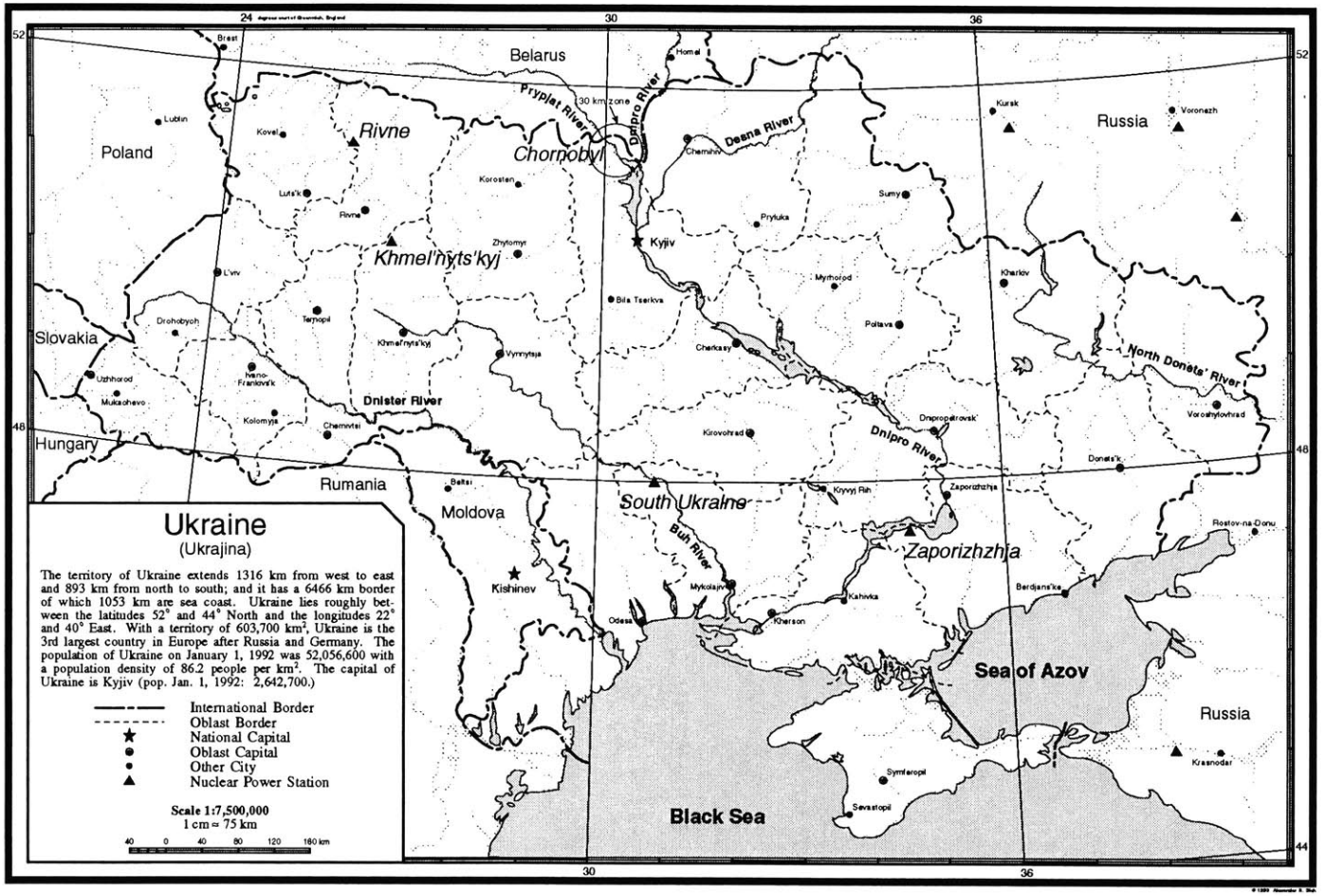


Table III.7
Basic Data on Ukrainian Nuclear Power Reactors

A. Operating Nuclear Power Stations

Station Name	Reactor Unit	Power (MWe) gross/net	Type & Model	Init Crit/ Power Startup
Zaporizhzhja	1	1000/950	VVER-1000 (320)	IX/84 / IV/85
	2	1000/950	VVER-1000 (320)	VI/85 / X/85
	3	1000/950	VVER-1000 (320)	IV/86 / I/87
	4	1000/950	VVER-1000 (320)	XII/87 / I/88
	5	1000/950	VVER-1000 (320)	VI/89 / X/89
Rivne	1	440/361	VVER-440 (213)	XII/80 / IX/81
	2	440/384	VVER-440 (213)	XII/81 / VII/82
	3	1000/950	VVER-1000 (320)	XI/86 / V/87
Khmel'nyts'kyj	1	1000/950	VVER-1000 (320)	XI/87 / VIII/88
South Ukraine	1	1000/950	VVER-1000 (302)	XII/82 / X/83
	2	1000/950	VVER-1000 (302)	XII/84 / IV/85
	3	1000/950	VVER-1000 (320)	IX/89 / XII/89
Chornobyl	1	1000/925	RBMK-1000/I	VIII/77 / V/78
	3	1000/925	RBMK-1000/II	VI/81 / VI/82
TOTAL		**12880/12095**		

B. Reactors Planned or Under Construction

Station Name	Reactor Unit	Power (MWe) gross/net	Type & Model	Startup
Zaporizhzhja	6	1000/950	VVER-1000 (320)	1994-5?
Rivne	4	1000/950	VVER-1000 (320)	1994-5?
Khmel'nyts'kyj	2	1000/950	VVER-1000 (320)	1994-5?
	3	1000/950	VVER-1000 (320)	?
	4	1000/950	VVER-1000 (320)	?
South Ukraine	4	1000/950	VVER-1000 (320)	?
Crimea	1	1000/950	VVER-1000 (320)	?
	2	1000/950	VVER-1000 (320)	?
TOTAL		**8000/7600**		

C. Reactors Shut Down or Construction Cancelled

Station Name	Reactor Unit	Power (MWe) gross/net	Type & Model	Shutdown or Cancelled
Chornobyl	2	1000/925	RBMK-1000/I	X/91
	4	1000/925	RBMK-1000/II	26/IV/86
	5	1000/925	RBMK-1000/III	IV/87
	6	1000/925	RBMK-1000/III	IV/87
Kharkiv	1	1000/?	VVER-1000 ATET	X/87
	2	1000/?	VVER-1000 ATET	X/87
Kyjiv	1	1000/?	VVER-1000 ATET	X/87
	2	1000/?	VVER-1000 ATET	X/87
Odesa	1	1000/?	VVER-1000 ATET	XI/87
	2	1000/?	VVER-1000 ATET	XI/87
TOTAL		**10000/3700+?**		

Table III.8

Summary of Nuclear-Generated Electrical Energy in Ukraine

YEAR	Chornobyl	Rivne	South Ukraine	Zaporizhzhja	Khmel'nyts'kyj	Ukraine Total
1977	602570	0	0	0	0	**602570**
1978	5894722	0	0	0	0	**5894722**
1979	12233084	0	0	0	0	**12233084**
1980	14212778	6788	0	0	0	**14219566**
1981	13439192	1903656	0	0	0	**15342848**
1982	17261002	4160177	22077	0	0	**21443256**
1983	18657219	4251558	2763490	0	0	**25672267**
1984	28059950	5970080	6375657	171850	0	**40577537**
1985	29215132	6028691	13170290	4896767	0	**53310880**
1986	13046522	6101007	12332367	11203103	0	**42682999**
1987	13571548	11409332	8027588	19586595	46788	**52641851**
1988	19697000	12119000	10855259	25379000	3915000	**71965259**
1989	20252000	12605000	8768593	18633000	6236000	**66494593**
1990	17329982	12726025	14426225	24805658	6891372	**76179262**
1991	14477428	11318243	16714037	27084456	5467074	**75061238**
1992	5269556	13147663	17817102	31436880	6060565	**73731766**
1993						
TOTAL	**243219685**	**101747220**	**111272685**	**163197309**	**28616799**	**648053698**

Figure III.7
Nuclear-Based Electricity Generation in Ukraine, 1977–1992

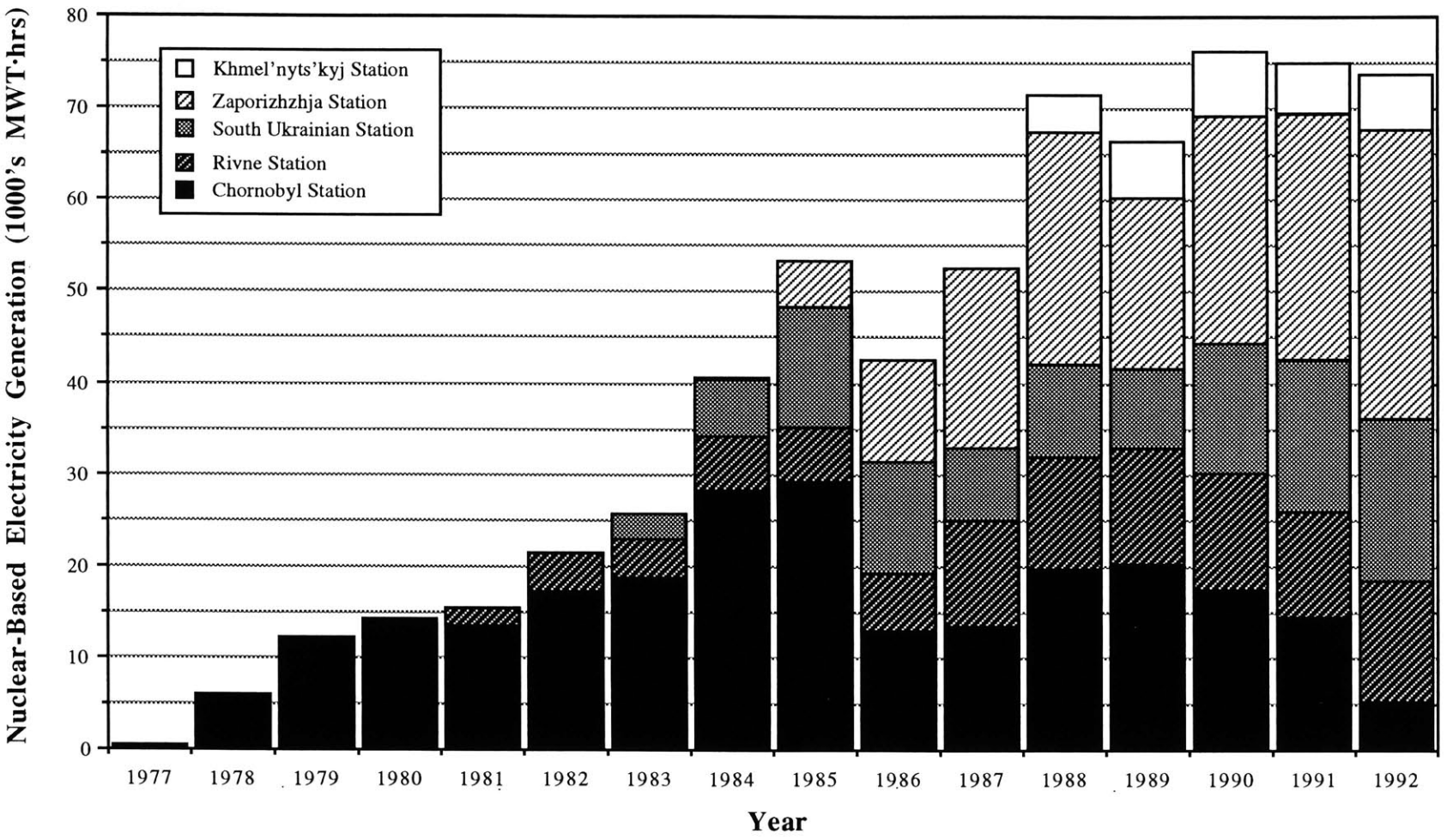


Figure III.8
Electricity Generation in Ukraine, 1967–1992

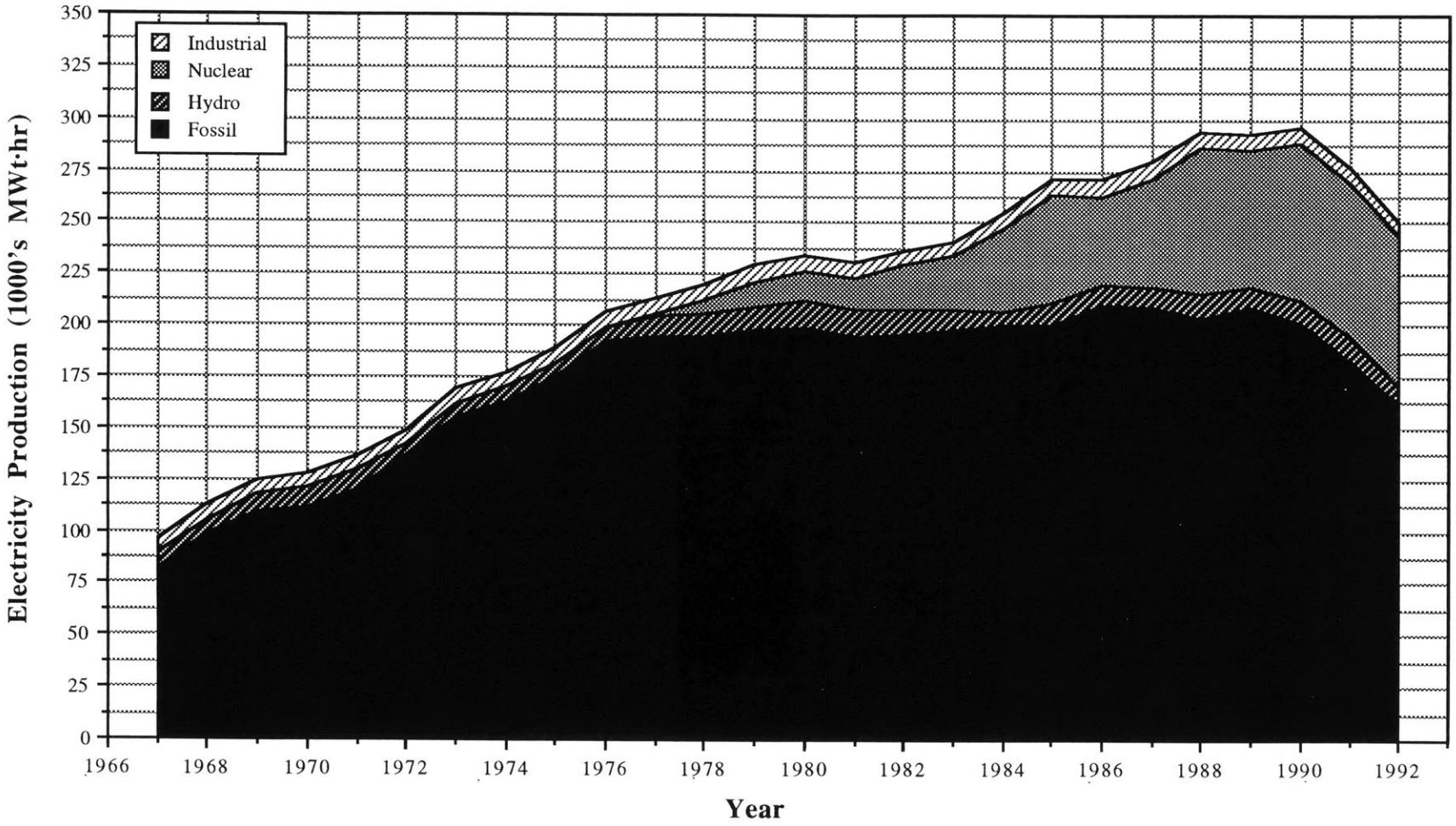


Figure III.9
Fractional Contribution of Electricity Generation in Ukraine, 1967–1992

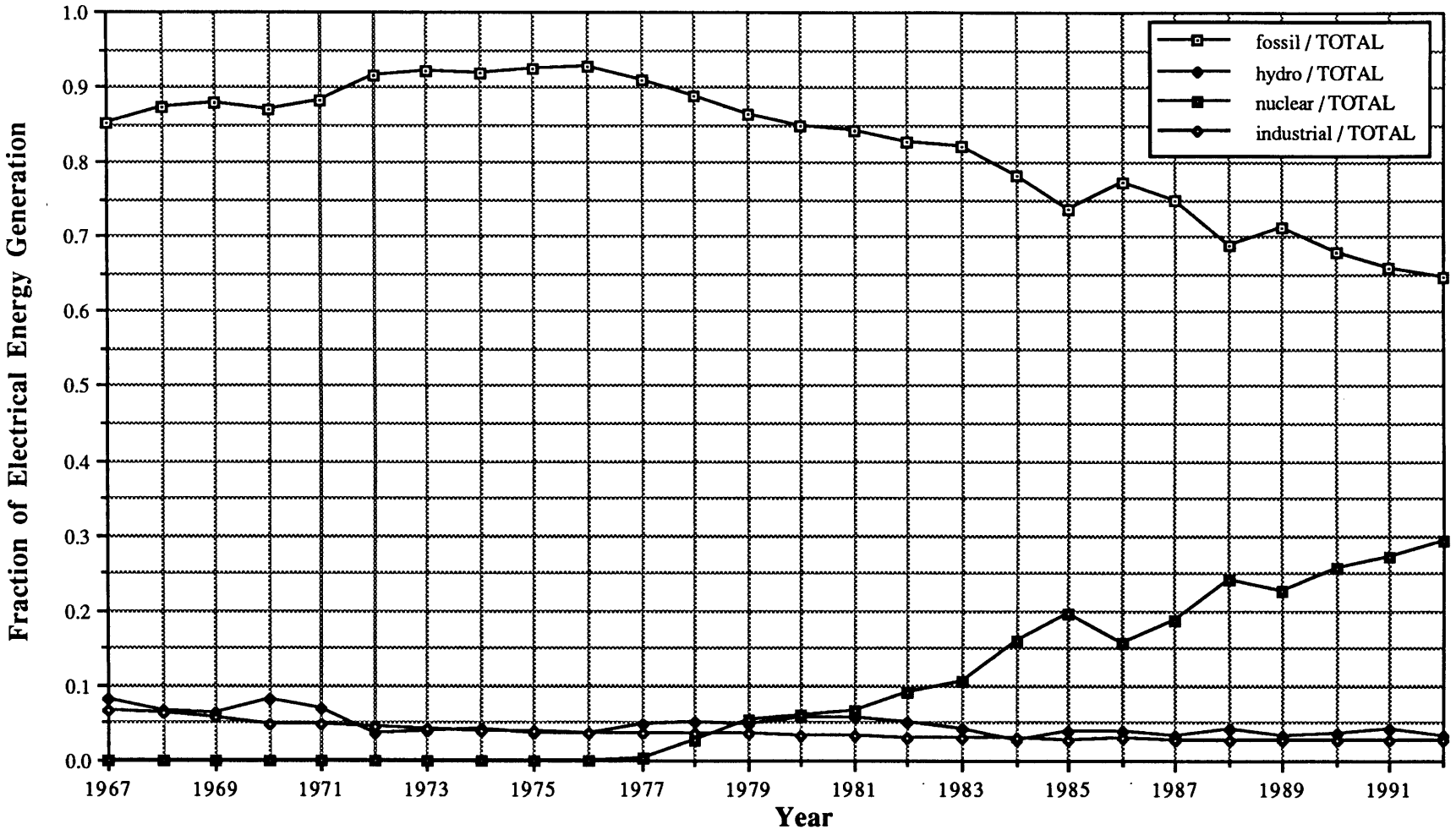
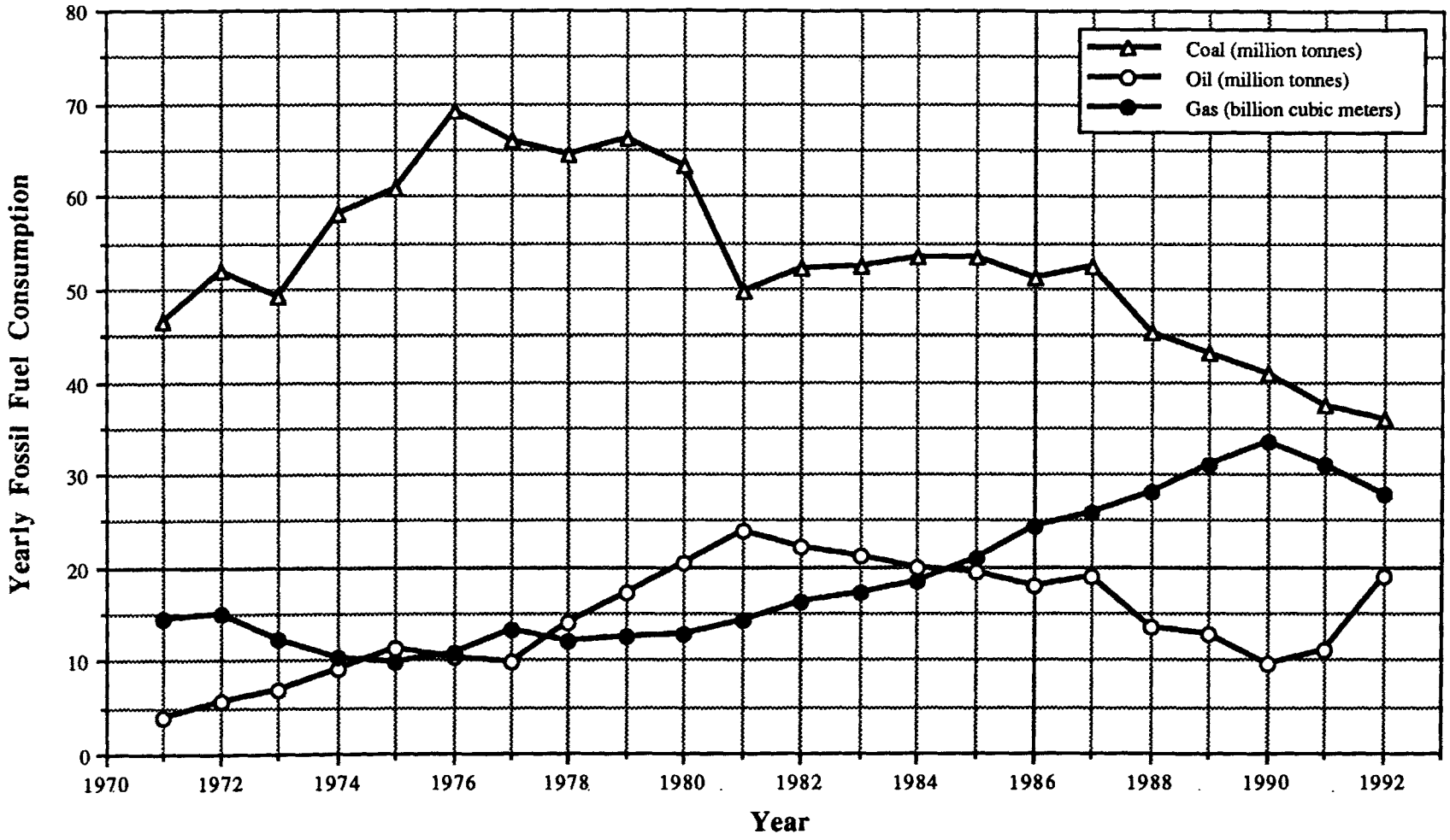


Figure III.10
Fossil Fuel Consumption in Ukraine, 1971–1992



III.3. The RBMK-1000: Technical Description and Characteristics[69]

III.3.1. Core Design

Design deficiencies of the RBMK-1000 reactor at Chornobyl Unit-4 predetermined the severe consequences of the accident.

– A major conclusion of the Shteinberg Commission of the Soviet State Committee for Nuclear Oversight (*GosAtomNadzor*) that reassessed the causes of the Chornobyl accident.[70]

"Operating the RBMK reactors in the ex-Soviet Union is like driving a 1928 Ford... safe only with very special handling."

– IAEA Director General, Hans Blix.[71]

The RBMK is a heterogeneous, thermal neutron, graphite-moderated, channel-type, boiling-water nuclear reactor with on-line refueling. The light water coolant flows upwards in the central "fueled" portion of the core through vertical channels that pierce 1661 graphite stacks of blocks (columns) in the core. The core has the form of a large cylinder with an equivalent diameter of 11.8 meters and height of 7.0 meters. Its central fueled portion is surrounded on the periphery by a reflector in the form of a ring of graphite columns with equivalent thickness of 0.88 meter;[72] and it is covered on the top and bottom by an additional 0.5 meter of graphite reflector – extentions of the core columns with their corresponding channels. (See Figure III.11 below.)

---

[69] The information summarized in this section is outlined in detail in Appendix III.B. Except where indicated by reference notes with additional detailed information, this section is based on section 2.1 of Доллежаль, Н. А. и И. Я. Емельянов, *Канальный ядерный энергетический реактор*, Москва: Атомиздат, (1980): 11–13. In addition to this, other excellent sources of information on the RBMK are NUREG-1250, *Техническое описание конструкции реактора РБМК-1000*, *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие»*, *Восстановление динамики разрушения....*

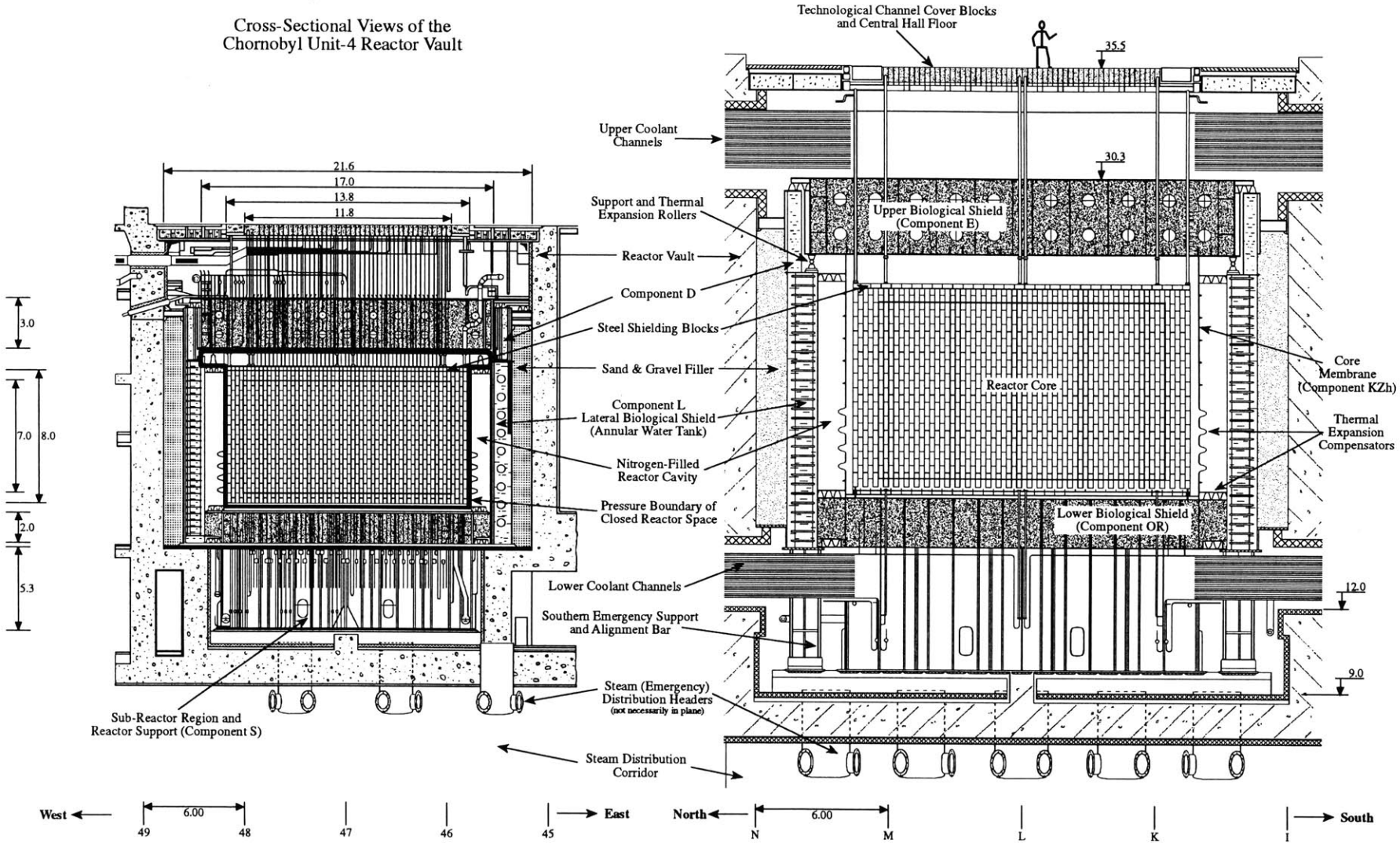
[70] INSAG-7, 85.

[71] Ariane Sains, "Blix: RBMKs Can't Meet Safety Norms, But Nuclear is Necessary," *Nucleonics Week*, (September 24, 1992): 14.

[72] The radial thickness of the reflector is 1.0, but graphite blocks forming the outer ring is pierced through the entire length by steel rods which provide rigidity and are cooled by water to remove heat from the stack. NUREG-1250, 2-8.

Figure III.11

Cross-Sectional Views of the
Chornobyl Unit-4 Reactor Vault



The entire graphite (ρ=1.65 gm/cm^3) superstructure consists of 2488 vertical columns of 250 x 250 mm blocks that come in various lengths: 200 mm, 300 mm, 400 mm, and 600 mm – the latter making up the core and peripheral reflectors, while the rest the top and bottom reflector. The entire length of each of the 1884 *core* (i.e., central "fueled" as opposed to the peripheral reflector) columns along the central axis is nominally hollow with a 114 mm inner diameter. All of these core "hollows" in turn contain Zircaloy-2.5 pressure tubes that are called by Soviet designers either "technological channels" that contain fuel assemblies or "control channels" that contain control and scram assemblies.

There are 1661 technological channels in the core. The outer part of the channel (the pressure tube which contains the fuel assemblies and coolant) is made from a Zirconium–2.5% Niobium alloy (Zircaloy-2.5) with an outer diamter of 88 mm and a wall thickness of 4 mm (88 x 4 mm). Between the outer wall of the pressure tube and the inner wall of the graphite block are located 272 graphite rings (see Figure III.12)[73] fitted alternately to the tube and graphite channel, centered about the core midplane, and running along the active fuel length for 5.44 m.[74] These provide a path for heat flow from the graphite stack, through the pressure tube, and into the coolant. They also allow pressure tube expansion within the graphite column while holding it firmily in place. From the given information (see also ahead description of control channel graphite contact rings and control rod followers), the total mass of graphite in the core is calculated to be 1882.2 tonnes. Approximately 6% of the reactor's thermal energy (188.4 MWt at 100% power) is generated in the graphite stack.[75] Nominal average operating temperature for the graphite columns is 600 °C, while maximum allowable measurable temperature is 750 °C.[76]

---

[73] Дементьев, 70–71.

[74] *Техническое описание конструкции реактора РБМК-1000*, 37.

[75] Дементьев, Б. А. *Ядерные энергетические реакторы: Учебник для вузов*. Москва: Энергоатомиздат (1990): 172.

[76] Ю. С. Панитков, И. А. Банель, А. М. Бернадская, В. П. Бескоровайный, Н. В. Горбачева, Н. М. Груша, В. В. Котович, Л. Н. Козловская, В. Г. Молодых, Н. К. Мышкина, Н. В. Нитей, В. В. Ничипор, Т. А. Павлина, В. В. Скурат, Л. А. Станкевич, Э. М. Тащилова. *Отчёт о науч-но-исследовательской работе: Восстановление динамики разрушения 4-го блока ЧАЭС на основе физического и математического моделирования: Разработка физической модели чернобыльской катастрофы*. Минск, Беларусь: Академия Наук Беларуси, (1991):10.

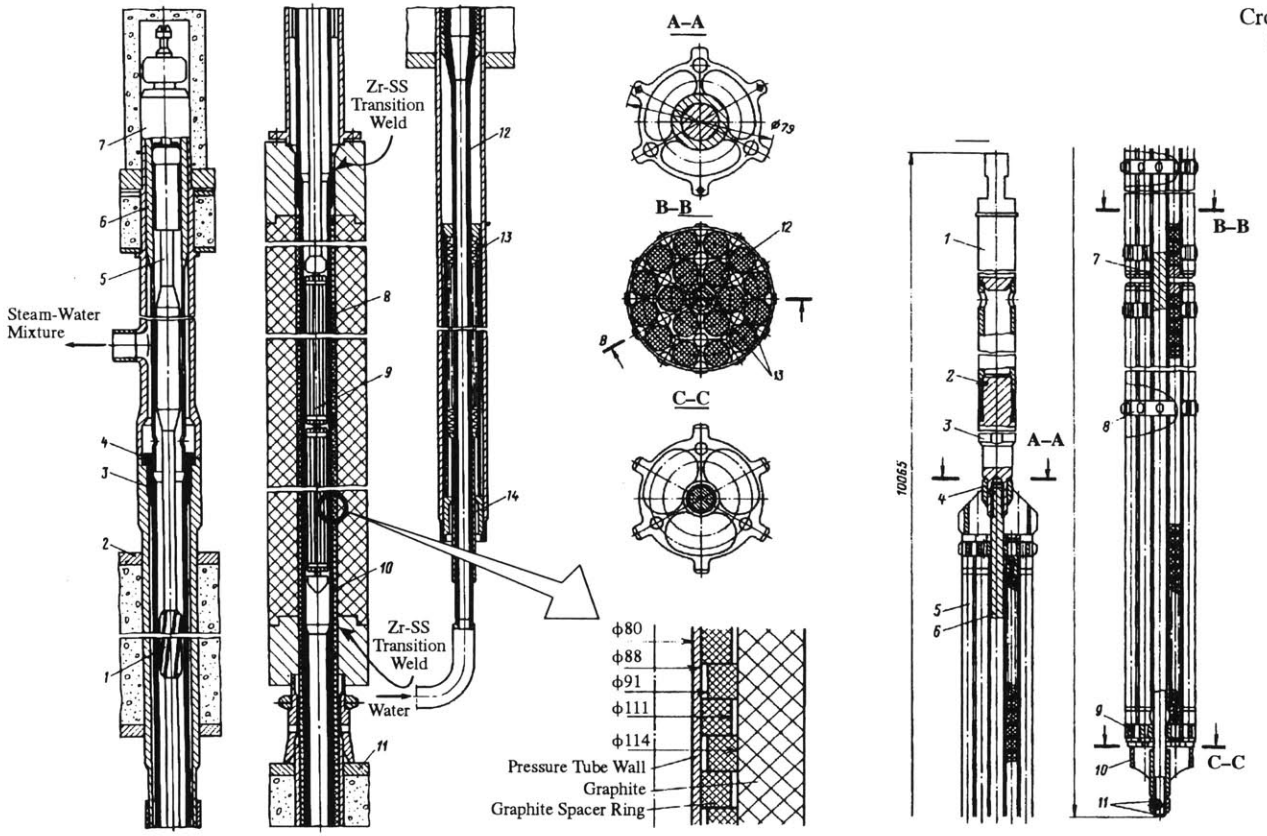


Figure III.12
Cross-Sectional Views of a Technological (Fueled) Channel and an RBMK-1000 Fuel Assembly

KEY

RBMK-1000 Fuel Assembly

1. Suspension/Hanger
2. Pin
3. Transition Adapter
4. Stem/Shank
5. Fuel Element
6. Carrier/Support Rod
7. Sleeve
8. Nose/End Cap
9. Nuts

RBMK-1000 Technological (Fueled) Channel

1. Biological Shielding Plug
2. UBS Stainless Steel Cover Plate
3. Stainless Steel Tube (08X18H10T)
4. Welded "Trendil" Seam
5. Fuel Assembly Suspension
6. Channel Cartridge
7. Channel Cap
8. Graphite Thermal Expansion Rings
9. Fuel Assembly
10. Zr–2.5%Nb Pressure Tube
11. LBS Stainless Steel Cover Plate
12. Stainless Steel Tube (08X18H10T)
13. Thermal Compensator Bellows
14. Stuffing Box (Sealing Gasket)

Located within a technological channel are two fuel assemblies stacked one on top of the other separated vertically by 20 mm; and the entire assembly unit is 10015 mm in length[77] Each assembly consists of 18 fuel rods, with an active fuel length of approximately 3.5 meters, distributed in two concentric rings of six and twelve rods about a central hollow Zircaloy-2.5 support rod 15 x 1.25 mm and held in place by stainless steel spacer grids at ten positions along the length and one at the end of an assembly.[78] The central support rod can contain either a 12 mm diameter solid rod of Zircaloy-2.5 or another hollow Zircaloy-2.5 tube 12 x 2.5 mm, which in turn contains free space for detector motion along the length of the two assemblies. Light water coolant enters each fuel channel from the bottom and during normal operation begins to boil approximately 2.5 meters above bottom level of the active fuel zone,[79] while nucleate boiling occurs over the remainder of the active fuel length. As it reaches the top of the active fuel zone, the average steam quality across the core is 14.5%.

The 13.5 x 0.9 mm fuel rods[80] (Figure III.13)[81] are made from a Zirconium–1.0% Niobium alloy (Zircaloy-1) containing sintered and dished UO_2 fuel pellets with a diameter of 11.5 mm and height of 15.0 mm with an initial fuel pellet stack height of 3428 mm.[82] The pellets are enriched to 2.0% (by weight) U-235, have a theoretical density of 10.6 gm/cm^3, while the average mass of UO_2 in a fuel rod is 3186 grams.[83] The fuel rod is filled with a helium-argon cover gas mixture at an initial pressure of 0.1 MPa. At initial reactor startup, some of the fuel assemblies are replaced with auxilliary absorbing rods to suppress surplus reactivity of 1.5–1.8% (30–36 RR control rods).[84] The total mass of

---

[77] Ю. С. Панитков, et al, 28–29.

[78] Ibid., 28.

[79] А. С. Герасимов, Т. С. Зарицкая, А. П. Рудик, *Справочник по образованию нуклидов в ядерных реакторах*, Москва: Энергоатомиздат, (1989): 144.

[80] The Soviet/IAEA August 1986 Vienna report, page 5, indicates a wall thickness of 0.825 mm.

[81] Дементьев, 72.

[82] Soviet/IAEA Vienna report, 5. Note there is a substantial difference in fuel rod dimensions as presented by the Soviet report and that presented in Figure IV.3 (Дементьев, 72.)

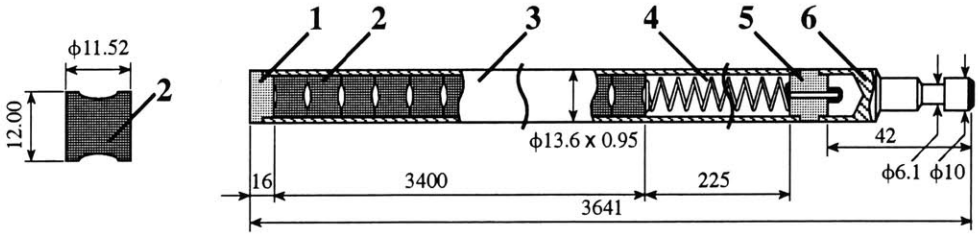
[83] The Soviet/IAEA, pg. 5 report incorrectly states that the amount of fuel in a fuel rod is 3600 gm.

[84] Ibid., 29.

Zircaloy-2.5 and Zircaloy-1.0 in the core are 103 tonnes and 74 tonnes respectably.[85]

The 156 water-cooled graphite columns on the extreme periphery of the reflector (which help cool the reflector) have the same dimensions as the fuel channel blocks but lack the graphite contact rings surrounding the pressure tube. Water flows in from the top of the core, down between an outer 95 x 3 mm outer stainless steel tube and an inner 80 x 3 mm inner stainless steel tube, and then back up and out of the core to a separate, independent system for cooling the periphery reflector columns. All of this is contained in a 113.5 x 4 mm stainless steel tube that lies flush against the inner graphite wall of the column – not only bracing the tube against the wall but also connecting and pinning the graphite block at the top and bottom for rigidity.[86]

Figure III.13
RBMK-1000 Fuel Rod



1. End Plug 2. Dished and Sintered Fuel Pellet 3. Zr-Nb 1% Fuel Cladding 4. Compression Spring 5. Compression Spring Brace 6. Welded Stainless Steel Flange

The control system channels are located in the same way as the fuel channels, that is, along the central axis of 211 out of the core + reflector's 2488 total graphite columns, and have a total length of 22,180 mm. Within each of these channels is located a Zircaloy-2.5 pressure tube 88 x 3 mm which, in turn, contains the control rods and detectors. The pressure tube for the control channels, just as for the fuel channels, has graphite contact rings along its length, but the arrangement and dimensions are more complex.[87] The control

[85] А. С. Герасимов, Т. С. Зарицкая и А. П. Рудик, *Справочник по образованию нуклидов в ядерных реакторах*, (Москва: Энергоатомиздат, 1989), 143.

[86] *Техническое описание конструкции реакторе РБМК-1000*, 43–45.

[87] See description in *Техническое описание конструкции реактора РБМК-1000*, 41. The total

rods themselves, divided into five functional groups (Table III.10),[88] are shown in the core mapping of Figure III.15,[89] and are composed of sections of boron carbide (B_4C, ρ = 1.65 gm/cm^3). The control rod system consists of 211 movable rods divided into manual control rods (RR), two sets of automatic control rods (AR and LAR†), emergency power reduction (scram) rods (AZ), and shortened absorbing rods (USP). (See Table III.9 below for summary of specifications.) A section is composed of an outer aluminum tube 70 x 2 mm and an inner aluminum tube 50 x 2 mm, in between which is located the poison in 65 x 7.5 mm pellets with a total length of 984 mm (Figure III.14). A separate independent cooling system pumps water down the control channel (cooling both the inner and outer walls of the control rod) at a normal operating temperature of 40–60 °C.

Table III.9[90]
Control Assembly Specifications

Control Section	
Absorber Material	Boron Carbide, B_4C
Absorber Density	1.65 gm/cm^3
Clad Material	Aluminium Alloy
Absorber Length/Section	98.4 cm
Total Length/Section	102.4 cm
Outer B_4C Diameter	6.5 cm
Inner B_4C Diameter	5.75 cm
Outer Clad Diameter	7.0 cm
Outer Clad Thickness	0.2 cm
Inner Clad Diameter	5.0 cm
Inner Clad Thickness	0.2 cm
Displacer or "Follower" Section	
Displacer Length/Section	100 cm
Displacer Material	Graphite
Cladding Material	Aluminium Alloy
Clad Diameter	7.4 cm
Clad Thickness	0.25 cm

volume of graphite over the core in these contact rings is 2.152 x 10^7 cm^3.

[88] *Техническое описание конструкции реактора РБМК-1000*, 60. Note that the first generation RBMK-1000 had 1693 Technological Channels and 179 control channels.

[89] Дементьев, 73.

† The LAR rods define twelve local zones in the reactor core and are controlled by two detectors close (<1 mm) to each rods. In the 10–100% power range the LAR rods are used to automatically regulate overall power. They have (had) a limited insertion & withdrawl speed of 0.2 m/sec. Twelve rods moving out at the same time and at the maximum rate insert approximately 0.7 β_{eff}/sec.

[90] See NUREG-1250, Chapter 2 for more information.

Table III.10
Summary of Reactor Channels and Sensors

I. Technological (Fueled) Channels

A. Fueled Channel 1 [TK] 1353
These contain only fuel assemblies (active fuel length ≈ 7 m.)

B. Fueled Channel 2 [TK + DKE] 130
In addition to fuel assemblies, these contain beta emission detectors for energy generation control based on the radial flux distribution.

C. Fueled Channel 3 [TK + GGK] 130
In addition to fuel assemblies, these contain compensated ion chambers (graduated gamma chambers).

D. Fueled Channel 4 [TK + LRM] 48
In addition to fuel assemblies, these contain detectors for the local power regulation system.

1661

II. Reflector (Non-Fueled) Channels

A. Graphite Reflector Channel 1 444
A solid column of graphite.

B. Graphite Reflector Channel 2 156
A graphite column with water cooling.

C. Graphite Reflector Channel 3 4
A graphite column with fission chambers.

604

III. Control Channels (SUZ)

A. Manual Regulation [RR]† 139
Operator controlled – a portion is used to shape power while the rest are reserve; composed of five sections, total length 5120 mm.

B. Scram [AZ] 24
Scram assemblies are normally withdrawn from the core; composed of five sections, total length 5120 mm.

C. Overall Automatic Power Regulation [OAR] – no followers 12
Maintain total (overall) reactor power. Three sets of four ganged rods that operate on signals from ionization chambers external to the core; composed of five sections, total length 5120 mm.

D. Local Automatic Regulation [LAR] – no followers 12
Move independtly of each other to maintain power shape using signals from the four lateral ionization chambers; composed of five sections, total length 5120 mm.

E. Axial Power Regulation (Shortened Absorber) [APR] 24
Enter from the bottom and manually controlled, used to control the axial power shape; composed of three sections, total length 3050 mm.

F. [Auxiliary Absorber Rods] ..... [240]
At initial startup, these take the place of TK channels, and are replaced with fuel as burnup increases.]

211

IV. Non-Fueled Sensor Channels
Contain beta emission detectors distributed at seven different elevations for energy generation control based on the axial flux distribution.
(12 x 7 = 84 detectors total) **12**

TOTAL REACTOR CHANNELS **2488**

Table III.10 (con't)

V. Monitoring Instrumentation

A. Reflector Temperature Monitors ..... 9 x 3
Monitor temperature of graphite channels in the reflector; located at three different elevations.

B. Core Temperature Monitors ..... 8 x 3
Monitor temperature of graphite channels in the core; located at three different elevations.

C. Core Cover Plate Temperature Monitors 381
Monitor temperature of the Upper and Lower Biological Shields.

D. Core Cover-Gas Humidity/Temperature Monitors ..... 4 x 511 = 2044
Monitors leaks in the pressure tubes; (25.975 m, 23.945 m 21.845 m, 19.745 m).

E. Fuel/Control Channel Flowrate Measurement 1661/227

F. Coolant Activity Measurement 1661

G. Radial and Vertical Power Measurement ..... (12 x 7) + 130 = 214

VI. Ionization Chambers for Power Monitoring

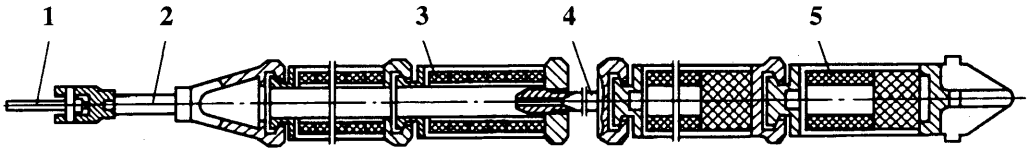
A. IC-1 "Active" 8
Ionization chamber over the operating range 5% – 100% power.

B. IC-2 "Hot Standby" 8
Ionization chamber over the operating range 5% – 100% power.

D. IC-3 Low Power Range 8
Compensated ionization chamber over the operating range 0.5% – 10% power.

† Manual control is provided by 139 manual control (RR) rods. These rods are divided into four groups as a function of their location in the reactor. One group is located in the periphery of the core, and the remaining three are located centrally in the core. The central rods are divided into three regular, intermixed lattices. Control of excess reactivity is accomplished by the RR rods of one of these central groups and by the peripheral rods, which are moved up or down to equalize the current in the peripheral ionization chambers. The rods of each central group are moved sequentially to maintain the position within 0.5 m of each other. The rods of the two other central groups are at the extreme upper or lower positions depending upon the reactivity reserve. [*Report of the U.S. Department of Energy's Team Analyses of the Chernobyl-4 Atomic Energy Station Accident Sequence*, (DOE/NE-0076; DE87 003614) Washington, D.C.: U.S. Department of Energy, (November 1986).] More information on the operation of the control assembly system is contained in this report.

Figure III.14[91]
RBMK Control Element Design



1. Belt 2. Aluminum Alloy Support Stem 3. B_4C Annular Control Pellet 4. Aluminum Alloy Connector Stem 5. Annular Graphite Pellets in Displacer (Follower) Section

[91] Дементьев, 74 and NUREG-1250, pg 2-31.

Figure III.15
RBMK-1000 Core Coordinate System, and
Technological Channel and Detector Mapping

Technological (Fueled) Channels

- I.A. Fueled Channel 1 [TK]
- I.B. Fueled Channel 2 [TK + DKE]
- I.C. Fueled Channel 3 [TK + GGK]
- I.D. Fueled Channel 4 [TK + LRM]

Reflector (Non-Fueled Graphite) Channels

- II.A. Graphite Reflector Channel 1
- II.B. Graphite Reflector Channel 2
- II.C. Graphite Reflector Channel 3

Control Channels (SUZ)

- III.A. Manual Regulation [RR]
- III.B. Scram [AZ]
- III.C. Overall Automatic Power Regulation [OAR]
- III.D. Local Automatic Regulation
- III.E. Axial Power Regulation (Shortened) [APR]

Non-Fueled Sensor Channels

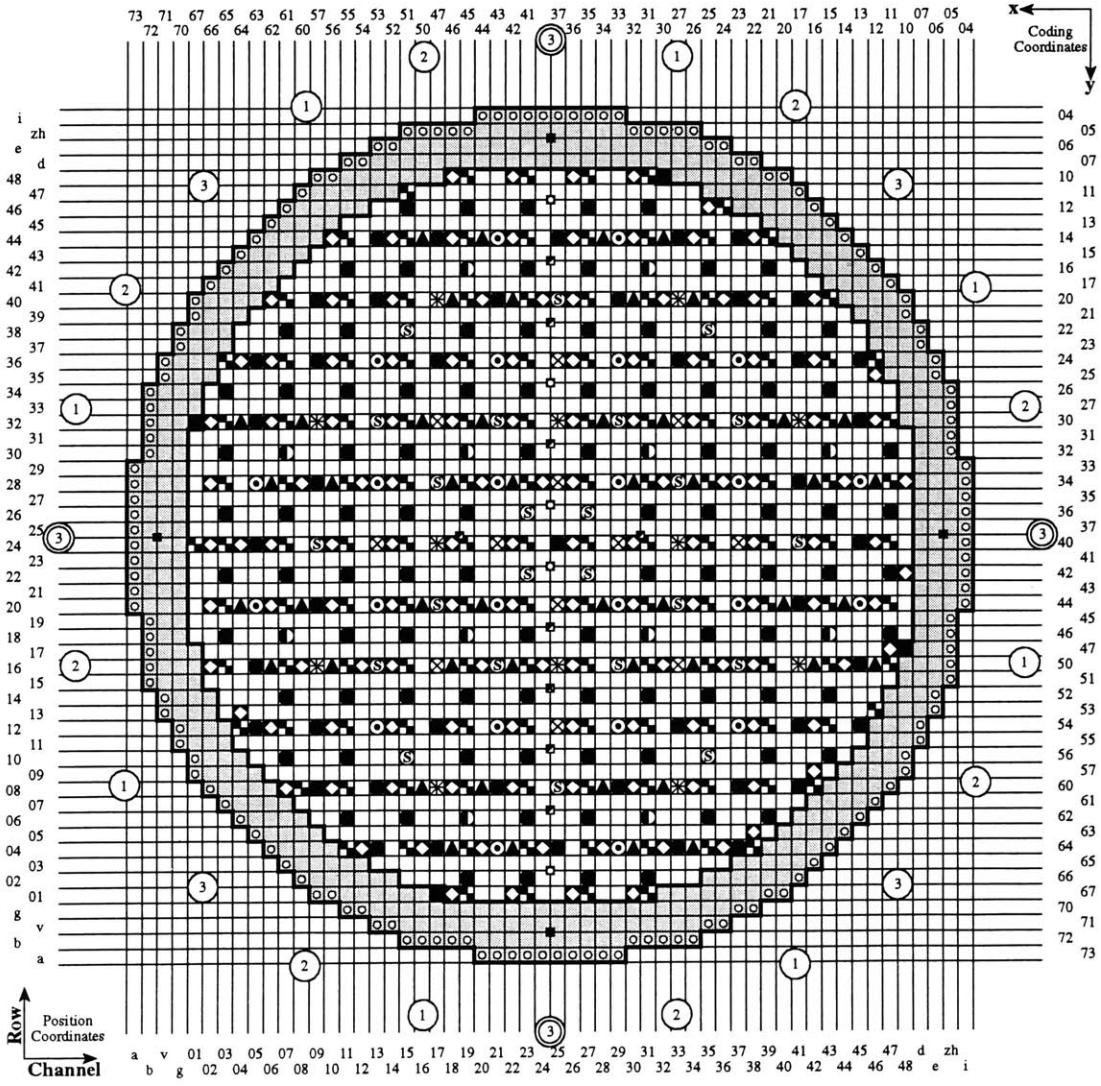
- IV. Beta Emission Detectors at 7 Elevations

Monitoring Instrumentation

- V.A. Reflector Temperature Monitor (at 3 elevations)
- V.B. Core Temperature Monitors (at 3 elevations)
- V.C. Temperature Monitors in Upper/Lower Core Plates
- V.D. Core Cover Gas Humidity Monitor

Ionization Chambers (in Lateral Biological Shield Tanks)

- (1) VI.A. IC-1 Operating Power (5%–100%) "Active" Ionization Chamber
- (2) VI.B IC-2 Operating Power (5%–100%) "Hot Standby" Ionization Chamber
- (3) VI.C. IC-3 Low Power (0.5%–10%) Compensated Ionization Chamber



A characteristic of these control rods is that they have "followers" or "displacers" (with the exception of the AR* rods) connected to the bottom poison section. This is reversed for APR rods which enter from the bottom and thus have the follower (leader, in this case) located above the poison (see Figure IV.3 in Chapter IV). The design of these followers is now known to be responsible for the accelerated rise in core power (ironically, by the operator's action of scraming the reactor) seconds before the explosions destroyed the reactor. The followers are five-sectioned hollow 74 x 2.5 mm tubes composed of an aluminum alloy with a total length of 5000 mm, within which are located graphite pellets (Figure III.14). As a control rod is raised out of the core, the aluminium-graphite follower replaces it helping to "smooth out" the local neutron flux. (Recall that in this type of reactor, the water acts as a strong poison.) When fully withdraw, the end of the graphite follower is located 1000 mm above the bottom of the active fuel zone; so that in this area the reactor is being poisoned by a column of water. As the fully withdrawn rod is reinserted, positive reactivity is inserted at the bottom of the core – by virtue of the replacement of the water column by the aluminum follower. The AR rods have no followers so that when withdrawn from the core, water replaces them.

III.3.2. Major Reactor Systems and Reactor Building Description†

RBMK reactors were built in pairs within one large main building, which permitted the construction of the main structures to begin at the same time while allowing flexibility in construction planning and fabrication of secondary equipment (see Figures III.16 – III.19). The overall dimensions of the reactor building, not including the turbo-generator hall but including Units 3 and 4 and the auxilliary support building located between them, is 72 m wide x 160 m long x 75 m high. The RBMK reactor building is generally con-

* For convenience of operation during nominal power conditions, the reactor is divided into twelve independent zones automatically controlled by one OAR assembly and one LAR assembly. The LAR system is divided into three groups of four assemblies. One of the groups is used to regulate low power operation, one for medium power, and one for full power power regulation.

† Please refer to NUREG-1250, Chapter Two which generally provides a good description of the plant design.

structed of reinforced concrete, but thicker walls (> 50–60 cm) are built using prefabricated reinforced form panels. More than 200,000 m^2 of internal building surface in each separate reactor building has a special protective covering stated to be polyethylene, presumably for ease of surface decontamination.[92] The turbo-generator hall adjoining the building is 51 m wide x 400 m long x 30 m high; while the area between the reactor building and the turbo-generator hall is occupied by an intermediate building in which on the upper floors are housed deaerators.[93]

The reactor Central Hall is a large open workspace containing the refueling machine and an upper, high-bay area. The refueling machine, which weights about 450 tonnes, is mounted on a traveling bridge/gantry (free span > 25m, elevation above floor > 30m) and traverses the Central Hall floor (at Level 35.5 m) over the 1872 fuel and control channels in the reactor building's central hall (about nine meters above the core) replacing or switching fuel assemblies at the rate of 1–2 per day.[94] The refueling machine can also be used to move spent fuel assemblies between two spent fuel pools, located a few meters east of the reactor, and the reactor itself. The inside dimensions of the reactor hall are about 24 meters wide x 80 meters long x 35 meters high. The lower bay is constructed of reinforced concrete and has walls about 1.5 meters thick. The massive walls and columns support the refueling machine and provide shielding for the steam separators located adjacent to the Central Hall. Two spent fuel storage pools are located in each reactor hall. The high-bay portion of the reactor hall is a steel frame construction built using precast concrete panel sheathing for the walls. The reactor hall roof, atop the high bay, is supported by steel trusses about six meters deep. The mass of a preassembled roof block is 50 tonnes. The reactor has four roof blocks, and each block is 20 m x 24 m x 6 m.

---

[92] NUREG-1250, 2-15. This is an important point when considering plate-out onto internal surfaces after the accident.

[93] Ibid., 2-16.

[94] The reactor refueling machine is designed to refuel five channels per day while the reactor is at full power, or at least ten channels per day while the reactor is shut down. NUREG-1250, 2-16.

Figure III.16

North-South Cross Section of the Chornobyl Unit-4 Reactor Building (Prior to the Accident) As Viewed from the East

	Component	#	Mass (te)
1.	Reactor Core (graphite only)	1	1850
2.	Component "S" Reactor Support	1	126
3.	Component "OR" Lower Biological Shield	1	280
4.	Component "E" Upper Biological Shield	1	450
5.	Component "KZh" Core Membrane	1	79
6.	Component "L" Lateral Biological Shield	1	592
7.	Component "D" Lateral Biological Shield	1	236
8.	Steam-Drum Separators	4	278
9.	Main Circulation Pump (MCP)	8	67
10.	MCP Electrical Motor	8	33
11.	Main Isolation Gate Valve (800 mm nominal bore)	8	5.7
12.	Intake Header	2	46
13.	High Pressure Header	2	46
14.	Group Dispensing Headers (GDHs)	44	1.3
15.	Lower Water Coolant Piping	1	400
16.	Upper Water-Steam Coolant Piping	1	450
17.	Downcomers (300 mm nominal bore)	1	16
17a.	Main Coolant Circuit Piping (800 mm nominal bore)	1	350
18.	Refueling Machine	1	450
19.	Central Hall Overhead Bridge Crane, Q = 50/10 t	1	121
20.	MCP Overhead Bridge Crane, Q = 50/10 t	2	176
21.	Exhaust Ventilation Plant	30	3.5
22.	Plenum Ventilation Plant	50	3.5
23.	Leakage Tank	2	1.4
24.	Leakage Tank Heat Exchanger	2	0.2
25.	Preventive Maintenance Tank	4	25
26.	Accident Confinement System (ACS)	1	270
27.	Check Valve	11	2.5
28.	ACS Release/Bypass Valve	8	2.0
28a.	Steam Distribution Header (SDH)	11	—
29.	ACS Condenser	36	3.7
30.	Carriage–Container	1	146
31.	Overhead Crane, Q = 30/5 t	1	45
32.	Turbo-Generator	2	3500
33.	Condenser	2	–
34.	Moisture Separator – Steam Superheater	8	15
35.	Low-Pressure Heater	4	37.5
36.	First Stage Condensate Pump	6	2.5
37.	Turbo-Generator Hall Overhead Crane, Q = 125/20 t	1	211
38.	Deaerator	2	45
39.	Pipe Aisle	1	–
40.	Modular Control Board	1	–
41.	Location Beneath Control Board Room	1	–
42.	House Switchgear Locations	1	–

Reactor Building	
Carbon Steel Piping	**3500 te**
Stainless Steel Piping	**760 te**
Machine Hall	
Carbon Steel Piping	**3825 te**
Stainless Steel Piping	**1300 te**

Location of Control Room:
Axes (B & V, 54) at Level 12.0 m

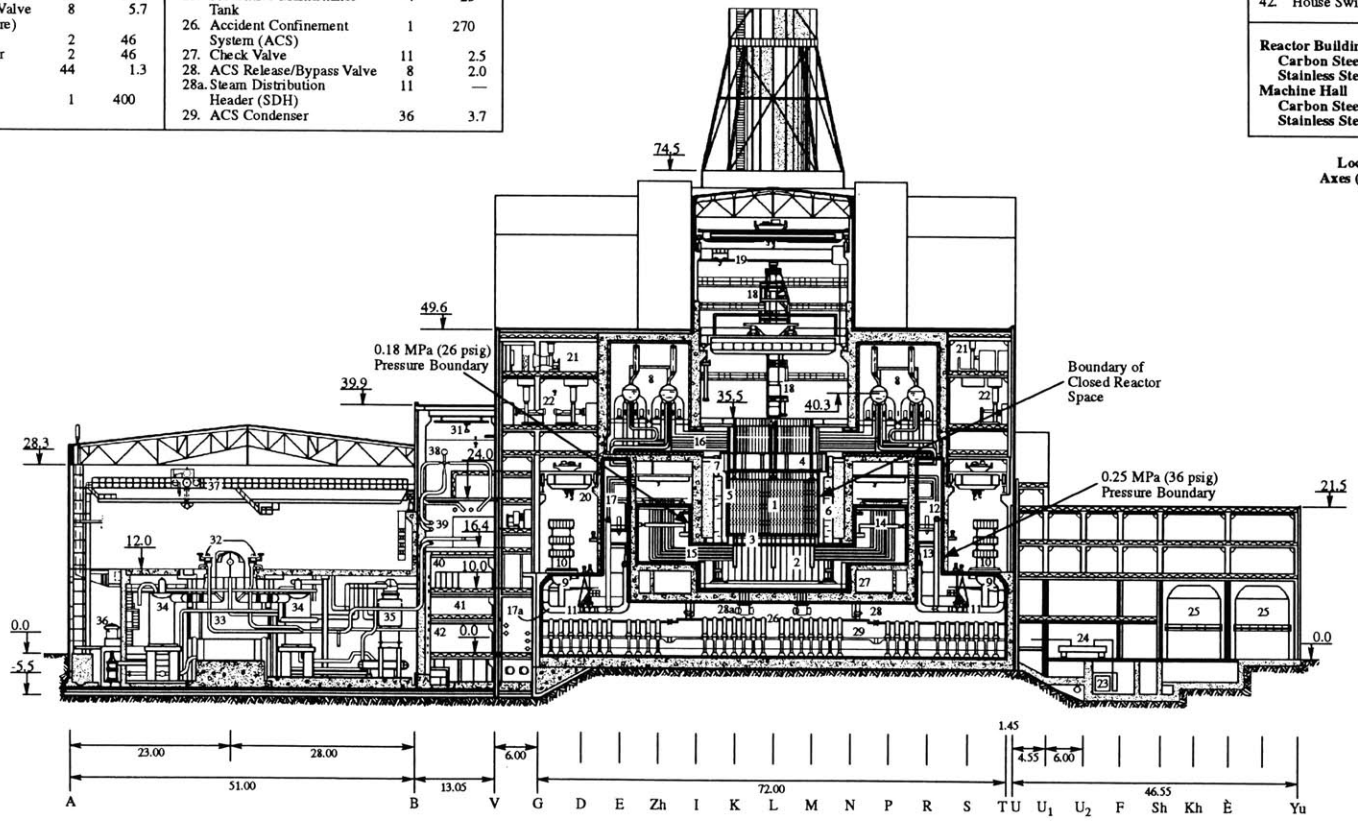


Figure III.17

East-West Cross Section of
Chornobyl Units 3 & 4
(Prior to the Accident)
As Viewed from the South

1. Helium-Cleaning System
2. Transport Corridor
3. System to Review Fuel Channel and Fuel Assembly Integrity
4. Exhaust Ventilation Plant
5. Refueling Machine
6. Reactor Core
7. Sub-Reactor Region
8. Control Assembly Cooling System
9. Pressure Suppression Pool
10. Spent Fuel Pool
11. Transport of Technological Equipment
12. Specialized Water Treatment Systems
13. Deactivation Systems
14. Ventilation Shaft

Location of Control Rooms:
Unit-3 — Axes (B & V, 21) at Level 12.0 m
Unit-4 — Axes (B & V, 54) at Level 12.0 m

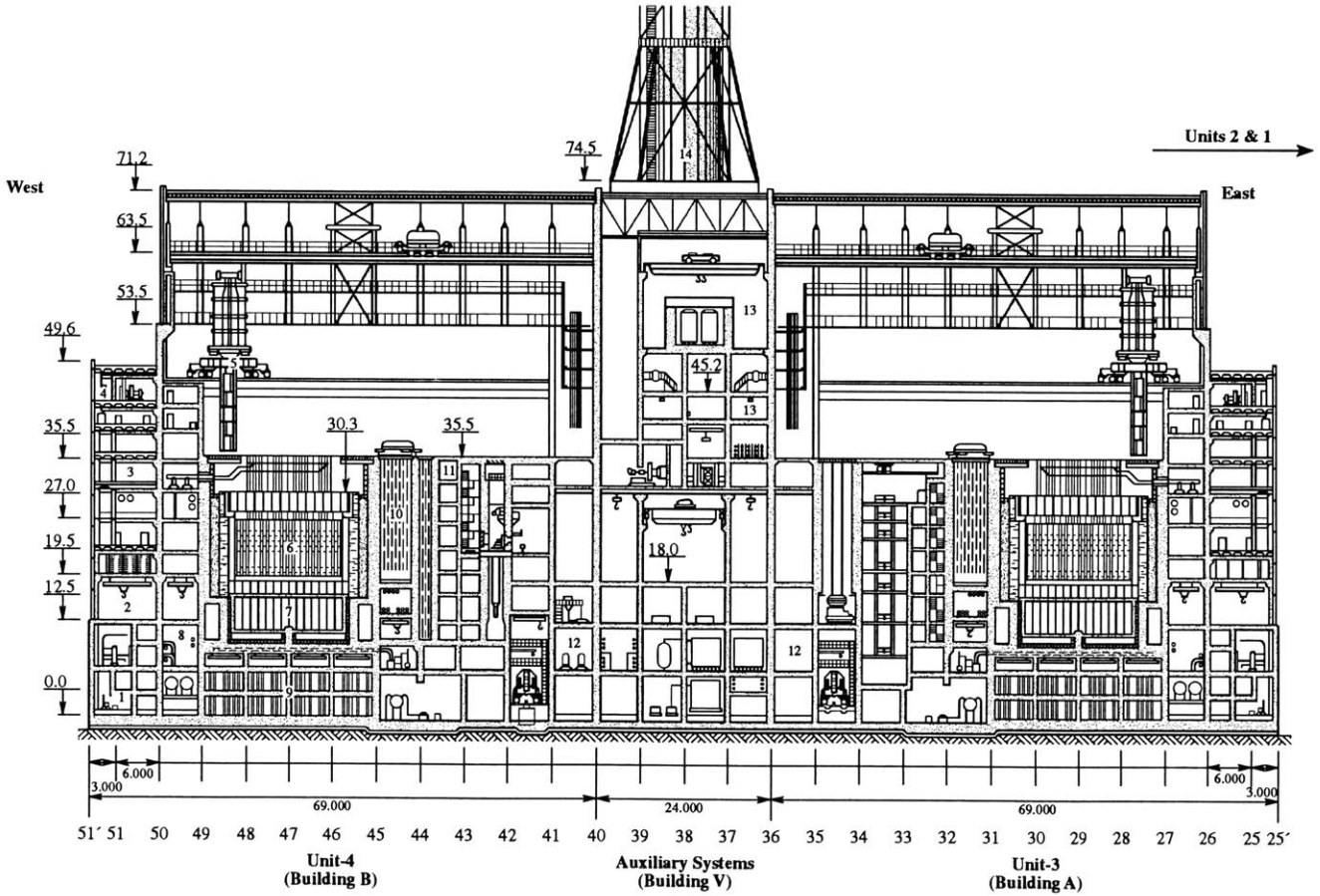
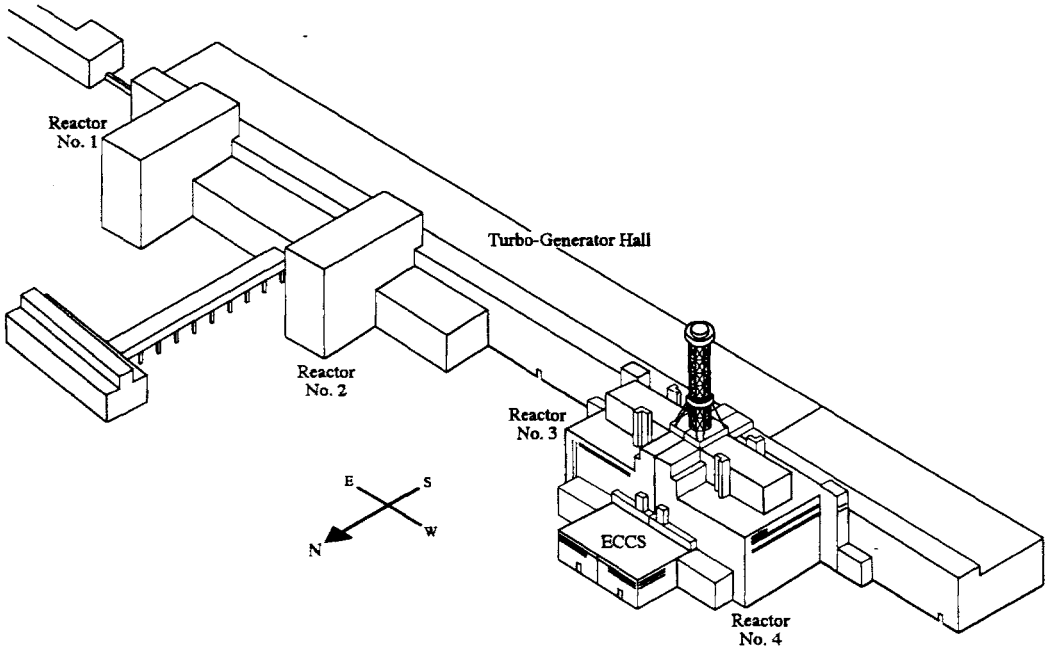


Figure III.18

The Chornobyl Nuclear Power Plant As Viewed from Above
and Prior to the Accident



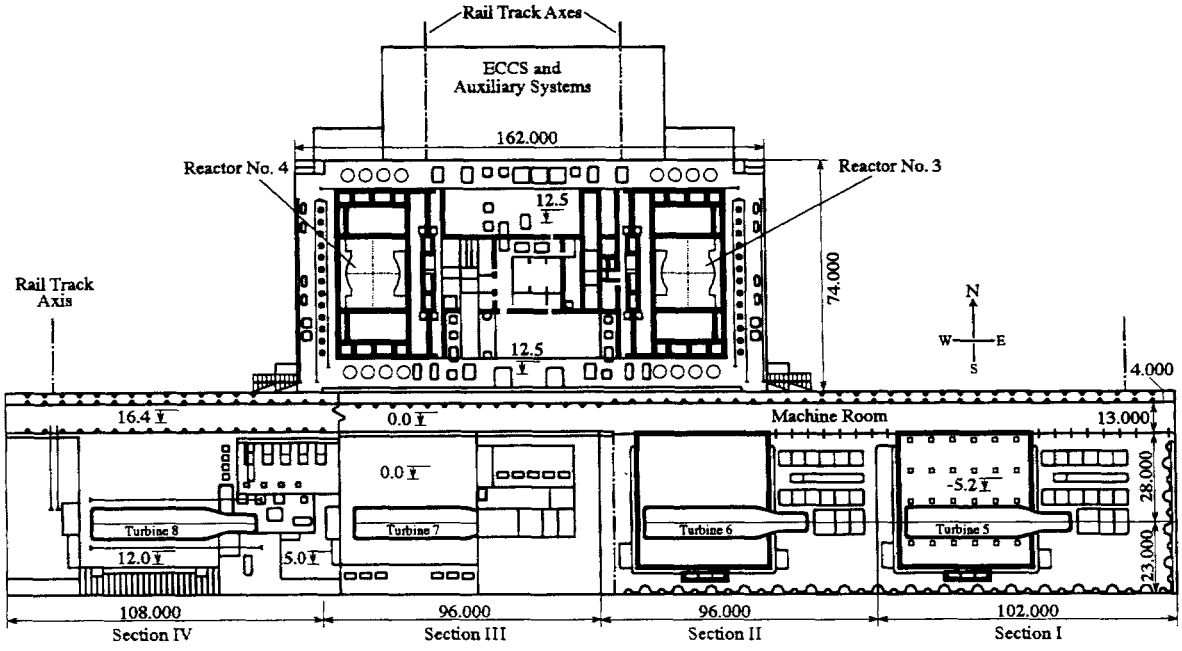
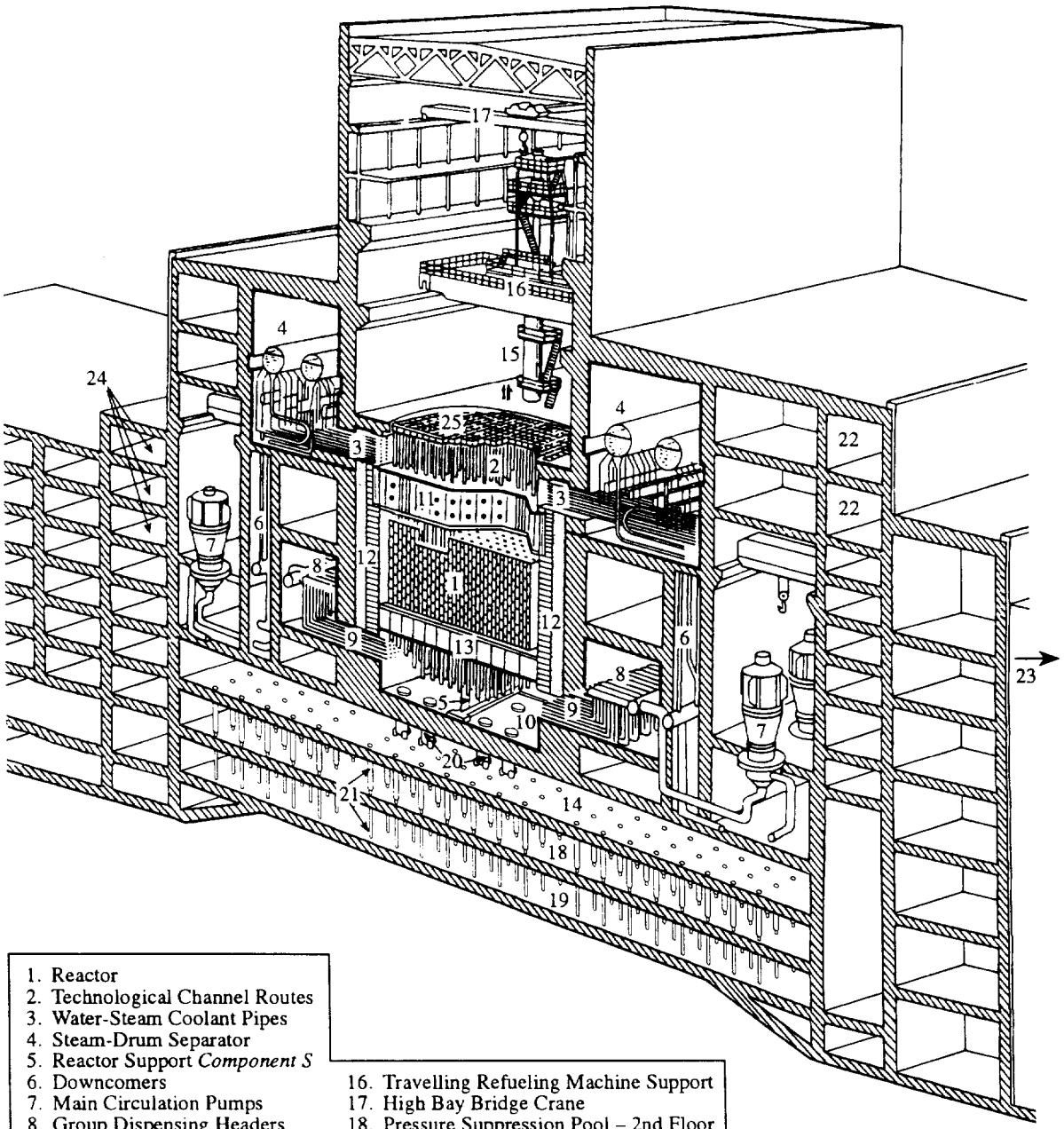


Figure III.19

Sectional View of Chornobyl Unit-4 (A 2nd Generation RBMK-1000)
Prior to the Accident



1. Reactor
2. Technological Channel Routes
3. Water-Steam Coolant Pipes
4. Steam-Drum Separator
5. Reactor Support *Component S*
6. Downcomers
7. Main Circulation Pumps
8. Group Dispensing Headers
9. Water Coolant Pipes
10. Sub-Reactor Region
11. Upper Biological Shield
12. Lateral Biological Shield
13. Lower Biological Shield
14. Steam Distribution Corridor
15. Refueling Machine
16. Travelling Refueling Machine Support
17. High Bay Bridge Crane
18. Pressure Suppression Pool – 2nd Floor
19. Pressure Suppression Pool – 1st Floor
20. Steam Distribution Headers
21. Steam Distribution Pipes
22. Dearator Systems
23. To Turbo-Generator Building
24. Location of ECCS
25. Removable Channel Service Blocks

Each reactor is constructed within its own reinforced concrete cavity or "shaft" (the dimensions of Unit-4's are: length – 21.6 m; width – 21.6 m; depth – 25.5 m; wall thickness – 2.0 m) and has two independent primary coolant loops that serve separate halves of the reactor. (The reactor shaft region, including the core and all metallic superstructures, are design lifetime of 30 years.) All major equipment associated these coolant loops (steam separators, main cooling pumps, feedwater pumps, piping, etc.) are positioned symmetrically along a vertical plane on two opposite sides of the reactor (at Chornobyl Units 3 & 4 they are located on the north and south sides of the core). Four 500 MWe steam turbines (model K-500-05/3000 for Unit-4) are located lengthwise along an east-west axis running through the turbo-generator hall. The two reactors are operated independently from one another, but share an entire series of interchangeable auxilliary equipment that creates a definite operational advantage over other reactors, especially when equipment repair is necessitated.

The reactor's graphite core is located in a sealed cylindrical vessel formed by a 14.52 meters diameter 9.75 meters tall steel shell (*Component KZh* — see Figure III.11) that is 16 mm thick. This reactor "vessel" serves as a gas barrier and primary structural restraint and support for the graphite stack. It is bounded on top by Upper and Lower Biological Shields (*Components E and OR* respectively), and on the sides by a nitrogen gas-filled space followed by a Lateral Biological Shield, *Component L*. The double-walled vessel *Component L* has a 16.6 m inside diameter x 19.0 m outside diameter, surrounds the reactor vessel inside the reactor cavity. The vessel consists of sixteen water-filled compartments and provides shielding in the lateral direction; and the vessel walls are 30 mm thick. The space between the water-filled shield and the walls of the reactor cavity is filled with sand. The space beween the water-filled shield and the reactor vessel is filled with nitrogen. A gas mixture, nominally 80% helium and 20% nitrogen,† is fed into a chamber below the reactor where it is distributed across the bottom face of the reactor.

† During reactor startup or shutdown procedures, this core cover gas is "purged" (replaced) with pure nitrogen.

This mixture flows between the graphite columns providing a heat-conducting medium for transmitting graphite heat (about 188 MWt at full power) to the coolant channels. The reactor vessel contains the circulating gas mixture at a pressure of approximately 0.0015 MPa. The space outside the reactor, between *Components KZh and L*, is filled with nitrogen gas at a pressure of 0.0017 MPa.[95]

The Upper Biological Shield, *Component E*, is a cylindrical shell approximately 17 meters in diameter and 3 meters tall. It consists of two circular (sectioned) plates 40 mm thick welded to a cylindrical outer shell. Additional strength is provided by vertical stiffening ribs and stainless steel pressure tubes welded to cylindrical tube ducts at either face. The space within *Component E* not occupied by tubes or support ribs is filled with serpentenite and nitrogen gas. The entire structure, including superstructure, serpentenite filler, and pressure tubes, nominally has an equivalent mass of about 2400 tonnes. In addition to providing biological shielding, the entire structure (which rests on 16 rollers to accomodate thermal expansion) also provides support for the weight of the fuel channels, control rod drive channels, the upper reactor outlet piping, and the removable floor covering (*Component G*). The Lower Biological Shield, *Component OR*, consists of two section each two meters tall: an inner cylindrical section similar to *Component E*, and an outer hollow cylinder surrounding the inner one within the thermal compensator (expansion joints) region surrounding the reactor. The inner section has a diameter of 14.5 meters, while the outer section has a diameter of 16.6 meters. The central section transmits the load of the core, reflector, and lower coolant piping to the cross-shaped reactor support (*Component S*) immediately beneath it. The nominal total mass of *Component OR* is about 1200 tonnes. The main reactor support, *Component S*, is made of two steel plates with stiffening ribs 5.3 m tall, (40 mm thick, and a total mass of 109.4 tonnes) placed perpendicularly to each other in a cruciform shape. This support in turn transmits the weight of the lower shield and the reactor to the building's foundation.[96]

---

[95] NUREG, 2-8 – 2-11.

[96] NUREG-1250, 2-12 – 2-13; and Гострой СССР, Чертежи ВНИКИЭТа, Москва, (Ноябрь 1976,

The floor of the Central Hall is constructed of removable sections that allow access to the fuel channels, instumentation leads, and control rod drives. The floor serves as both a radiological shield and a thermal barrier. The removable sections are made of steel structures filled with a iron-barium-serpentenite concrete and rest on the channel ducts of the Upper Biological Shield. Air is extracted from the reactor hall through gaps in the floor to provide for cooling and to prevent the possiblity of radioactive steam entering the reactor building.

III.4. The Vladimir I. Lenin (Chornobyl) Nuclear Power Station

III.4.1. Physical Geography of Regions Surrounding the Station

The Chornobyl Nuclear Power Station is located in the eastern part of a rather large, sparsely-forested region, called the Belarusian–Ukrainian *Polissja* (woodland), along the banks of the Prypjat River at an elevation of 114 meters above sea level. (See Figures III.20 – III.22.) The *Polissja* is the largest peat bog and swamp region in Europe (5,290 km^2 out of a total 18,000 km^2 are peat bog)[97] and consists mainly of soggy forests.* Approximately 15 kilometers southeast of the station at the mouth of the river, the Prypjat flows into the Kyjiv Reservoir and Europe's third longest river, the Dnipro. Of its total 2,201 kilometer length, 981 kilometers of the Dnipro River flow through the territory of Ukraine. The river's basin occupies 65% of the land area of Ukraine (392,400 km^2 out of a total basin area of 504,000 km^2) and approximately 32,000 rivers and streams flow into it including eighty-nine whose lengths exceed one hundred kilometers.[98] After winding through seven major dams, hydroelectric stations, and Ukraine's fertile *Chornozem* (black earth) region, the Dnipro flows into the Black Sea approximately 420 kilometers south of

---

Октябрь 1979). *Component S* itself stands upon a 0.5 m-high stainless steel-plated reinforced-concrete cross on the floor of Room 305/2 (Sub-Reactor Region).

[97] Маценко, Г. О., *Україна в цікавих фактах: Книга рекордів України*, Львів: Слово (1992): 7.

* During 1960–1985 many parts of the area were transformed into agricultural land through large-scale reclamation projects. Ecological systems of this type have a very high retention capacity for radiocesium because it moves very quickly into indigenous flora; and approximately 100,000 km^2 of land including the *Pollisja* region were most seriously affected by the fallout. [Zhores Medvedev, 90.]

[98] Маценко, Г. О., *Україна в цікавих фактах*..., 5.

Figure III.20
Map of the Kyjiv Oblast Showing the Location of the Chornobyl Station and Kyjiv

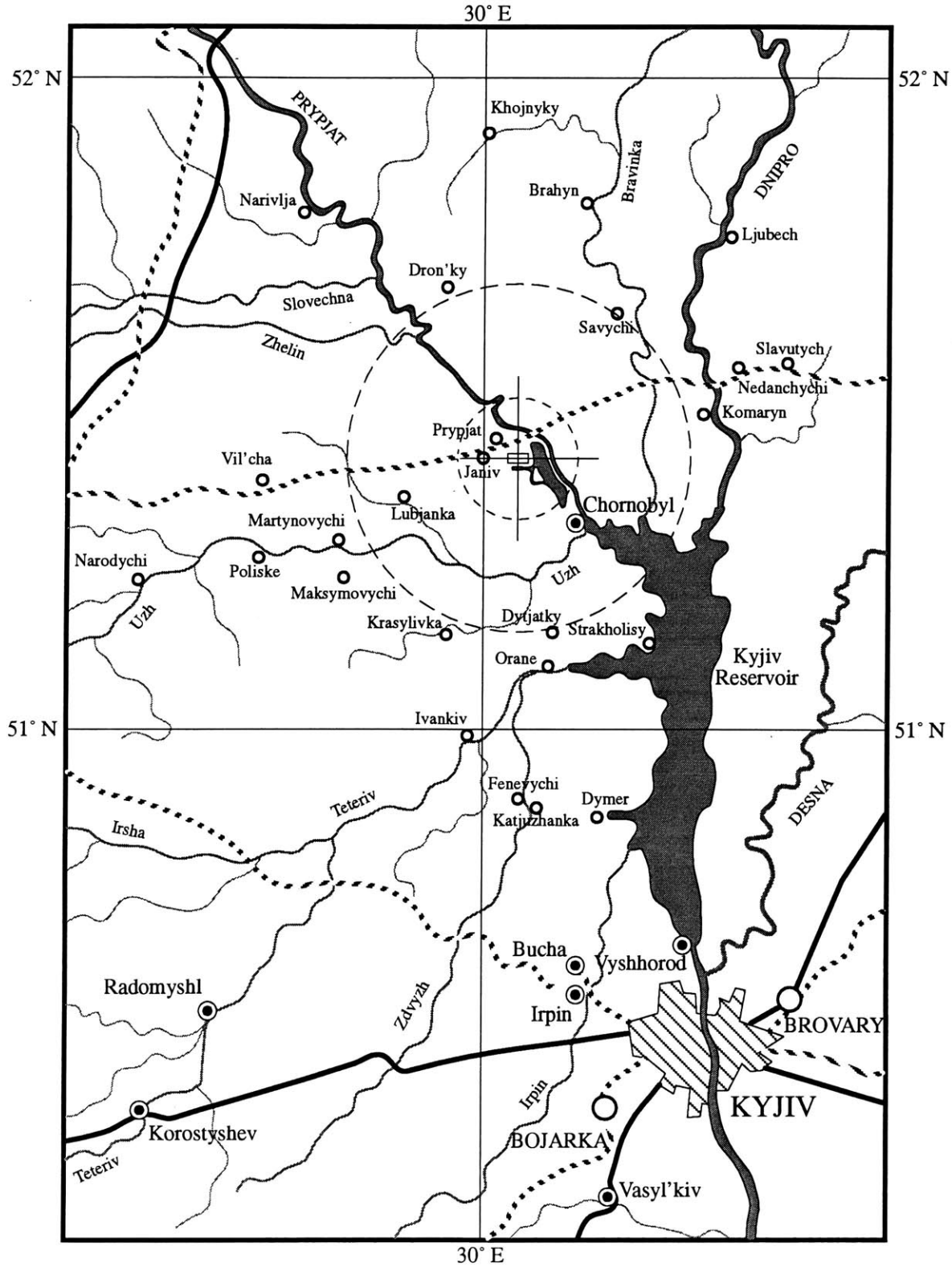
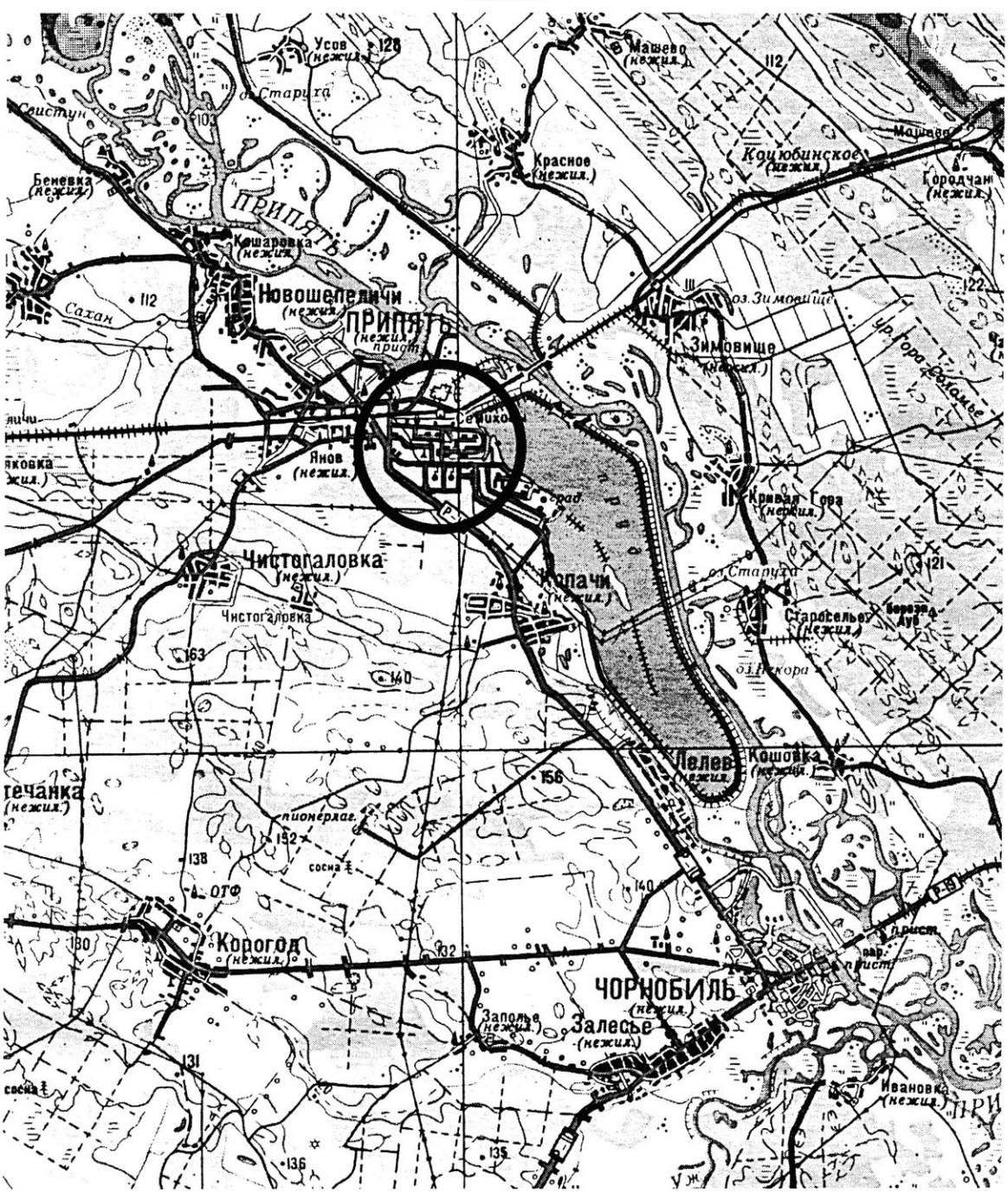


Figure III.21

Map of the Region in the Immediate Vicinity of the
Chornobyl Nuclear Power Station



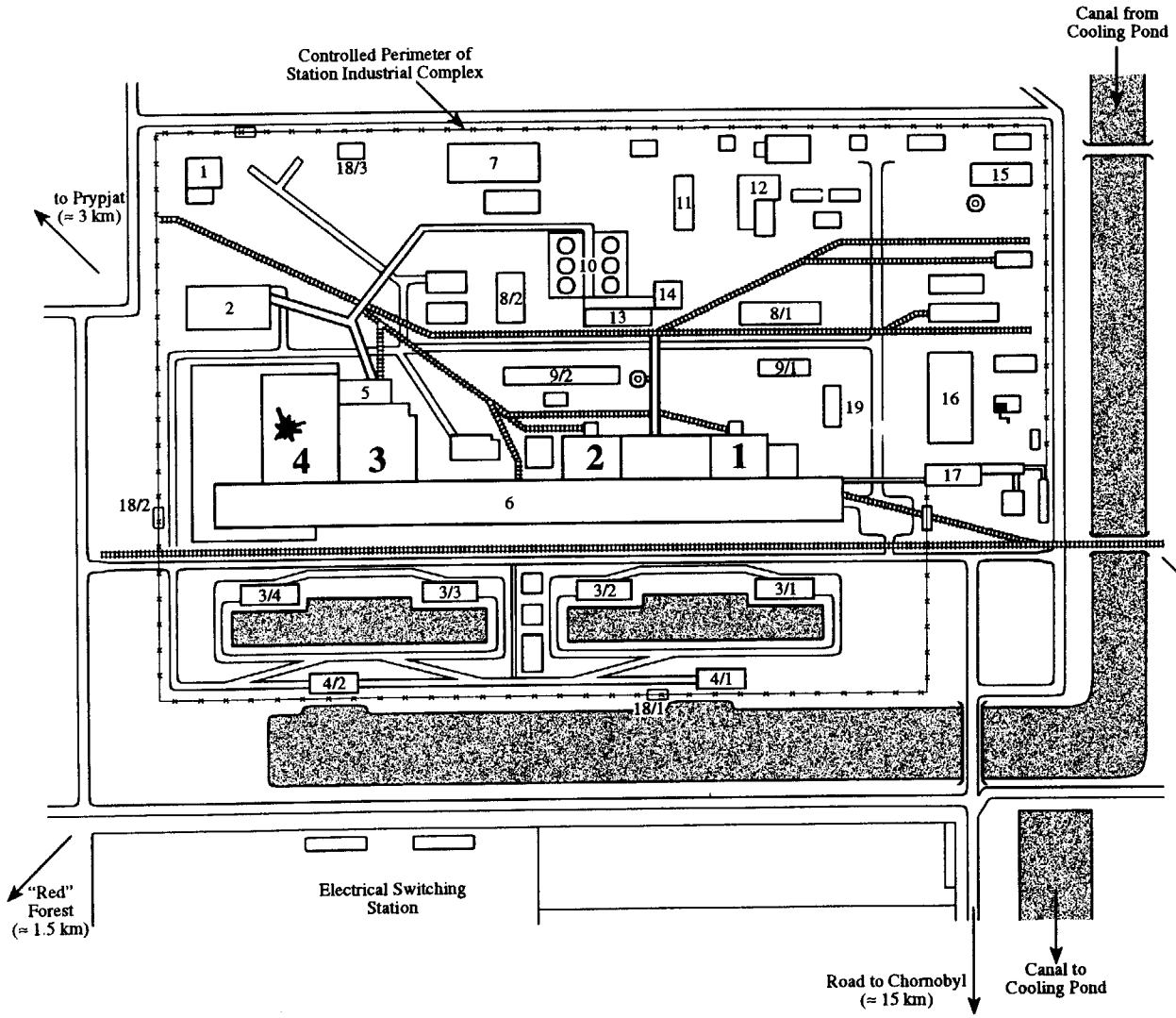


Figure III.22

Map of the Chornobyl Nuclear Power Station (4 x 1000 MWe RBMKs)
(1.25 cm ≈ 100 m)

1 Spent Fuel Storage Building
2 Liquid Waste Repository
3 Condensor Circulation Pumps
4 Canal Cooling-Water Pumps
5 Emergency Core Cooling System (ECCS), Unit-3
6 Turbo-Generator Hall
8 x 500 MWe Turbo-Generators
(total length ≈ 750 m)
7 Tar/Asphalt Preparation & Supply
8 Diesel Emergency Power
9 Liquid N_2 and O_2 Makeup & Storage
10 Liquid & Low-Level Waste
11 Transport Cleaning & Garage
12 Storage & Equipment
13 Waste Water Processing
14 Waste Gas Containers
15 Construction Boiler / Generator
16 Administration Building
17 Visitor Center and Main Entrance
18 Security Entrances
19 Compressor Station

Kyjiv eventually reaching the city of the once ancient Greek settlement, Kherson. Table III.11 below presents general information on the Dnipro Reservoir-Cascade System.

Table III.11[99]
The Dnipro River Reservoir-Cascade System

Reservoir	Average Length (km)	Average Width (km)	Average Area (km^2)	Average Volume (km^3)
Kyjiv	110	12	922	3.73
Kaniv	162	5	672	2.62
Kremenchuk	149	28	2252	13.50
Dniprodzerzhins'k	114	8	567	2.45
Dnipro	140	3	410	3.30
Kakhovka	240	23	2155	18.20

The length of the Prypjat River from its source near the city of Brest, Belarus to the Dnipro River is approximately 748 kilometers; and the area of the river which serves the needs of Belarusians and Ukrainians living along its banks is 106 km^2, with an average width of 200–300 meters. The average flow speed is 0.4 – 0.5 m/sec and the average discharge is 400 m^3/sec. The region's water table which served regional agricultural needs and small-industry as well as the population's fresh-water needs, lies at a depth of only 10–15 meters below ground level at the banks of the river, and is separated from ground level by essentially impervious layer of sand and clay.[100]

Hydrogeological conditions directly beneath the sarcophagus encasing Unit-4 can be described as follows:[101] The area directly under the station is located near the junction of the Prypjat and Dnipro Rivers artesian basins. The water-bearing layer (a quaternary water-bearing complex used as the region's water supply) is directly and hydraulically cou-

---

99 *Українська Радянська Соціалістична Республіка – Енциклопедичний Довідник.* Київ: Українська Радянська Енциклопедія, (1986).

100 *Техническое Обоснование Ядерной Безопасности Объекта "Укрытие,"* Под редакцей группы в составе: С. Т. Беляев, А. А. Боровой, Ж. Г. Волков, А. Ю. Гагаринский, Н. Е. Кухаров, Г. А. Шароваров, В. Ф. Шикалов, Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, (1990): 9.

101 Минчернобыль Украины и Академия Наук Украины, *Описание объекта «Укрытие» и требования к его преобразованию*, Киев: Наукова Думка (1992): 9–11.

pled with the Prypjat through break or clefts in a 10 – 30 meter thick layer of chalky clay, and is supplied mainly by the infiltration of atmospheric precipitation. Above the layer of chalky clay, water-bearing sandy alluvial deposits about 20 – 25 meters thick are also found. During spring flooding ground waters rise approximately 1 – 1.5 meters. The current state of ground waters in the vicinity of the station in many ways is determined by an anti-filtration wall "Casa Grande" about one meter thick, 30 – 35 meters deep, and about 2.1 kilometers long to the east of the station along the banks of the river.† Observations of the ground water level has shown that its yearly rise over the first clay level is 0.4 – 1.7 m, and its current level is approximately 4.5 meters below ground level.

The part of the *Polissja* region where the Chornobyl station is located is characterized by a relatively flat relief with very slight incline towards the Dnipro River or its feed streams. The area has long been considered a problem for agricultural cultivation (only about one-third of the overall territory is suitable for crops), consisting mainly of sandy podzolic soil, peat bogs, and marshland. Before the construction of the power station, what little industry was there consisted of food processing and small-scale shipbuilding The main specialty of a handfull of state farms and eighteen collective farms was dairy farming[102] (farms in the region average 60 head of catttle per 100 hectares) where meadows comprised fifty percent of the land – although potatoes, feed vegetables, grain, and flax were cultivated on 25% of the agricultural land.[103] Although not quite suitable for major crop farming, the area long enjoyed a proud reputation as one of the cleanest and most frequented rest and recreation areas for people from Kyjiv and surrounding cities.

Seismically, the 30-km exclusion zone is located in a 5 - 6 Richter scale region influ-

---

† The construction of the "Casa Granda" ground-water containment wall was an accident management action designed to prevent radionuclides from reaching the Prypjat River's ground water supply. The wall was to surround the station with a circumference of 8.4 kilometers in a roughly oval shape from the banks of the river westward. Unfortunately, the project turned out to be a fiasco because it was never completed. In fact, the 2.1 kilometers of the wall that were completed (the eastern section along the banks of the river) act as a dam that block ground water flow and has raised it to the current level of approximately 4.5 meters below ground level.

102 Ф. М. Рудич (голова редколегії), *Історія Міст і Сіл Української РСР*, Институт Історії Академії Наук УРСР: Київ, Україна, (1971).

103 Zhores Medvedev, 106.

enced by the Carpathian, Crimean, and Moldovan fault systems. The probability for the occurance of 7 Richter-Scale earthquake is once in 10,000 years.[104] Meteorologically, the area surrounding the Chornobyl station is catagorized in the following table:

Table III.12[105,106]
Meteorological Characterization of the Chornobyl Administrative Region

Highest / Mean temperature (July):	42.2 °C / 19.1 °C
Lowest / Mean temperature (January):	-44.9 °C / -5.6 °C
Annual average relative humidity:	77%
Normal depth of soil freezing in winter:	110 cm
Earliest "lasting" snow cover:	October 6
Latest "lasting" snow cover:	December 15
Earliest disappearance of snow cover:	February 21
Lastest disappearance of snow cover:	April 22
Total snow cover days	90 – 102
Average snow cover in open country:	8 cm
Average high snow cover in open country:	17 cm
Maximum snow cover in open country:	41 cm
Maximum daily precipitation:	190 mm
Maximum 20-minute precipitation:	72 mm
Predominant wind direction:	northwest (17%)
Secondary winds:	southwest, west, northeast (in equal proportions)
Average yearly wind speed:	4.2 m/sec
Maximum wind speed	47.3 m/sec
The 30-km exclusion zone has an "elevated tornado occurance probability:"	
yearly probability of tornado occurance in zone:	$1.2e^{-02}$
yearly probability of tornado occurance at station:	$3.0e^{-06}$
vortex maximum rotational speed:	72 m/sec
average tornado translational speed:	18 m/sec
average width of tornado:	290 m
average tornado pressure drop:	64×10^9 Pa

104 Минчернобыль Украины..., *Описание объекта «Укрытие»*, 11-12.
105 *Техническое Обоснование Радиационной Безопасности*... 9.
106 Минчернобыль Украины..., *Описание объекта «Укрытие»*, 8–9.

III.4.2. History of the Chornobyl Station

The Belarusian–Ukrainian forest region as a whole is characterized by a low population density. While Chornobyl is located (by Soviet standards) close to the major population centers of Kyjiv, Chernihiv, Zhytomyr, and the city of Homel in Belarus,† it is in one of the most sparsely poulated areas of Ukraine. At the start of construction of the station in 1970, the population density was approximately twenty-four people per square kilometer; while at the moment of the accident it was approximately thirty-five people per square kilometer.* In the 1970s, the population of the entire Chornobyl *rajon* ("region" – equivalent approximately to a county in the United States) was only about 47,000. The regional administrative center (county seat), Chornobyl, located at the junction of the Prypjat and Uzh Rivers about fourteen kilometers south of the station, had a population of just over 10,000, and was surrounded by sixty-nine tiny villages with populations of 500 to 700 residents. At the beginning of 1986, the population within the later-defined 30-km exclusion zone surrounding the station was close to 100,000 people, of which 49,000 lived in the newly-built "atomic" city of Prypjat located three kilometers to the northwest of the station's 1.5 kilometer boundary, and 12,500 in Chornobyl.† About twenty-eight kilometers to the north lies the Belarus border and the Homel oblast. The Zhytomyr oblast of Ukraine is located about fifty kilometers to the west, while the Chernihiv oblast (also of Ukraine) is located across the 13-kilometer wide Kyjiv Reservoir to the east. From the capital of the Chernihiv oblast, Chernihiv, the Desna River flows southwest to merge with the Dnipro River just north of Kyjiv. Chornobyl itself is a twelfth-century town that celebrated the 800th anniversary of its founding in 1993. During the 1970s, the

† Kyjiv, the capital of Ukraine, is located approximately 105 kilometers south by southeast of Chornobyl and on January 1, 1992 had a population of approximately 2,642,000 people. Chernihiv, with a population of some 310,500, lies 85 kilometers east by northeast; Homel, in Belarus, had a population of approximately 275,000 and lies 130 kilometers northeast; and Zhytomyr, population 299,400, lies 150 kilometers southwest.

* Compare this with Ukraine's overall population density on January 1, 1991 of approximately 86.2 people per square kilometer.

† The town of Chornobyl is located 16 kilometers south-by-southeast of the power station and 19 kilometers south-by-southeast of the city of Prypjat.

large majority of the population was made up of Ukrainians, although there were sizeable numbers of Russians, Poles, and Belarusians. The proportion of Ukrainians declined somewhat since the construction of the power station because labor reserves were brought in from several republics of the former Soviet Union.[107]

Just prior to 1970, Soviet central planners decided that this remote region of rural Ukraine, which was not part of the traditional "breadbasket" that lies further to the south, would be suitable for the location of Ukraine's first nuclear power plant. From the outset, a huge facility was anticipated: in addition to the then four operating 1000 MWe units and two more 1000 MWe units under construction, an additional six 1500 MWe units were to be built to "welcome the 21st century"[108] – bringing the total capacity of the Chornobyl station to 15,000 MWe. Prypjat, a city built specifically to accomodate construction and power plant workers for the Chornobyl station, was invisaged to grow to between 150,000 and 200,000 people at its peak.[109] The first set of reactors at the Chornobyl station, Units 1 & 2, consisted of two first-generation† 1000 MWe units built during the period 1972 – 1978. Second-generation 1000 MWe Units 3 & 4 were built between 1977 and 1983. In 1981 construction began on two more 1000 MWe units (5 & 6) about 1.5 kilometers to the southeast of the original four-unit station as the third phase of the Chornobyl power plant.[110] These were eventually abandoned after the accident.

---

[107] *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие»*, Чернобыль, Украина; Минск, Беларусь: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, Институт радиоэкологических проблем при АН Беларусь, 1992.

[108] Personal conversation with the 1st Deputy Minister of the Ukrainian Chornobyl Ministry, Borys Samojilovych Prister, and Head of the Inter-Branch Scientific & Technical Center "Shelter" of the Ukrainian Academy of Sciences, Volodymyr Serhyjevych Karasëv, December 2, 1992.

[109] Наука і Суспільство, (листопад 1991).

† The first-generation 1000 MWe RBMK did not include a pressure suppression pool in its design. Leningrad Units 1 – 4, Kursk Units 1 & 2, and Chornobyl Units 1 & 2 are first-generation RBMK-1000 reactors. The second-generation 1000 MWe RBMK design includes a two-story pressure suppression pool. Kursk Units 3 & 4, Chornobyl Units 3 & 4, and Smolensk Units 1 & 2 are second-generation RBMK-1000 reactors. The third-generation 1000 MWe RBMK includes a single-level pressure suppression pool in its design, and was to be represented by Chornobyl Units 5 & 6.

[110] At the time of the accident Units 5 & 6 were 85% and 15% complete. Their construction was abandoned during the summer of 1987, ostensibly over concern for the health of construction workers, but more likely over mounting pressure from ecology protesters in Ukraine, the demonstrated failure [!] of the RBMK design, and rising costs. [David R. Marples, *Ukraine Under Perestroika: Ecology, Economics, and the Worker's Revolt*, (New York: St. Martin Press, 1991), 43.] Unfortunately, construction at Units 5 & 6 continued unabated until three days after the accident when workers were told they should stay home.

Toward the southeast from the station along the length of the Prypjat River a 21.4 km^2 (25 kilometer perimeter, 5 meters deep) cooling pond was built to serve the 4000 MWe full-power cooling needs (hotest sustained summer temperatures) of the first four units. Units 5 & 6 were to be cooled with the help of convection-cooling towers.

In a September 19, 1966 resolution issued by the Soviet Council of Ministers, a proposal was confirmed to increase the electrical power capacity of the USSR utilizing nuclear power stations during the period 1966–1977. The nuclear-based capacity was to increase to 11,900 MWe – including the use of eight RBMK-1000s. The first nuclear station employing this type of reactor design was the Leningrad (now Sosnovyj Bor) station. According to the proposal, one of the nuclear power stations would help alleviate an electrical power deficit in the so-called "central energy region" of the Southern Unified Electrical System, which was the biggest of all Unified Electrical Systems in the European part of the Soviet Union. This system was comprised of twenty-seven oblasts of Ukraine together with the Rostov oblast in Russia, and had an area of over 700,000 km^2, a population of approximately 53 million people, and energy demand equal to 25% of the electrical energy requirements of the European part of the Soviet Union. It was originally planned for this particular station to have two 1000 MWe units. On January 18, 1967 the Ukrainian Government Planning Commission (*DerzhPlan UkrRSR*) chose an area of land within the administrative territory of the Chornobyl Rajon (region) close to the village Kopachi, 105 kilometers north by northwest of Kyjiv, and named the future station the Chornobyl Atomic Power Station in honor of Vladimir I. Lenin.[111]

The design task for this "1st Generation" RBMK-1000 at Chornobyl was assigned to the Urals Division of the Thermal Power Project Institute of the USSR Ministry of Energy, and confirmed by decree of the USSR Council of Ministers on December 14, 1970. By order of the USSR Ministry of Energy on March 30, 1970 further design work and

---

[111] Сивинцева, Ю. В., В. А. Качалова общие редакторы, *Чернобыль: Пять трудных лет*, Сборник материалов о работах по ликвидации последствий аварии на Чернобыльской АЭС в 1986–1990 гг, Москва: ИЗДАТ (1992): 13-15.

implementation plans for the Chornobyl Station were assigned to the Hydro-Project Institute of the Ministry of Energy – which was made the general designer and contractor for the project. Design tasks for the reactor as well as engineering support for systems design and construction were assigned to the All-Union Power Technologies Scientific-Research and Design Institute (VNIPIET) of the Soviet Ministry of Medium-Machine Building (*MinSredMash*). Scientific research concerning RBMK-1000s was directed by the Kurchatov Institute of Atomic Energy in Moscow, while the major contractor (somewhat akin to an architectural-engineering firm in the West) was the Scientific Research and Construction Institute of Power Technologies (NIKIET) of *MinSredMash*. The technical and economic basis for expanding the station to four RBMK-1000s was confirmed by the Ministry of Energy of USSR on April 6, 1972, and confirmed by the USSR Council of Ministers on December 1, 1975. Greater safety characteristics (including a pressure suppression pool) were implemented in the second generation design of the RBMK-1000 and confirmed by the Ministry of Energy on November 9, 1983.

CHAPTER IV

CHRONOLOGY OF EVENTS AND ACCIDENT SCENARIO

IV.1 Introduction

To properly tackle a source term problem as complex as that presented by the Chornobyl accident, at a minimum one requires as complete a scenario as possible – in the case of Chornobyl, from those actions and events that initiated the accident, through the end of the Active Phase approximately nine days later. To date, although the sequence of events and causes of the explosions leading to the destruction of Unit-4 are fairly well understood, a number of unanswered questions and inconsistencies remain. It is not the intent here, however, to present new information regarding this first stage of the accident, nor is it the intent of this dissertation to address and analyze these problems. Rather, as a point of reference for the Active Phase, the next section of this chapter provides as detailed a chronology as possible based on what is known to date, and when necessary further elucidates on a number of important points relavent to the source term analysis.

Unfortunately, the Active Phase of the accident and source term release mechanisms operating during this period have been studied to a far lesser extent; and it is for this reason that a reliable scenario for the Active Phase becomes critically important. Especially significant will be a reappraisal of the effectiveness of Accident Management Actions (AMAs) undertaken during the Active Phase to mitigate the consequences of the accident. It is the efficacy of the AMAs (during the Active Phase) that would have affected radionuclide releases to the environment most directly. As mentioned earlier, for example, new information regarding the dumping of over 5000 tonnes of materials into the reactor building in an attempt to smother the burning core, and the supposed purging of the core with liquid nitrogen to cool the core and limit the availability of oxygen will show

that prior scenarios and understandings of what may have been transpiring in the core during the Active Phase are incorrect.

IV.2 Chronology of Events and Actions That Initiated the Accident

The following time table (with accompanying narration and referenced comments following) provides a detailed sequence of events from approximately twenty-four hours before the accident, when operators began to take the reactor through a power decent in prepartion for a safety experiment and then planned outage, through the destruction of the reactor and the approximate beginning of the Active Phase. Where further elucidation of the narrative is required, references are made to the end of this section. This table was prepared while reviewing a number of sources that were published over a period of approximately five years;[1,2,3,4,5,6,7] and it is for this reason that some inconsistencies arose. Although every attempt was made to reconcile these differences and inconsistencies, not every problem was successfully explained or question completely answered. These cases are noted in the narrative and appropriate sources are referenced.

---

[1] U.S.S.R. State Committee on the Utilization of Atomic Energy (comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Part I: General Material,* report presented at the International Atomic Energy Agency Expert's Meeting, Vienna, Austria, (August 25–29, 1986).

[2] U. S. Nuclear Regulatory Commission, comp, *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250), Washington, DC: U.S. Government Printing Office, (1987).

[3] The International Nuclear Safety Advisory Group (INSAG), *Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident.*, August 30 – September 5, 1986, International Atomic Energy Agency (IAEA): Vienna, Austria, GLC(SPL.I)/3 Safety Series No. 75-INSAG-1, (September 24, 1986).

[4] Государственный Комитет СССР по надзору за безопасным ведением работ в промышленности и атомной энергетике, *О Причинах и обстоятельствах аварии на 4 блоке чернобыльской АЭС апреля 1986 г.,* Доклад Комиссии Госпроматомнадзора СССР, Москва (1991).

[5] The International Nuclear Safety Advisory Group (INSAG), *INSAG-7 The Chernobyl Accident: Updating of INSAG-1*, International Atomic Energy Agency (IAEA): Vienna, Austria, Safety Series No. 75-INSAG-7, (November 1992). INSAG-7 is important for those interested in events leading up to the accident because of its detailed reappraisal of information presented by the Soviets in August 1986.

[6] Kress, T. S., M. W. Jankowski, J. K. Joosten, and D. A. Powers, "The Chernobyl Accident Sequence," *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987).

[7] U.S. DOE, *Report of the U.S. Department of Energy's Team Analyses of the Chernobyl-4 Atomic Energy Station Accident Sequence*, (DOE/NE-0076; DE87 003614) Washington, D.C.: U.S. Department of Energy, (November 1986).

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.525 **01:06:00** 3140 MWt	Began power descent to 700–1000 MWt as required for a safety test [a] and as part of a planned maintenance outage. Operating Reactivity Margin (ORM) [b] was 31 manual rods.	The test was to simulate the failure of off-site electrical power following an accident that trips the reactor, and then verify whether forced cooling of the reactor could continue. It was intended to exploit the inertia of a rotating turbo-generator as a source of energy to power emergency cooling pumps (an integral part of the third subsystem of the ECCS) until diesel generators could be started and accept the required loads.	A slow reduction in power was planned to help reduce the effects of xenon buildup. The range for the test power level was chosen by test designers above the minimum allowable operating power of the reactor (~700MWt) because of thermal-hydraulic and core neutronic instabilities below this power level.
8604.525 **03:45:00** decreasing	Operators begin to replace the nitrogen-helium core cover gas with pure nitrogen. [c]	At power levels below ~2500 MWt and as part of normal operating procedure for reactor startup and shutdown, the graphite stack cover gas can be changed.	Blow-down of reactor graphite stack is assumed (in calculations) to take approximately one hour. Note that nitrogen has much poorer heat transfer characteristics.
8604.525 **03:47:00** 1600 MWt	Reactor power at 1600 MWt.	1540 MWt power drop in 2 hr. 41 min.	Power level given according to operating log. However, according to INSAG-7 reactor power was held at 1500 MWt.
8604.525 **04:13–12:36** 1600 MWt	Reactor power held at 1600 MWt. Tests of systems conducted for the experiment.	Alternate measurements of the characteristics of the reactor control system and vibrational characteristics of Turbo-Generators 7 & 8 (TG7 & TG8) were conducted while the reactor thermal power is held constant.	These are normal procedures as preparations for the experiment.
8604.525 **07:10:00** 1600 MWt	ORM is equal to 13.2 manual control rods.	It may have been that the operators dropped to this level to compensate for xenon buildup after dropping to one-half full power.	The ORM was given according to operator's log. This was in violation of ORM limits and the reactor should have been shutdown. [d]
8604.525 **13:05:00** 1600 MWt	TG7 is disconnected from the grid. Power for auxiliaries (four main cooling pumps (MCP), two electrical feedwater pumps, other vital equipment) is transferred to the bus bars of TG8.	As part of the safety test, equipment connected to TG8 (whose output is required for the test] will be permitted to run down with it when steam to TG8 is shut off. Other necessary equipment is to be powered from off-site.	As a result, four MCPs were drawing power from TG8, two MPCs were drawing from the grid, and two were on standby but connected to the grid. Thus, six MCPs were supplying the core with coolant at 42,000 m^3/hour. Also, the feedwater flow rate in the drum separator of each loop of the circulation circuit was 200–250 tonnes/hour.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.525 **14:00:00** 1600 MWt	The ECCS is disconnected from the two primary coolant loops as required by safety test procedure. Preparations for the test begin.	The test required (and approved) disconnecting the ECCS to avoid possible actuation during the safety test so that it could be repeated if required. Strictly speaking, however, this was a violation of safety principles and normal operating procedures.	Reactor operates with ECCS disconnected from the multipass forced circulation circuit (MFCC). Note, however, that the blocked ECCS played no role in the transient which destroys the core.
8604.525 **>14:00:00** 1600 MWt	Power reduction is halted and delayed for approximatley nine hours.	The regional power grid dispatcher at *Kyjivenergo* orders a delay to meet an ostensibly unanticipated demand. [e]	Operation of the reactor with the ECCS disconnected is a violation of normal operating and safety test procedures. This hold in power would, however, reduce the rate of xenon buildup at the test's power level.
8604.525 **15:20:00** 1600 MWt	ORM equal to 16.8 manual control rods.	ORM still low but higher than earlier.	The ORM was given according to operator's log. This was in violation of ORM limits and the reactor should have been shutdown.
8604.525 **18:50:00** 1600 MWt	Auxiliary electrical supply of equipment not required for the safety test is switched to the operating transformer T-6.	Done as part of the normal test procedure.	
8604.525 **23:10:00** 1600 MWt	Power reduction resumed to safety test level. ORM is equal to 26 manual control rods.	*Kyjivenergo* load dispacher permits continuation of power reduction. Power was held at 1600 MWt for a total of 19 hours 23 minutes.	Power descent to 700–1000 MWt resumed. ORM given according to operating log.
8604.525 **23:20:00** 1200 MWt	Slow power reduction continuing.	Power reduction to safety test level as planned.	Power level given according to operating log.
8604.626 **00:00:00** 760 MWt	Slow power reduction continuing.	Power reduction to safety test level as planned.	Power level given according to operating log.
8604.626 **00:05:00** 720 MWt	Change in reactor operating personnel. Slow power reduction continuing.	Power reduction to safety test level as planned. New shift must "come up to speed" regarding the progression of the experiment.	Power level given according to DREG printout.
8604.626 **00:25:00** 650 MWt	Slow power reduction continuing.	Power reduced to below 700 MWt – in direct violation of normal and safety test procedures.	Power level given according to operating log. Subsequent actions ("mistakes") by the new shift defines the "start" of the accident.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
		"Start" of the Accident	
8604.626 **00:28:00** ≈ 500 MWt	Operator switches off Local Automatic Control (LAR) as permitted at low power operation. However, the operator made an error: *he transferred from LAR to global power or full automatic control (1-AR & 2-AR) without entering hold power at required level.*	Because AR (global) power setpoint was inadvertently left preset to a low power level, the control system automatically took it down to below 30 MWt (<1%) and the neutron power essentially dropped to zero. [f]	The reactor power begins to be driven down to below 30 MWt despite operator efforts to prevent this. Abrupt power reduction results in a negative reactivity insertion from xenon buildup. Withdrawal of control rods is therefore required to maintain criticality and raise power to acceptable levels *if* test is to proceed.
8604.626 **00:30:00** <30 MWt	Power drops to below 30 MWt owing to inability of the AR rods and lack of prompt operator action to compensate for the void due to powerflow mismatch. Operators pause several (4–5) minutes before attempting to raise power.	The Chief Reactor Operator, during the transfer from local control (LAR) of the power distribution over the core to automatic control (AR) of the overall power of the reactor, was unable to compensate for and eliminate the inbalance quickly enough over the next few minutes.	Operating below 700 MWt is, ostensibly, in direct violation of normal operating and safety test procedures. [g] This pause allows time for xenon (poison) to build up.
8604.626 **00:34:03** ~30 MWt	Operators begin attempt to raise power.	There is a great desire to complete the experiment so the decision is taken to "revive" the shutdown reactor.	Xenon poisoning will make it difficult to bring the power up without reducing further the ORM.
8604.626 **00:34:03 – 01:18:52** ~30 MWt	Deviation of the Steam Drum Separator (SDS) level beyond the limits of the first range of the emergency setpoint "-600."	The emergency setpoint of the steam drum level reduction was left at "-1100"	This actually occurred several times during this period: at 00:34:03, 00:43:37, 00:52:27, 01:00:04, 01:09:45, and 01:18:52. (time on printout of DREG.)
8604.626 **00:36:24** ~30 MWt	The emergency set point for low pressure in the steam drums dropped to a lower value.	This is done to avoid a trip due to low pressure in the steam drums.	The setpoint is lowered from 55 to 50 kg/cm^2.
8604.626 **00:39:32 – 00:43:35** ~30 MWt	The DREG system does not operate during this period. *Operators disconnect (block) the trip signal for operation with loss of both turbo-generators.*	This is recorded in the operating log. *Disconnecting this trip signal is in accordance with test procedures and* ***occurs at 00:39:27.*** *According to INSAG-7 this occurs at 00:43:37.*	Xenon poisoning continues to increase. *According to INSAG-1, this occurred later at 01:23:04; and invalidates the claim that "this trip would have saved the reactor."*

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **00:40:00** ~30 MWt	Operators begin to withdraw control rods in an attempt to increase reactor power to test level.	Operation below 700 MWt is in direct violation of normal and safety test procedures which forces the operators to raise the power *if* the experiment is to proceed.	"Many" control rods withdrawn and ORM drops.
8604.626 **00:41–01:16** variable	TG-8 disconnected from the grid.	This is done to determine vibration characteristics in the "free-running" or coast-down (idle) mode.	Xenon poisoning continues to increase.
8604.626 **00:52:35 – 00:59:54** variable	The DREG system does not operate during this period. [h]	This is recorded in operating log.	Xenon poisoning continues to increase.
8604.626 **>01:00:00** <200 MWt and variable	Power quasi-stabilized at this level. ORM is at 7.2 rods. *Control difficulties throughout this period – substantial power fluctuations encountered.*	Attempts to increase power to the desired (and required) 700–1000 MWt level were unsuccessful because of the low ORM – again, a violation of normal operating and safety test procedures. There is difficulty even in obtaining this power level and holding. *Reactor operating below the minimum permissible power level; required reactivity reserve margin violated.*	Xenon poisoning has built up to greater than that anticipated for the safety test. As a result, after the operators stabilized the power at 200 MWt, the ORM was approximately 7.2 rods worth – substantially below and in violation of the 30 rods required by normal operating procedure. *No excess reactivity was available to raise power to that required by test procedures.*
8604.626 **01:03:00** ~200 MWt varies slightly	An additional (7th–#12) MCP is engaged – *the 3rd MCP from the grid (4th MCP in left loop) was connected to the left loop of the heat transport system.* Power level better stabilized.	As specified by the safety test (experimental) procedure but not at such a low power level. The operators decide to stabilize at this power level and to conduct the experiment. (The reason given: "to cool down the reactor during the test.") According to Operating Log entry. *The coolant inlet-to-core temperature approached saturation (ie., there is little if any boiling in the core) due to low power / high flow rate of coolant through core heat transfer system.*	Based on the planned test power level, only four MCPs were required for safe operation. Thus in this configuation, four MCPs would coast down at test initiation (TG8 tripped) while four would remain running supplying coolant to the core at a nominal rate. *This adds negative reactivity to the system, necessitating eventual (automatic) withdrawal of more rods to compensate.*

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:06:00** ~200 MWt varies slightly	Feedwater flow rate increased to 1200–1400 t/hr.	Done to restore a normal level in the SDSs.	
8604.626 **01:07:00** ~200 MWt varies slightly	The last (8th–#22) MCP is engaged – it is the 4th MCP powered from the grid (4th MCP in left loop) and is connected to the right loop of the heat transport system at approximately 01:07.	As specified by the safety test procedure – but not at such a low power level. *Flow rate in some of the MCPs exceeded the permissible value. Flow vibration limits were violated based on potential cavitation problems.* Note: when all eight MCPs are operating with a total capacity of 56,000 m³/hour and the pressure in the SDSs is 6.57 MPa, coolant transport time from the SDSs to the core inlet is about 32 seconds. Therefore, every moment a mixture composed of the circuit water and the feed water (produced 32 seconds earlier in the SDSs) is fed into the core inlet. Also, the time of coolant transfer from an MCP to the core inlet is about 14 seconds.	The total flow increases to 57,000 m³/hour in excess of the maximum flow permitted given the (low power) operating conditions. The coolant temperature approaches saturation. A low power-to-flow ratio possibly reduced core void to 10% or less. This resulted in a significant decrease in steam pressure and water level in the steam separators. *This mode of operation (low core void, very low ORM, slow power measurement response, pumps near cavitation) is very unstable* – besides the fact that control of the main cooling systems made difficult. Moreover, the MCPs may have been operating close to the point of cavitation. [i] Because the reactor was in such a low void condition with low system thermal hydraulic resistance, the pumps delivered excessive flow to the point where they exceeded their allowed limits derived from cavitation considerations. The Soviets were concerned that these pumps may have been operating close to point of cavitation. The throttling valves could not be trimmed further, and the increased core flow led to problems with the level in the steam drum. Eventually: further (automatic) control rod withdrawal and thus a further decrease in the reactivity reserve margin.
8604.626 **01:09** variable	Sudden reduction in the feedwater flowrate to 90 t/hr on the right side and 180 t/hr on the left for a total flow rate in the circuit of 56,000–58,000 t/hr.		As a result, the temperature at the MCP inlet reached 280.8°C (left side) and 283.2°C (right side.)

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:12:10 – 01:18:49** variable	The DREG system does not operate during this period.	This is recorded in operating log.	
8604.626 **01:18:52** variable	DBA signal on.	According to DREG program printout.	
8604.626 **<01:19:00** ~200 MWt varies slightly	Further automatic and manual control rod withdrawal occurs.	Reduced coolant void content poisons the core and necessitates further rod withdrawal to maintain constant power level – *hence a further decrease in the reactivity reserve margin.*	ORM reduced even more; continued violation of normal operating and safety test procedures.
8604.626 **01:19:00** ~200 MWt varies slightly	Steam drum level was hovering near the emergency level. Operators block the emergency protection (trip) signals related to low steam pressure and low water level in the steam drum separators.	By blocking these protection signals, the operator was able to continue operating the reactor and avoid a scram. This is a serious violation of normal operating procedure.	Either this signal must be blocked or feedwater flow must be increased to avoid a reactor trip. Fluctuations in the power (see 01:00:00) and difficulties in controlling main cooling systems (see 01:03:07) would normally cause the reactor to trip and terminate the test. The relationship between pressure, coolant flow, and voiding are all interlinked, so that they determine the control system actions. The system response to these ineractions is futher sensitized by the low power condition.
8604.626 **01:19:10** ~200 MWt varies slightly	Operator begins manual replenishment of feedwater to the steam drum separators.	Apparently *anxious* to establish this water level well within the normal range, the operator sharply increased the feedwater flow and exceeds its nominal value. Particularly at low power levels, a reduction in core voids (reduced steam generation) produces a negative reactivity insertion.	The feedwater is injected at the downcomer from where it takes 20 seconds to reach the core inlet. As this cooler, denser water (with a 30 second or greater transit time through coolant loop) reaches the reactor core, there is a sharp drop in the steam fraction of the coolant and a corresponding reduction in the reactivity and thus a power decrease. *Core subcooling increased resulting in a greater void collapse thus poisoning the core.*

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:19:30** ~200 MWt varies slightly	The automatic power regulation (AR) rods move upward. *The AR rods rose up to the upper tie plate (ie., completely out of the core.)* To compensate, the operator removes some of the manual control rods entirely to allow insertion of the AR rods.	*Calculated core average void was then zero. Rods move out to compensate for the addition of negative reactivity and a reduction in power.* The operator assisted the AR rod system by withdrawing the manual control rods but overcompensated for the reactivity reduction causing the AR rods to move too far back into the core.	The ORM decreases even more... The Soviet/IAEA report *implies* that this is not permitted, ie., a violation.
8604.626 **01:19:39** ~200 MWt varies slightly	The #1 PK-VVERKh signal is registered and then immediately goes off.	The operator has overcompensated for the reactivity reduction.	This is the "one overcompensation upwards" signal. Note that during the period when a #1 PK-VVERKh signal is registered the AR rods cannot move into the core.
8604.626 **01:19:40** ~200 MWt varies slightly	*Water level rises in SDS.* The feedwater flow to the steam separators had increased by a factor of three over the balanced flow for this power level. *Onset of steam drum steam pressure drop.*	The feedwater flows into the steam separator at the nozzles of the downcomers leading to the primary coolant pumps. Hence, the core inlet flow temperature responds rapidly to any change in feedwater flow.	Steam drum water level increases. *Feedwater entering the system exceeds the steaming rate.*
8604.626 **01:19:44 – 01:23:30** ~200 MWt then increase	The #1 PK-VVERKh signal is registered and then goes off later.	The operator has overcompensated for the reactivity reduction.	This is the "one overcompensation upwards" signal. Note that during the period when a #1 PK-VVERKh signal is registered the AR rods cannot move into the core.
8604.626 **01:19:58** ~200 MWt varies slightly	Turbine steam bypass (steam to the turbine) valve (steam dump) closed.	This was done to stabilize and then raise the steam pressure which was too low – due to the introduction of cooler water into the core and hence the addition of negative reactivity and a decrease in the reactor power.	Nonetheless, the steam pressure continued to drop but more slowly until the start of the test (01:23:04). The valve was probably only partially open, since reactor steam was being used to power the turbine generator.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:21:50** ~200 MWt varies slightly	*The feedwater flow exceeds by four times the balanced flow rate.* Operator reduces the feedwater flow rate abruptly.	*Steam drum level still rising; pressure still falling.* Done to compensate for falling pressure and increasing negative reactivity. The reactor is very difficult to control at this point.	*Control rod position was constant as modeled by the computer. The reduction in pressure produces enough void to compensate for the additional feedwater flow.* This will cause the core inlet temperature to increase in about 20 seconds. The core will "feel" this action later – the rods will not immediately reinsert. This action will compound events about one minute later.
8604.626 **01:22:10** ~200 MWt varies slightly	Core outlet steam begins to increase, coolant core inlet temperature increases. Water level in the steam-drum separators stabilized. *AR rods begin to insert.*	Core void content increases. *Rods drive in to compensate for the rise in the average core void produced by warmer water reaching the core inlet.*	As voiding increases, moderation also increases followed by a power increase, and the rods move in to compensate for this power increase. Recall that ~20 seconds earlier the abrupt reduction in feedwater flow initiated this behavior.
8604.626 **01:22:30** ~200 MWt varies slightly	The operator initiates a feedwater flow reduction for a target value of two-thirds of balanced flow. *The distribution of power density and the positions of every control rod were printed out.* Operator notes from the Skala printout that the ORM was about 6–8 rods. The flux was "practically arched" in the radial direction an double peaked axially. [j]	The feedwater flow is too high in the first place, and the water level in the steam drums had stabilized at 01:22:10. *Printing was done to establish the flux distribution and reactivity margin before beginning the test.* Control rods by now have moved in (from initiation at 01:22:10) to compensate for the added reactivity of increased voiding. But according to Skala, the ORM is still far below (<1/2) the value where immediate reactor shutdown is required. At this highly unusual power shape, the error in estimating the control rod worths was extremely large, hence the error in estimating the ORM was also large.	*Unfortunately, the operator is unable to stop the feedwater flow rate at the desired level because of the coarseness of the control system – it is not designed for this operating regime.* *However, because of the lengthy computer calculation time it is actually provides the core conditions a few minutes earlier.* A clear violation, but no operator action was taken – the reactor should have been carefully and immediately shut down. (Actually, the operator did not have enough negative reactivity reserve in the rods to meet his shutdown requirement.)

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:22:37** ~200 MWt varies slightly	The positions of the AR rods are registered for the last time.	Bank 1 AR rods – 1.4 m into the core, Bank 2 AR rods – 1.6 m into the core, Bank 3 AR rods – 0.2 m into the core.	Note that during the period when a #1 PK-VVERKh signal is registered these rods cannot move into the core.
8604.626 **01:22:45** ~200 MWt varies slightly	Feedwater flow rate is stabilized at a value of approximately two-thirds of balanced flow. The pressure begins to rise.	The increase in steam quality stops because the feedwater flow is stabilized and the pressure increases.	*Stabilization of steam quality in the core; the pressure starts to rise.*
8604.626 **01:23:00** ~200 MWt varies slightly	ORM is 8 RR rods, the neutron flux in the core is double-peaked with the major peak near the top of the core, the coolant flowrate is 56,000 m^3/hr, and the feedwater flowrate is 200 tonnes per hour.	According to a PRIZMA code calculation done later, the ORM was found to be this value **at 01:22:30.** (The parameters were recorded onto magnetic tape and the calculations were performed at the Smolensk plant after the accident.)	This flux shape was very unstable for a loosely-coupled RBMK-1000 core. The major peak is at the top because the coolant is least dense at the top of the core – it thus has less of a poisoning effect.
8604.626 **01:23:04** ~200 MWt varies slightly	"Oscillograph On!" command given. Start of the safety experiment. The coastdown was started on four of the MCPs: MCP-13, MCP-14, MCP-23, MCP-24. To begin the test the TG8 turbine (emergency) stop valve was closed while the turbine generator bypass valve remained closed (steam was diverted away from TG8.) Witnesses outside hear loud "steam blowdown."	Decision was made to start the TG8 safety test. Because the operators blocked the trip signal for operation with loss of both turbo-generators at 00:39:27, by avoiding this scram it would be possible to repeat the test using reactor-generated steam. *The operator was fully aware he was inducing a transient which required shutdown.* Closing of the inlet valve to the turbine. The turbine would now begin to slow down because no steam was being supplied. The experiment was to determine whether the stored energy of the spinning turbine could be tapped to power emergency cooling pumps until diesel generators could be started and accept the required loads.	TG7 had been switched off more than twelve hours earlier. At this point the only reactor protection signals left in operation were the trips of high power and low period. The flow rate begins to fall as the four MCPs powered by TG8 began to run down. The steam pressure increased due to removal of the turbine-generator steam load and the reduction (by operator action) of the feedwater rate at 01:21:50. These factors combine to increase the coolant void fraction (positive reactivity insertion) and hence the power.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:23:10** ~200 MWt slow increase	*A pressure increase causes the voids to temporarily collapse and thus the reactivity to go down.* State of the reactor: (1) feedwater flow minimized voiding in the coolant (2) low power operation (3) very low ORM The MDBA (maximum design basis accident) button is pressed.	*Pressure increase because of removal of turbine-generator steam load, reduction of feedwater rate (by operator) at 01:21:50, and an increase in power causing an increase in steam production.* Because of the reactor conditions at the time of the test, the void fraction is believed to have increased many times more sharply than it would have at normal power. This sharp increase in void fraction results in a sharp increase in reactivity. (Soviets stated that the normal void reactivity coefficient of 2.0e-4/% steam volume increased to 3.0e-4/% steam volume at the test conditions.) According to the test program, the MDBA button was intentionally installed to simulate an MDBA signal and use it for starting up the diesal generator and the TG run-down device. It should have been pressed simultaneously with the emergency regulating valves.	*One group of AR rods begins withdrawing to compensate.* The increasing pressure, reduced feedwater flow, and reduced flow through the reactor are competing factors which determine the volumetric steam quality an hence the power of the reactor. The reactor was in such a state (average sub-cooling in the core was 3°C and the steam content was insignificant except at the top of the core) that small changes in power would have led to much larger changes in steam void (positive reactivity insertion, where it was more significant at the bottom of the core than at the top) with consequent large changes in the power. The combination of these factors ultimately led to a faster power increase beginning about 20 seconds later.
8604.626 **01:23:21** >200 MWt slow increase	As the four pumps continue to coast down, the flow rate drops, void and power increase. Two groups of AR rods begin to reinsert.	*Reduction of the coolant flow rate and the approach of the warmer water to the core increase reactivity and thus power.* Voids increase because: (1) MCPs connected to TG8 are running down, therefore more steam is produced at constant power; (2) The loss of load reduced drain-off of steam, therefore coolant goes above saturation point; (3) 01:22:45 reduced and stabilized feedwater flow now begins to take significant effect. Additional detrimental effects: (1) control rod configuration disturbed; (2) subcooling of coolant reduced; (3) hydralic resistance increased with decreased flowrate.	To compensate, two AR rod groups begin to drive in to try to balance the increased reactivity brought on by the reduction in the coolant flow rate and the approach of the warmer water to the core. When the solid coolant system just below saturation had its flowrate decreased, the power then increased – saturating and forming voids. The one-phase system became a two-phase system and thus the hydraulic resistance increased further reducing the coolant flowrate and compounding the problem even more. *The core was acting more and more like a sponge through which water was being squeezed.*

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:23:30** increasing	The #1 PK-VVERKh signal goes off.	It had been on since 01:19:57 for 3 minutes 33 seconds.	Note that during the period when a #1 PK-VVERKh signal is registered the AR rods cannot move into the core.
8604.626 **01:23:31** increasing	Net reactivity is increasing with accelerating power increase because of pump coastdown and increasing inlet temperature. Operator notices the power increase.	Power rise accelerating because positive power coefficient accelerated reactivity imbalance.	Power increasing but not yet to the point where fuel melts. AR rods helping to limit the magnitude of the power increase, but overall they are unable to balance out the reactivity insertion.
8604.626 **01:23:36–39** increasing	The flowrates in the MCPs powered by TG8 drop below the minimum permissible level.	Below the minimum permissible flowrate of 5500 m^3/hour for *each* MCP, their emergency protection systems should engage.	When these MCPs lose power completely (at approximately 01:23:41–42), the coolant flow will decrease very rapidly, voids will form even more rapidly, and the reactor power will eventually be driven by prompt neutrons alone.
8604.626 **01:23:40** ~320 MWt and increasing	EPS-5 (emergency protection system 5) signal recorded. The Unit-4 shift foreman gives the order to press the emergency scram (AZ-5) button. (According to the teletype registration, this was actually done at 01:23:39.)	Operators see the power increasing rapidly. However, at their trial the operators gave as a reason for pressing AZ-5 that the test was proceeding well (no repeat was necessary), and "the AR rods were moving." Unfortunately, there was insufficient reactivity in the rods that were in the core, and the others at the top of the core could not be inserted fast enough to counteract the power increase caused by the competing actors noted earlier.	It has not been clearly established why this order was given at this particular time. There was no *apparent* effect. However, the control rod followers of the AR and RR rods entered the core first – adding approximately +0.5 β to an already out-of-control reactivity increase. Additionally, this begins to deform and "push" the flux peak at the top to the bottom where it is more effective. [k]
8604.626 **>01:23:40** power increasing	Central hall shift foreman feels strong and frequent shocks and sees fuel channel caps on central hall floor vibrating violently up and down. Reactor's main relief valves trigger, releasing steam but are subsequently destroyed.	V.I. Perevozhchenko was shift foreman in charge of the reactor section. He entered the central hall at Level +50 m (14.5 m above floor of central hall) for a routine visual check of Central Hall. The refueling machine was standing against the far (west) wall. Two central hall operators were behind doors also at the west wall not observing events. He rapidly descends 30 m downstairs and sprints 50 m down a corridor to control room No. 4.	There are 2488 steel and concrete caps (about 80 kg each) covering the top of fuel channels. [l] While this is going on, the machinest monitoring the MCP during their coast-down, Valeri Khodemchuk, sees and feels pumps shudder violently, followed by a blast. He is killed by the initial explosions and his body is never recovered from the wreckage.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:23:40.2** power increasing	The four MCPs (two in each loop) connected to TG8 are disconnected automatically. The oscillograph (used to record MCP electrical parameters for the experiment) records that the operating time of the MCPs connected to TG-8 (before automatically disengaging) is 36.2 seconds.	When the coolant flow decreased to a set point (which was not, interestingly, overridden by the operators), those four pumps drawing their electrical energy from TG8 lost their power through automatic disconnection.	A very rapid decrease in coolant flow then occurred, with a consequent sudden increase in the steam content of the coolant and a large increase in the reactivity, helping to drive the reactor to prompt criticality.
8604.626 **01:23:42** power increasing	According to subsequent calculations, the net reactivity becomes equal to $1.	The net reactivity in this case is a combination of the positive void coefficient, positive reactivity insertion from the tips of the scram rods, and negative Doppler feedback. The expansion of the fission product vapor and the steam resulting from a local fuel-coolant interaction, ejected water from portions of the core – adding more reactivity and further increasing power.	The reactor becomes critical on prompt neutrons alone that initiates a runaway nuclear reaction. *Once a certain thermal inertia of the fuel elements in the region of highest power densities had been overcome, steam generation began, which, owing to the large local void coefficient of reactivity, made a significant contribution ot the non-uniform reactivity runaway and rapid fuel damage in the regions of greatest power density and began to expand out of control over the entire core.*
8604.626 **01:23:43** >530 MWt and accelerating	Rapid increase in power. *The high power (AZM shows P > 530 MWt) and short period alarms (AZS shows period <20 seconds) in all lateral ionization chambers are triggered.*	The emergency protection system is not efficient enough to prevent the power runaway. The Doppler effect only partially conpensated for the void reactivity increase.	Soviet calculation indicates power at this time to be 3800 MWt (120%) and rising rapidly. Calculated fuel temperatures increased sharply. Note that most of the instrument recording and sensing of the reactor and coolant loop parameters are "behind the times" at least 2-3 seconds.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments

Start of the "Active Phase" of the Accident

8604.626 **01:23:44** 345 GWt (calculated)	Reactor core attains first power peak at approximately 109 times nominal full power. *The operators heard banging noises and noted that the rods stopped before reaching bottom (inserted only 2–2.5 of the 7 meter active core height).*	The very large and rapid power surge led to fuel fragmentation that caused a large steam spike (rapid pressure increase) which reversed the flow and closed main reactor pump check valves as indicated by recorded data. The resulting void produces another neutron pulse and then a second power surge. *The first power surge may have distorted the core so that the control rods could not be bottomed. The banging noises may have been initial ruptures of pressure tubes or bursting of the reactor cylinder. [m]*	Calculations indicate the first power surge was terminated by Doppler effect and by partial rod insertion. The coolant flow continued to decrease (due to rundown of four MCPs) and the power continued to increase, ie., the geometry may not have been completely lost. *The first "smaller" explosion may have been the rise and fall of the 2500 tonne Upper Biological Shield – lifted by the overpressurization of the reactor space. This would have rapidly released steam (loud blowdown noise?) and severed the tops of the channels – the weakest part of the coolant loop where there is a stainless steel-to-zirconium diffusion weld. This in turn would have failed the entire reactor space – resulting in the second "very loud" explosion. [n]*
8604.626 **01:23:45**	Coolant flow rates dropped at least by one half (28,000 m^3/hr). Pressure in the left-loop SDS rose by 0.31 MPa/sec and in the right by 0.49 MPa/sec.	A rapid pressure increase reverses the flow and closes the main reactor pump check valves. The resulting void produces another neutron pulse and then a second power surge.	The MCP flow rate and the SDS pressure readings are taken by bellows differential manometers designed for measuring slowly varying processes. The Soviet data, therefore, has magnitude and time delay (1–2 sec) errors.
8604.626 **01:23:45.5** 1,480 GWt (calculated)	The reactor core attains a second power peak at approximately 470 times nominal full power.	With the main coolant check valves closed, the coolant flow was stopped completely and caused the steam volume fraction in the core to increase even faster and probably to a very high fraction.	This, most likely, was a major factor in contributing to the second power surge in the core. Other factors may have been (1) further positive reactivity insertion caused by expelling of water columns at the bottom of the core, (2) ingress of steam to core inlet from the cavitation of MCPs, (3) boiling of slightly subcooled water at the throttle (inlet) control valves.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:23:46** 12560 MWt (calculated)	Steam drum pressure exceeded "accident level" and pressure relief valves open. First pair of "wild-running" MCPs disconnected.	Pressure rise rate as calculated by the Soviets was 8–10 atm/sec.	Coolant (assembly) tube ruptures permit coolant and fuel fragment injection into the graphite, which, in conjunction with steam flashing into reactor cavity, lifts the 2500+ tonne Upper Biological Shield – severing most coolant tubes at the upper Zr-steel diffusion weld.
8604.626 **01:23:46.5** ??	Second pair of "wild-running" MCPs disconnected.		
8604.626 **01:23:47** core destroyed	Large increase in coolant flow as channels rupture because of pressure spike. Abrupt changes in flow rates, pressures, and levels noted in major coolant system components.	As the pressure in the fueled tubes relieved itself through the ruptured upper tube ends, the check valves in the major coolant inlet lines opened, allowing water to enter whatever was left of the coolant channels. Abrupt decrease (by ~40%) of flow rates of MCPs not taking part in the run-down (MCP-11, -12, -21, -22). "Non-credible" flow rates in MCPs taking part in the run-down (MCP-13, -14, -23, -24). Abrupt pressure increase in the steam separators. Abrupt increase in the steam separator level. "Failure of instrumentation" recorded by both mid-range auto-regulators 1-AR & 2-AR.	If initial ruptures occurred at (01:23:44), this flow increase could be consistent with the Upper Biological Shield being lifted by the pent-up steam in the reactor cylinder and the resultant severing of all pressure tubes and control rod channels.

Date & Time Power	Action / Event	Motivation / Significance / Interpretation	Implications / Results / Comments
8604.626 **01:23:48** core destroyed	High-pressure failure (from the steam "explosion") blew the top off – destroying the reactor, Central Hall, and upper parts of the reactor building. Flow rates of MCPs not taking part in the run-down are back to near initial values. Further increase in the level and pressure in the steam separators (right side 88.2 kg/cm^2; left side 75.2 kg/cm^2). Pressure relief valves (fast-acting reaction valves BRU-K1 & BRU-K2 to turbine condensors) engage.	The vaporization of water now entering through open check valves (above) by molten and fragmented fuel caused another pressure pulse which propelled additional fuel into the atmosphere. Flow rates for left-side MCPs taking part in rundown ≈ 15% lower than initial values, flow rate for right-side MCP-23 ≈ 10% of initial, flow rate for right-side MCP-24 still "non-credible." Automatic release of steam to the turbine condensers.	This could have been the second explosion which people reported hearing. Still unanswered remains the question of how pieces of the high-bay wall (some from the level of the steamdrum separators) managed to fall to the bottom of the reactor shaft. One credible explanation is that hydrogen generated early on during the accident may have accumulated and detonated in the steamdrum separator chambers – blowing in toward the Central Hall parts of the wall. Another hypothesis is that pressure waves from the steam explosion may have reflected into the steamdrum separator chambers along the water-steam coolant channel path also blowing out parts of the wall. It is difficult to guess how many explosions there may have been because some of the "smaller" ones may have been masked by larger ones.
8604.626 **01:23:49** core destroyed	"Failure of 1-AR & 2-AR drives" signal engages, and power loss signal on servo drive clutches engages. Emergency protection signal "growth of pressure in reactor space" (fuel channel rupture in reactor space) engages.	Operator notes failure of rod drives and disengage the servo drive couplings to allow rods to fall into core by gravity.	
8604.626 **>01:23:50** core destroyed	Concentrations of hydrogen (4.2% in air) & oxygen in various compartments may reach ignition levels.	Hydrogen produced rapidly from reaction of hot Zircaloy with steam/water liberating large quantities of heat energy.	According to the log entry at 01:24, there were "Severe shocks; the RCPS rods stopped moving before they reached the lower-limit stop switches; power switch of clutch mechanisms is off"
8604.626 **05:00**	Unit-3 shut down.	"Extreme situation" in Unit-4 and contamination of adjacent units.	Unit-3 is shut down 3 hours 36 minutes after the accident.
8604.727 **01:13**	Unit-1 shut down.	"Extreme situation" in Unit-4 and contamination of adjacent units.	Unit-1 is shut down 23 hours 49 minutes after the accident.
8604.727 **02:12**	Unit-2 shut down.	"Extreme situation" in Unit-4 and contamination of adjacent units.	Unit-2 is shut down 24 hours 48 minutes after the accident.

This Page Has Been Left Intentionally Blank.

Narration and References to the Accident Chronology

[a] Safety test: On April 25, the plant staff was to conduct a special safety test on Unit-4 just before it was shut down for inspection and "medium" (routine) maintenance. This test was designed to demonstrate that following a reactor trip along with a resulting loss of off-site power (plant blackout), the stored kinetic energy in a coasting-down turbo-generator (K.E. = $^1/_2 \cdot I\omega^2$) could be utilized to generate enough electrical power to energize emergency feedwater pumps in the "fast-acting" part of the ECCS during the approximately three minutes required for the emergency diesel generator system to startup[1] and take over load requirements.

In the test, the steam supply to one of the turbine generators was to be cut off. The system of four main coolant pumps and two feedwater pumps normally associated with the coasting-down turbo-generator were to remain electrically connected to the voltage regulating system to simulate the electrical load of the emergency feedwater pumps – rather that using the actual emergency feedwater pumps. Continued cooling of the reactor during the test was to be provided by the other four main coolant pumps normally associated with the other turbo-generator unit that, by the test procedures, was to be already shut down. The power for these four pumps was supplied from off-site.[2] The valving arrangement was such that two of the pumps that were to coast down and two of the pumps powered from the grid were to continue running were to serve each half of the core so that uniform cooling would be maintained. The reactor power operation was needed only to provide steam for the initial turbine operation. The turbine was being loaded primarily by four of the reactor's eight primary coolant pumps. The four other pumps were being powered off-site so that even upon complete turbine rundown there would still be substantial coolant flow through the reactor.

Similar tests had been conducted at the Smolensk NPS and with the Chornobyl Unit 4 in 1982 and 1984. In these tests the busbar voltage from the turbo-generator fell off much faster than the available inertial energy in the coasting-down system. This particular test was to determine whether a new generator magnetic field regulator would maintain the voltage output from the generator for a longer period.[3] It was, therefore, strictly an electrical engineering test, directed by an electrical engineer with no nuclear ex-

[1] NUREG, 3-39. The U.S. DOE in their *Team Analysis Report* (3-1) appear to disagree with the amount of time needed to bring the emergency generators on line, "... long enough for the emergency diesel generators to get up to speed, nominally 40–50 seconds."

[2] Kress, et al, 3.

[3] NUREG, 4-1.

perts on hand.[4] The reactor was needed only to provide steam for initial turbine operation.

[b] The Operating Reactivity Margin (ORM) is defined as the number of equivalent absorber rods fully inserted into the core in the area of high differential worth. 26–30 rods ORM was the minimum for nominal non-varying power operation. (When the ORM is about 30 effective manual control rods – approximately 100 control rods, each lowered to the 1.4 m level – a strong negative reactivity is introduced into the reactor core.)[5] The Minimum Reserve Margin (MRM) was 16 equivalent control rods required by plant operating procedures for safe operation during power changes;[6] while the minimum calculated for a "cold" reactor was 17 rods plus a 20% error to equal a 21 rod minimum. The ORM requirement was a means of specifying an overall rod configuration that ensured a certain minimum initial negative reactivity insertion rate during a scram; while the presence of neutron absorbers within the core also decreased the magnitude of the positive steam void reactivity coefficient.[7]

[c] Cover gas: A gas mixture, nominally 80% helium and 20% nitrogen, is fed into a chamber below the reactor where it is distributed across the bottom face of the reactor. This gas flows between the graphite columns at a rate of about 200 to 400 m^3/hr providing a heat-conducting medium for transmitting the graphite heat to the coolant channels. The cover gass also prevents oxidation of the graphite and permits channel-by-channel monitoring of the pressure tube's integrity during operation. Monitors are provided at the top of each channel to sense the relative humidity and temperature of the exiting gas. These data are used to detect any leaks that may be present in the various pressure tubes. The space between the tubes in the channels is fitted with graphite rings, which are fitted alternately to the tube and graphite channel opening. During reactor startup and shutdown operations a pure nitrogen cover is used. (Note that nitrogen has much poorer heat transfer properties.) The graphite temperature is can reach 750°C under these conditions (normal operation 600 – 650°C). The gas mixture is monitored for moisture to detect leakage from the tubes.[8]

[d] Until the January 1993 INSAG-7 report, the official Soviet version of the cause of the accident (and accepted as true in the West) implied that it was not the design of the RBMK but rather "a number of violations of rules and procedures by the operation staff and by those responsible for authorizing the test." INSAG-7 squarely shifted the blame onto the reactor designers

---

[4] Bernard L. Cohen, "The Nuclear Reactor Accident at Chernobyl, USSR," *American Journal of Physics*, Vol. 55, No. 12 (December 1987): 1079.

[5] INSAG-7, 39

[6] NUREG, pg. 4-4.

[7] NUREG, pg. 5-2.

[8] NUREG, Pg. 2-8.

and on the lack of a "safety culture" among workers in the Soviet nuclear power field. In fact, contrary to what the Soviets stated at Vienna in 1986 and among other things, the operators were neither completely trained to understand the significance of the ORM nor is the ORM now considered appropriate to completely assure that the control rod configuration secures fully adequate reactor protection.[9]

[e] An interesting aspect of Soviet society was the unofficial work-place practice called the *shturm* or the periodic and frantic attempt to meet plan fullfillment quotas, i.e., "taking the plan quota by *assault* or *storm*." This was then followed by a period of a more relaxed work pace until the next quota had to be met, whereupon the cycle would repeat. The most important plan quotas were those imposed by yearly and five-year demands (hence the Five-Year Plan) for production. However, there were also quarterly and monthly quotas that became especially important just before State holidays such as the May 1st Socialist Labor Day celebration and vacation period which also informally brought in summer and was second only to the October Revolution celebrations.

The importance of this period for meeting production quotas cannot be overemphasized. In fact, some have argued that the drive to fulfill these quotas (at the end of April just before the May Day celebrations) may have had an indirect effect on the workers and operators at the Chornobyl station to unconsciously relax their safety practices – thus making it a contributing factor in the accident.[10] The operators were anxious to complete the experiment because they wouldn't have another chance to conduct a similar experiment for over a year (another RBMK station might be ordered to do it instead), and they would lose their holiday bonus for completing the experiment. They were therefore not very pleased to have to hold at 1600 MWt thermal for over nine hours before being allowed to decrease reactor power to the level required for the experiment. The halt in power reduction as required by the *Kyjivenergo* dispatcher (recall at the end of April before a major holiday) was needed to supply heavy industry with enough power to complete their monthly quotas and recieve their own bonuses. Interestingly, the only thing that counted was meeting or overfulfilling the quota. The demand imposed by the dispatcher was not so much an order by the Ministry of Energy and Electrification as it was haranguing by factory and industry managers to squeeze out as much power as possible before the holiday.

[f] To understand how difficult it is to control an RBMK-1000 at lower power, it is worth quoting at length here an excerpt from the original report

---

[9] INSAG-7. For brief summaries see Andrew Cruickshank, "INSAG Reconsiders the Causes of Chernobyl," *ATOM*, (March/April 1993): 44–46, andGamini Seneviratne, "INSAG Ready to Issue Revised Chernobyl Report Blaming Design," *Nucleonics Week*, Vol. 34, No. 2, (14 Jan 1993): 8–9.

[10] See for example Zhores Medvedev, *The Legacy of Chernobyl*, New York: W.W. Norton and Company, (1990): 25-26.

of the Soviet Nuclear Oversight Committee (GosAtomNadzor) which reappraised the causes of the accident:

> "...The local automatic control and local automatic protection system (LAC-LAP), which received signals from the ionization chambers inside the core, controlled the reactor at power levels greater than 10% of the nominal level. It is very difficult to control such a large reactor as the RBMK-1000 (core diameter 11.8 m, height 7.0 m) at low power levels using only the lateral ionization chambers. This is because at low power levels, when the LAC-LAP system is switched off, the lateral ionization chambers do not provide signals for the central parts of the reactor core and, moreover, do not indicate the axial power density distribution, since all the ionization chambers are located at the mid-plane of the core. Thus, at low power levels a reactor operator has to operate 'blindly,' relying more on experience and intuition than on the readings of the control instruments. Although 'blind' control of the RBMK-1000 is to some extent acceptable during startup of a poison-free reactor when its power density field is controlled in accordance with preliminary calculations, the situation is different when a non-uniformly poisoned reactor is being shut down. In this case, there is a risk of large field distortions and critically high non-uniformities of both the axial and radial power density distributions. these facts were not taken into account before the accident and, unfortunately, no limitations were imposed on reactor operation at low power levels."[11]

[g] Actually, according to INSAG-7, "The Commission considers that the personnel cannot be held to blame for operating the unit at a power of less than 700 MWt." This is because although operating at 200 MWt was a departure from the testing program, neither the design documentation, the regulatory documentation, nor the operating documentation prohibited operation of the unit at such a low power.[12]

[h] The monitoring and control system for an RBMK-1000 is composed of two basic subsystems: the control and protection system, and the reactor process monitoring system. The latter contains the centralized monitoring system known as the *Skala* (trans. *Cliff*) system. Information from the reactor process monitoring system is collected and processed by the *Skala* central monitoring system(designed to calculate the basic reactor parameters every five minutes) and by individual instruments or independent systems (channel failure detection, physical power monitoring system, fuel cladding failure detection) for some of the more important parameters. Built-in recording insturments "...are for recording relatively slow processes. They therefore make it possible to record peak values of the parameters concerned fairly reliably, but cannot be used to record fast non-steady processes."[13] The *DREG* program (diagnostic parameter recording program) and *PRIZMA* program (calculation of reactor parameters not measured directly) are subsystems of the *Skala* system. The DREG programs samples and records several hundred discrete and analog signals, but this does not include power, reactivity, and channel coolant flow rates, and records the positions of only nine of the 211 control rods.[14]

---

[11] INSAG-7, 40.

[12] INSAG-7, 77.

[13] INSAG-77, 52.

[14] INSAG-77, 56.

[i] Actually, according to INSAG-7, at the time of the accident no documents existed prohibiting the connection of all eight MCPs to the reactor at any power level. It was specified according to operating procedures, however, that at low power when the feedwater flow rate is less than 500 t/hr, each MCP was limited to 6500–7000 m^3/hr to prevent cavitation. The flow rates of certain MCPs actually exceeded the limit but did not cause cavitation of the pumps.[15] This contrasts with a western hypotesis that cavitation may have been a significant factor in introducing positive reactivity into the core.[16]

[j] "... the specific neutron field configuration with saddle points in the middle sections of the core (this is an objective and unavoidable factor for many reactor states), and the presence of water columns in the lower parts of the core (which occurs rarely, is subjective and permitted by personnel) were decisive factors [in establishing conditions for the subsequent reactivity runaway]... After [this] initial phase of neutron flux redistribution, caused by the design of the RCP rods and independent of the thermal-hydraulic state of the reactor..., the increase in power density caused the large void reactivity effect inherent in the RBMK-1000 reactor design."[17] (Figure IV.1.)

[15] INSAG-7, 77.

[16] Reisch Frigyes, "How Chernobyl Happened: A Second Opinion," *Nuclear Safety*, Vol. 28, No. 1. (January–March 1987): 43–45.

[17] INSAG-7, 68 – this section contains a good non-analytic sequence of events.

[k] This design flaw (of which the operators were not properly informed of in their training, Figure IV.3) has been identified as one of the leading contributors to the reactivity runaway. Unfortunately, although this flaw was identified by the Soviets as being critical to reactivity perturbations both well before the accident, and after the accident prior to the IAEA-sponsored Meeting of Experts in Vienna in August 1986, it was never identified as a major contributing factor to the accident. In fact, according to INSAG-7,

> "At the end of May 1986, after having analyzed the available data and performed various calculations, a group of experts of the USSR Ministry of Power... sent an addendum to the Report on the Investigation of Accident, in which they attributed the causes of the accident to the fundametally faulty design of the RCPS rods; the positive void and fast power coefficients of reactivity; the large coolant flow rate in conjunction with a low power level; inadequate safety features in the design and inadequate operating information for the personnel; and lack of indications in the design documentation and the technical reg ılationson the danger of ORM violations...."
>
> "At two meetings of the Interdepartmental Science and Technology council, chaired by A. P. Alexandrov (2 June 1986 and 17 June 1986), insufficient attention was paid to the calculations made by the All-Union Scintific Research Institute for Nuclear Power Plant Operation which demonstrated that the accident was largely due to deficiencies in the reactor design. In fact, all the causes of the accident were reduced exclusively to personnel errors. The decisions taken by the Interdepartment Science and Technology Council paved the way for the one-sided presentation of information on the causes and circumstances of the accident submitted to the IAEA, a wide range of specialists and the general public."[18]

[18] INSAG-7, 60.

There were thus two competing effects in the core when the AZ-5 emergency scram button was pressed: (1) Near the top of the core the reactivity goes down because the control rod (poison) enters from the top, and the upper portion of the graphite follower (moderator) is replaced by an aluminum connecting-stringer and water (acts as poison). (2) Near the bottom of the core, positive reactivity is added because water in the channel is replaced by the graphite follower (poison is replaced by moderator). If the lower core has a high flux, then introduction of positive reactivity is significant.

[1] The U.S. DOE in NUREG-1250 has commented on this possibility: "The steam released from a main steamline break in either steam separator room would fill the space above the Upper Biological Shield (see Figure III.xx), and below the shield blocks covering the pressure tube refueling connections. Steam would escape to the refueling floor via the gaps between the shield blocks (Figure IV.4 below). The steam would impinge on control rod drive mechanisms and could damage the control rod drive motors sufficiently to prevent operation. If steam blowdown is rapid, some shield blocks could be ejected off the floor."[19] NUREG-1250 also adds, "The leak or rupture of *a single fuel pressure tube* in the graphite region is the limiting design-basis event for the RBMK-1000 reactor vault [nominally at 0.22 psig with the Nitrogen-Helium cover gas]... [and] effects of tube rupture on surrounding graphite and the gas pressure boundary are uncertain. The reactor vault pressure boundary might be breached in such an event if operator detection and manual action are delayed."[20] One view of what may have happened just before the explosions has the Upper Biological Shield being raised by steam released from a few fuel channels rupturing (it is an easy matter to calculate that only a little over one atmosphere of pressure is needed to lift the 17 meter diameter, 2500 tonne equivalent Upper Biological Shield), subsequently shearing these channels at the weakest point – releasing more steam and leading to the "dancing blocks" observed before the 2nd major "expolosion."

This scenario was confirmed by a similar hypothesis put forth in the INSAG-7 report:

> "The design [of the reactor] did not provide the reactor space with a protection system against multiple ruptures of the fuel channels. A rupture of more than one of the fuel channels could, therefore, cause lifting of the reactor cover plate and upper structure of the reactor (structure [component] E), followed by failure of the whole RCPS rod insertion system and even withdrawal of the RCPS rods from the core. This leads to the introduction of positive reactivity, not to a fast and reliable termination of the chain reaction"
>
> "The possibility of more serious initial events was disregarded [in the design of the reactor], including accidents in which the reactor space is ruptured and extensive fuel damage is caused by multiple ruptures of fuel channels, resulting in lifting of the upper reactor cover

[19] U. S. Nuclear Regulatory Commission, comp. *Report on the Accident at the Chernobyl Nuclear Power Station* – NUREG-1250, (Washington, DC: U.S. Government Printing Office, 1987), 3-33.

[20] Ibid., 3-14.

and upper structure of the reactor (structure [component] E), as happened on 26 April 1986."[21]

INSAG-7 also proposes a non-analytic hypothesis concerning the sequence of events leading to the explosions,

> "Owing to the design characteristics of the reactor, substantial damage to even a few fuel assemblies (three or four assemblies are enough) can, and in this case did, result in destruction of the reactor itself and failure of its emergency protection system. The rupture of the pipes of several fuel channels caused an increase in pressure in the reactor space and a partial detachment of the reactor support plate from the shroud and consequent jamming of all the RCPS rods, which by that time were only half-way down."[22]

[m] "As is shown in [a] study performed by Japanese experts[23] based on direct experimental research, the fuel elements begin to disintegrate at an enthalpy of 220 cal/gm UO_2 (T = 3300 K). At an enthalpy of 285 cal/gm UO_2, the fuel elements rupture, and at 320 cal/gm UO_2 they explode and disperse in small pieces."[24] The NRC-sponsored *LWR Fuel Behavior Program*, conducted prior to the TMI-2 accident, investigated energy deposition in UO_2 fuel is the seminal study in this field.[25]

According to the Soviet model presented at Vienna, the first power peak occurred at 01:23:43.9 at 109 times full power (350 GWt), and that the fuel failed at 01:23:44.7. This caused the void fraction to increase from 41 to 100% by 01:23:44.9. The step increase in reactivity from this was estimated to be approximately $3.3 – which subsequently caused a second power peak at approximately 470 times full power (1,500 GWt).

The estimated fuel enthalpy at the time of the fuel failure (01:23:44.7) was estimated by adding the energy deposition during the transient to the initial enthalpy at the low power operation before the accident and subtracting for estimated heat loss to the coolant during the transient. It is estimated that 1242 J/g (298 cal/gm) was deposited into the fuel, and this magnitude is associated with UO_2 fuel melting. Using this as an average and knowing the core fuel load, the total fuel energy deposited into the fuel was approximately 142 MJ. Assuming the typical efficiency for the conversion of thermal to mechanical energy by a Fuel-Coolant Interaction is 0.5% or less, it is estimated about 0.7 MJ of mechanical energy was released, which is sufficient to cause appreciable damage to a piping system such as the Unit-4 fuel channels.[26]

---

[21] INSAG-7, 42, 47.

[22] INSAG-7, 69.

[23] "Analysis of the Destructive Forces Leading to the Chernobyl Accident," *Nuclear Engineering and Design*, Vol. 106, No. 2, (1988): 179–189.

[24] INSAG-7, 67.

[25] M. S. El-Genk, *Molten Fuel-Coolant Interaction Occurring During a Severe Reactivity Initiated Accident Experiment*, NRC Report NUREG/CR-1900 (EGG-2080), EG&G Idaho, Inc., (March 1981). For a summary of energy deposition studies as pertains to the Chornobyl accident see, D. A. Powers, T. S. Kress, and M. W. Jankowski, "The Chernobyl Source Term," *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 16–19.

[26] U.S. Department of Energy, *Report of the U.S. Department of Energy's Team Analyses of the Chernobyl-4 Atomic Energy Station Accident Sequence*, (DOE/NE-0076; DE87 003614) Washington, D.C.: U.S. Department of Energy, (November 1986): 6-3.

[n] It may not have taken the lifting of the Upper Biological Shield to fail the channels at the transition welds. The upper transition weld average temperature was calculated to rise by 55 K between 01:23:43.9–44.9. The predicted heatup rates over this interval thus correspond to an average value of 55 K/sec and attain a maximum of 95 K/sec. This exceeds by *four orders of magnitude* the Soviet operational limitation of 10–15 K/hour. As a result of these heatup rates, differential thermal expansion of the dissimilar zirconium alloy and stainless steel materials are expected to lead to failure of the pressure tube boundary within the upper transition weld region.[27]

---

[27] Ibid., 6-37.

Figure IV.1
Normalized Axial Neutron Flux for the Chornobyl Unit-4 Core
After the Emergency Control Rods were Scramed
(t = 0 at 8604.626/0123:40)

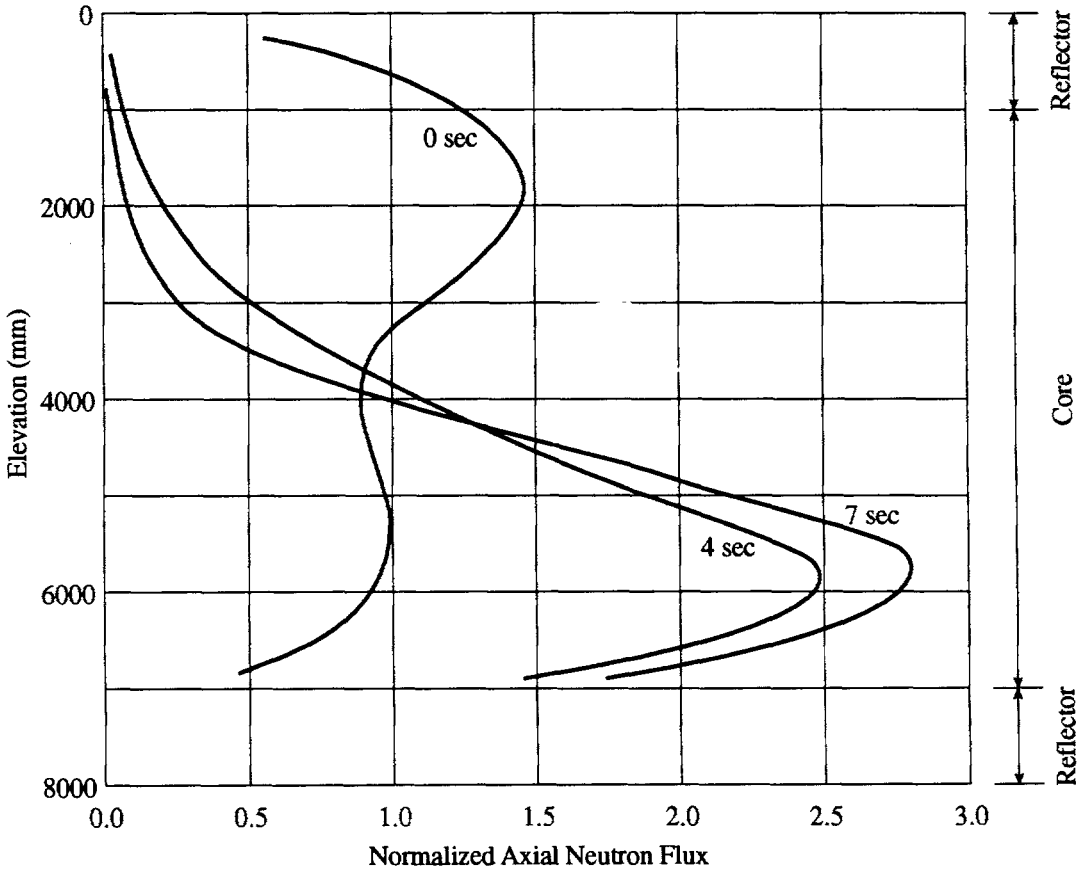


Figure IV.2
Schematic of a Scram (AZ) B_4C Control Rod and its Graphite Follower

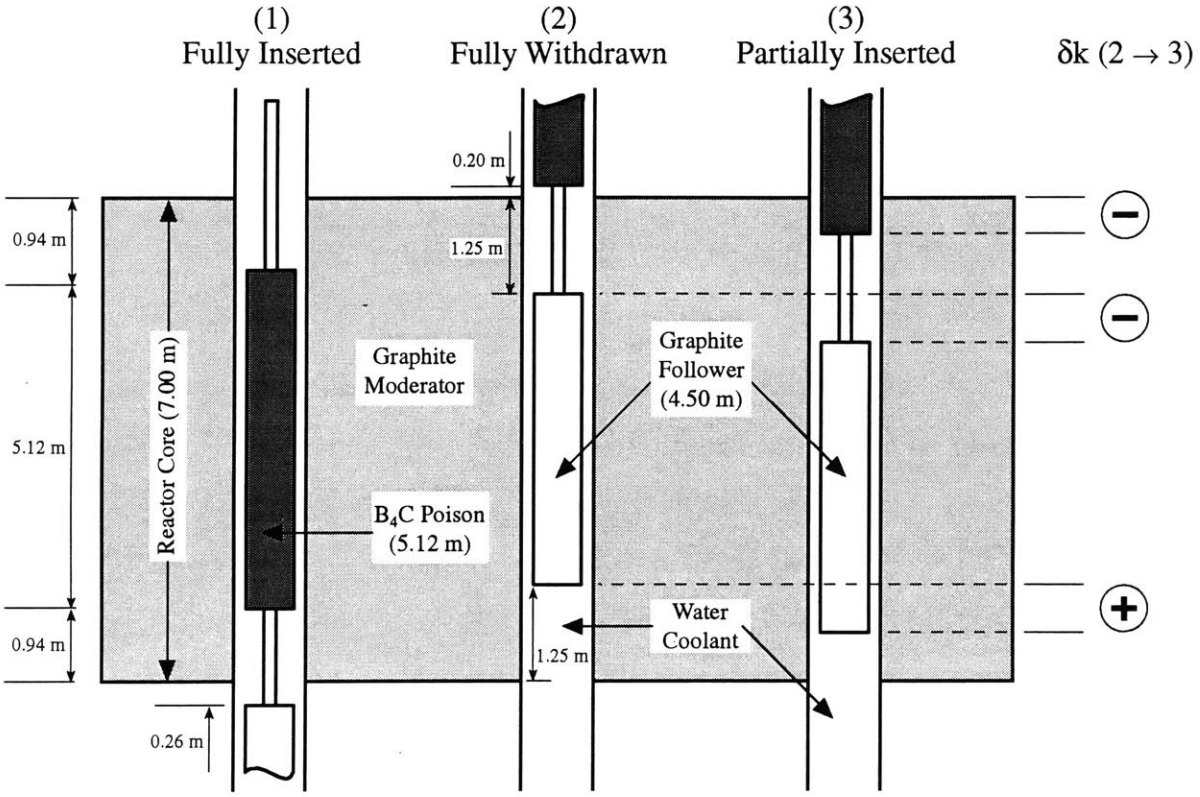
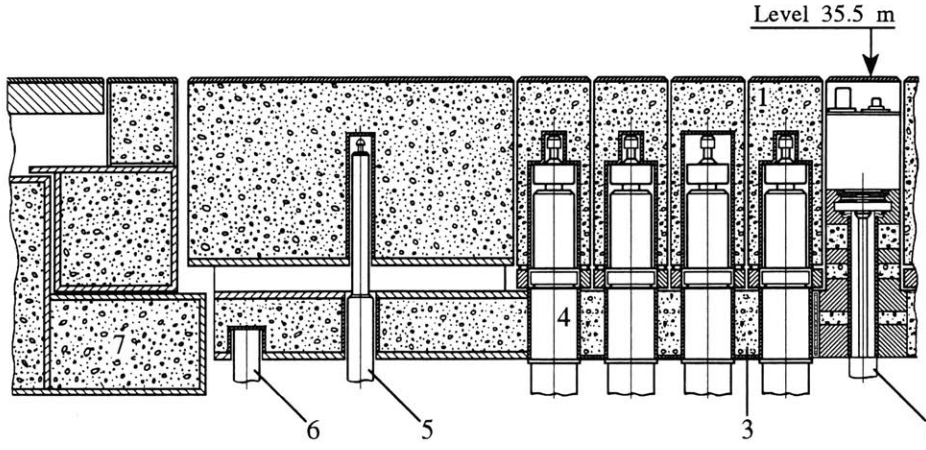


Figure IV.3
Technological Channel Cover Blocks and Central Hall Floor Over the Reactor



1. Removable Central Hall Floor Shielding Block 2. Upper Section of a Control Assembly Channel 3. Lower Block of Central Hall Floor Shielding 4. Upper Section of a Technological (Fueled) Channel 5. Upper Section of an Instrumentation Channel 6. Upper Section of a Reflector Cooling Channel 7. Peripheral Section of the Central Hall Floor Shielding

IV.3. Chronology of Events and Assessment of Mitigation Efforts Taken Following the Initial Destruction of Unit-4

It is common sense to take a method and try it. If it fails, admit it frankly and try another. But above all, try something.

– Franklin D. Roosevelt

The people would not understand. We have to be seen to be doing something!

– Valerij Legasov[1]

This section will re-examine the effectiveness of Soviet Accident Management Actions (AMAs) to mitigate the consequences of the Chornobyl accident. Particular attention will be paid to the two actions that have a direct bearing upon source term releases, namely the dumping of materials onto the core to smother the fire, and the purging of the core with liquid nitrogen to cool it and hinder its ability to interact with surrounding structures. Of minor significance to source term releases, but nevertheless interesting, are two other AMAs that will also be examined: the release of water from the pressure suppression pool to mitigate against the possible release of steam and enhanced transport of core materials if the molten core contacted the water, and the construction of a flat-bed heat exchanger under the foundation of the Unit-4 reactor building to mitigate against a possible "China Syndrome."

In fact, as will be shown, in contrast to what was reported by the Soviets in August 1986, the material thrown onto the core in an attempt to smother the burning fire and the purging of the core with (ostensibly *liquid*) nitrogen were not successful. The implication is that the core "burned" virtually uncovered during the Active Phase of the accident – releasing radioisotopes into the upper levels of the destroyed reactor building and directly into the atmosphere. This not only calls into question Soviet and western analyses of

[1] Piers Paul Read, *Ablaze*, New York: Random House, (1993): 133. Here, Mr. Read recreates a fascinating conversation that took place between members of the Government Commission at the site of the accident while brainstorming to come up with a "plan of attack."

Chornobyl source term releases,[2] but also may have important ramifications for the planning of western accident management actions. Moreover, the health impact to former residents of the 30-km exclusion zone surrounding the station (some of whom were not evacuated from this area until 8.5 days after the accident)[3] must be re-examined in light of the greater releases suggested by this scenario.

IV.3.1. Appraisal of the Situation and Fire Containment

The tremendous task of mitigating the consequences of the Chornobyl accident began almost immediately after Unit-4 was destroyed, that is, in the middle of the night of 26 April 1986. As a result of the explosion, significant quantities of reactor materials (in the form of large chunks of graphite, pressure tubes, and fuel assemblies) were hurled up to a distance of 150 meters from the center of the reactor. Because of their initial high temperature and decay heat , these materials started more than thirty fires on the roofs of the Unit-3 & 4 Auxiliary Building, the deaerator roof of Unit-3, and the Machine Hall above Turbo-Generator-7; and unfortunately, much of the roofing of these buildings was pitched with tar (bitumen) which exacerbated the fires. Inside the damaged Unit-4 reactor building, other fires had started because fuel and lubrication oil pipes and containers were

---

[2] Although lacking the new information about the fact that this material had not entered the core shaft, Powers et al provide an excellent source term analysis of the data presented by the Soviets in Vienna [Powers, D. A., T. S. Kress, M. W. Jankowski, "The Chernobyl Source Term," *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 9–28.] In contrast, a rather complex but poorly substantiated theoretical analysis of the supposed filtration cooling of the core through the dumping of the materials is presented in Maslov, V. P., Myasnikov, V. P., and Danilov, V. G., Filtering Cooling Model for the Pile-Up in the ChAPP Accident Block," *Fission Product Transport Processes in Reactor Accidents, Proceedings to the International Center for Heat and Mass Processes, Dubrovnik, Yugoslavia, May 22-26, 1989.* The conclusion section to this paper is particular poor because it seems to come to the conclusions that the authors wanted in the first place, namely that their filtration cooling model applies well to explain the drop and subsequent rise in total releases (hence giving the peculiar "bathtub" curve shape), that "the filtration cooling model of the pile-up *completely explains all the phenomena* taking place in the reactor after the accident" (emphasis added), and that "the convective cooling model convincingly explains, why [corium] fragments did not burn through the bottom of the reactor pit [Lower Biological Shield (LBS)]" – when, in fact, the LBS was completely penetrated by the corium.

[3] Ю. В. Сивинцева и В. А. Качалова, общие редакторы, *Чернобыль: Пять трудных лет*, Москва: Издат, (1992): 251. Evacuation of the more 49,000 residents of Prypjat began 36.5 hours after the accident, while evacuation of the remaining towns and villages (including the town of Chornobyl with 12,500 residents) took more than a week. Altogether, from April 27th through August 16th, 90,784 people were evacuated from seventy-five population centers in Ukraine – 89,489 from the Kyjiv oblast and 935 from the Zhytomyr oblast (see Chapter II.4).

damaged. The immediate task, therefore, was to localize these fires to prevent them from spreading to the adjacent Unit-3, and eventually to douse them. By 02:15 fires on the roof of the Machine Hall were localized, by 02:35 fires on the reactor and auxiliary buildings were put out, and by 06:35 all the fires in the vicinity had been extinguished.[4,5]

On Saturday morning (April 26th), governmental ministers and the Communist Party formed the Government Commission charged with coordinating accident "liquidation"* (mitigation) tasks, along with the mobilization of resources necessary to carry out such tasks.[6,7] Unfortunately, because initially no one seemed to know what had happened, nor was anyone sure of the extent of the damage,† incomplete information was being sent to Moscow as to the nature and extent of the accident.[8,9] According to Serhij Vasyl'ovich Shirokov (Head of the Division of Nuclear Power Stations in the Ukrainian Ministry of

---

[4] Ю. В. Сивинцева и В. А. Качалова, 72. (An excellent and detailed account of the fire-fighting efforts are outlined here. See also Международного консультативного кометета МАГАТЭ, *Международный Чернобыльский Проект: Технический Доклад*, Оценка радиологических последствий и защитных мер, Вена: МАГАТЭ (1992), 84.

[5] Immediately after the accident, two young senior reactor control engineers-in-training, Alexandr Kudryavtsev and Viktor Proskuryakov, were told to go the Central Hall above the reactor and manually insert the jammed scram rods into the reactor. Upon arriving they saw that, "A red and blue fire was burning from the mouth of the reactor, with a *powerful updraft.*" [emphasis added, Gregori Medvedev, *The Truth About Chernobyl*, New York: Basic Books, (1991): 103.] This appears to confirm that the graphite was burning within the reactor shaft while supplied with oxygen by a powerful draft of air. That night, Shcherbina noted the same from a helicopter, "[he] looked through binoculars at the reactor, now bright yellow from the extreme heat. Against the background he could clearly see the dark smoke and tongues of flame. And a glimmering blue light, not unlike starlight, shone from deep gashes to both right and left, deep within the bowels of the destroyed core. It seemed as if some immensely powerful hand was pumping invisible bellows, fanning that gigantic nuclear furnace, 20 m in diameter." [Gregori Medvedev, 177.]

* It is interesting that the word chosen in Russian and Ukrainian for mitigation is the stronger term "liquidation." To this day those that were or are engaged in clean up efforts at Chornobyl are officially called "liquidators."

[6] On Saturday morning, governmental ministers and the Communist Party formed the Government Commission charged with coordinating accident "liquidation" (mitigation) tasks, along with the mobilization of resources necessary to carry out such tasks. [Gregori Medvedev, 121, 174–178.]

[7] Piers Paul Read, op cit., 84. This and subsequent information are very important details that establish the fact that any *early* reconnaisance of the destroyed Unit-4 (let alone proper air sampling above the reactor) would have been impossible until the Government Commission approved such actions. Commission members did not leave on a flight from Moscow to Kyjiv until 10:00 A.M. (pg. 95), while Valerij Legasov, Academician, First Deputy Director of the Kurchatov Institute of Atomic Energy, and head of the Soviet delegation to Vienna, did not leave Moscow until 4:00 P.M. (pg. 96). Although there are a number of factual errors and misleading conclusions quoted from people interviewed, this book provides a fascinating account of oftentimes bungled efforts to contain the accident and its consequences.

† Even after the operators had been told how extensive the damage was, they didn't believe the firefighters who had been on the roof to look down into the Central Hall. [*Международный Чернобыльский Проект: Технический Доклад*, 84.]

[8] Ibid., 86.

[9] Read, Piers Paul, op. cit., 83.

Energy and Electrification at the time of the accident who was assigned coordinator of mitigation efforts in Kyjiv), at first it was very unclear what had happened – mainly because Anatolyj Djatlov, Deputy Chief Engineer of Units 3 & 4 and Viktor Brjukhanov, director of the station, refused to believe what had happened.[10] Although some plant personnel had risked their lives to climb to the roof and see what was going on,[11] they were either afraid to describe what they saw or were simply not listened to or believed. An attempt to cool the reactor with water seemed to fail,[12] although through a greater part of the day on Saturday some station engineers still thought the core was being at least partially cooled by water. It was not until 10:00 P.M. the day of the accident that a specialist from NIKIET (the RBMK design institute) flew over the reactor to assess the damage and reported that indeed it had been destroyed.[13] Apparently, first *official* recognition of what had occurred was around 3:00 o'clock in the afternoon.[14] However, it is more likely that the extent of the damage was not known by the *members of the Govenment Commission* until some time in the evening after the reconnaisance mission was flow over the reactor.[15] In response, the Government Commission decided to "bomb" the reactor with various materials to smother the fires inside the Central Hall area.[16,17]

---

[10] From a private communication with Shirokov, March 29, 1993 in Kyjiv.

[11] Read, Piers Paul, op. cit., 81–82.

[12] Ibid., 80.

[13] Ibid., 97. Boris Shcherbina (Soviet Deputy Prime Minister and 1st Chairman of the Government Commission on Chornobyl) and Valeryj Legasov did not arrive in Prypjat until 8:00 P. M. the day of the accident (pg. 101).

[14] Viktor Haynes & Marko Bojcun, *The Chernobyl Disaster*, London: The Hogarth Press, (1988):142.

[15] "[the team] had flown over the damaged reactor at a height of eight hundred feet in a helicopter belonging to the civil defense... The explosion had destroyed the reactor and ignited the graphite in its core. The Upper Biological Shield, weighing one thousand tons, had been blown to one side, leaving the inside of the reactor open to the sky. It was red-hot from the graphite fire." (Read, Piers Paul, op. cit., 101).

[16] *Международный Чернобыльский Проект: Технический Доклад*, 87-88.

[17] Read, Piers Paul, op. cit., 106–107.

IV.3.2. Active Phase Accident Management Actions

IV.3.2.1. Material Dumping to Smother the Reactor Fire

Current descriptions and appraisals of Soviet Accident Management Actions undertaken during the Active Phase to limit the release of radionuclides and to seal the reactor from the environment unfortunately do not fully reflect the reality of events during this period. One of the methods employed by the Soviets to smother the fire was the dumping of thousands of tons of materials by helicopter into the Unit-4 reactor building. The materials dumped and reasons for using these materials (as given by the Soviets) were:

— boron carbide, B_4C	to ensure against recriticality in the core
— dolomite, $MgCa(CO_3)_2$	to generate carbon dioxide to provide a smothering gas blanket and contribute to the dissipation of core decay heat
— a clay/sand mixture	to quench the fire and provide a filtration layer to limit radioisotope release
— lead*	to absorb heat and provide a liquid layer which would solidify upon cooling to seal the core and shield the surrounding environment from ionizing radiation.

Between April 27th and May 2nd more than 1,800 "bombing campaigns" dropped 5,020 tonnes of friable materials into the reactor building – although some dumping of sand and clay continued through May 10th.[18] (Helicopter logs indicate that to the end of May 1986 14,000 tonnes of solid materials, 140 tonnes of liquid polymers, and 2500 tonnes of trinatriphosfatum [dust-suppressing liquid] were dropped into the damaged reactor building.)[19] "At 7 P.M. on May 1st, [Boris Y.] Shcherbina [Deputy Chairman of the

* At some time during the bombing of Unit-4 with lead, sharp criticism was leveled against proponents of this idea. Melted and vaporizing lead, it was argued, would result in an ecological disaster through lead poisoning of the surrounding environment. Nonetheless, the bombing continued unabated until late May 2nd. (Personal conversation with Alexandr Alexandrovich Borovoi, Head of the Division of Radiation and Nuclear Safety of the Inter-Agency Scientific & Technical Center "Shelter", May 1992.) This is also confirmed in Read, Piers Paul, op cit., 133.

18 Ю. В. Сивинцева и В. А. Качалова, 83.

19 A. A. Borovoi, "Post-Accident Management of Destroyed Fuel From Chernobyl: Technologies Used and Lessons Learned," Chernobyl, Ukraine and Moscow, Russia: International Atomic Energy Agency, (1990): 15.

Soviet Council of Ministers and Chairman of the USSR Chornobyl Commission] announced that the volume to be dropped would be cut in half. There was reason to fear that the concrete structures supporting the reactor might not hold and that everything would collapse into the suppression pool, causing a thermal explosion and a massive release of radioactivity."[20] A summary of materials dropped is shown in Table IV.1.

Based on these actions, many explanations have been provided to account for the unusual shape of the "bathtub" curve that were based partly on the data in Table 4.10 of the Soviet report presented at Vienna (Figure IV.4), partly from ground and air radioactivity measurements, and partly on the assumption that the materials thrown into the reactor building covered the burning core. Today, most agree that the materials thrown into the core in the days immediately following the initial explosions gave rise to the unusual shape of the "bathtub" curve. For example, according to INSAG-1 there are four possible explanations for the apparent increase in fission product release rates beginning five to six days into the accident (May 1–2):

(a) Once the initial wave of material deposition was stopped (on May 2nd), heat losses from the debris declined, the temperatures rose and vaporization releases were enhanced;
(b) Some increase in gas flow over the debris occurred that enhanced material removal by vaporization or enhanced chemical (oxidation) reactions;
(c) The melting of deposited lead and the pyrolysis of dolomite came to an end so heat losses from the debris dropped, the temperature of the debris rose, and vaporization release again increased;
(d) Enhanced oxidation from some unidentified mechanism aided release.[21]

---

[20] Grigori Medvedev, 195. Actually it wasn't the 'concrete structures supporting the reactor' that the Soviets were worried about, but rather the integrity of the 5.3 m-tall steel cross-shaped reactor support, Component S. This seems to be confirmed by, "The U.S.S.R. team reported that they were concerned that any further additions of material could overload the *structural support of the reactor vault.*" [M. W. Jankowski, D. A. Powers, and Kress, T. S., "Onsite Response to the Accident at Chernobyl (Accident Management)." *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): pg. 38.]

[21] INSAG-1, 38; also, *Международный Чернобыльский Проект: Технический Доклад*, 90–91.

Table IV.1[22]

Summary of Materials Dropped Into the Reactor Building of Unit-4

Date	Days After Accident	Number of Sorties Flown	Mass of Materials (tonnes)	Mass–Running Sum (tonnes)
April 26	0		—	—
April 27	1*	44	150	150
April 28	2	93	300	450
April 29	3	186	750	1,200
April 30	4	?	1,500	2,700
May 1	5	?	1,900	4,600
May 2	6	?	420	5,020
May 3	7	0	—	—
May 4	8	0	—	—
May 5	9	0	—	—
May 6	10	0	—	—
By end of May	~35	total >1800	11,620	16,640

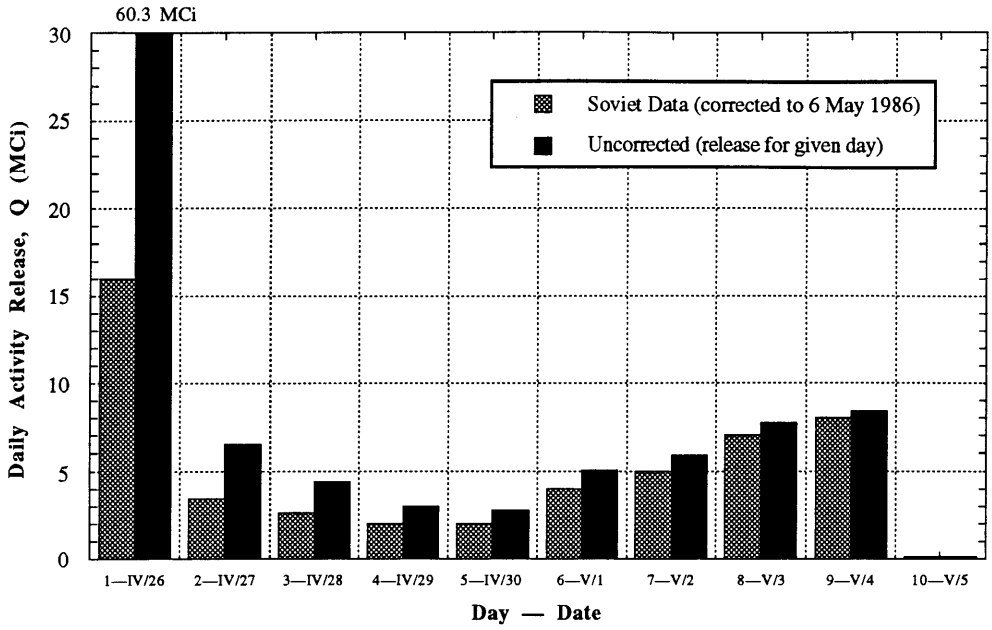
* Note that material deposition did not begin until at least 16:00 on April 27th, or approximately thirty-eight hours after the accident. (Private conversation with Serhij Vasyl'ovich Shirokov.)

Material	Chemical Formula	Mass (tonnes)
boron carbide	B_4C	40†
dolomite	$MgCa(CO_3)_2$	800
clay and sand	—	1,760
lead	Pb	2,400††
other solid materials	—	9,000
liquid polymers	—	140
trinatriphosfatum	—	2,500
TOTAL	—	**16,640**

† The boron carbide arrived Sunday night (April 27th) [Shirokov]
†† The lead arrived during the 5th day after the accident (April 30) [Shirokov]

[22] From helicopter pilot logs recorded in the research notes of Dr. Alexandr Alexandrovich Borovoi, Head of the Division of Radiation and Nuclear Safety of the "Shelter" Inter-Branch Scientific and Technical Center of the Ukrainian Academy of Sciences, Chornobyl, Ukraine.

Figure IV.4[23]
Total Chornobyl Unit-4 Releases Over the Active Phase – The "Bathtub" Curve



Perhaps of greater interest than the increase in release rates on the 5th and 6th days is the sudden drop to almost negligible levels approximately nine to ten days into the accident – signifying the end of the Active Phase. Till now, no definitive explanation for this phenomenon has been available. One hypothesis proposed also in INSAG-1 is, "that the release accelerates because core debris reheat and liquefy. The required temperature for liquefaction is 2300–2900 K depending on the amount of unoxidized zirconium present in the debris. Vaporization accelerates upon debris liquefaction. The liquefied debris can relocate, eventually falling into the lower pipe runs where it can freeze. Continuing cooling flows of gas into the pipe runs prevent the quenched debris from either melting or significantly attacking concrete and steel structures in this part of the reactor."[24] Also put

[23] U.S.S.R. State Committee on the Utilization of Atomic Energy, Volume II: Accompanying Material, Appendix 4, Table 4-10, (13).

[24] INSAG-1, 39. Also, in the *Международный Чернобыльский Проект: Технический Доклад* (91), it is expressly stated without substantiation that, "These phenomena [the alleged behavior of releases

forward is the hypothesis that bombarding the core with materials may simply have done what it was intended to do, i.e., smother and seal the remains of the reactor.[25,26]

Investigations conducted from 1986 through 1989 have shown that previous notions and descriptive models concerning to what extent damage may have occurred within Unit-4 after the accident, in most cases do not correspond to the actual conditions of the destroyed reactor. After a significant number of bore samples (about seventy) had been taken of the core region, Sub-Reactor Region, Steam-Distribution Corridor, and a number of other areas, radiation field measurements were taken to determine which areas were safe enough to approach for closer inspection.[27] Visual inspections of these areas were then conducted either by remote-control visual aids (video-cameras, periscopes, or small robots), or, if approachable, directly by researchers armed with photo- and video-cameras. The most startling discovery was that the core region, rather unexpectedly, turned out to be practically empty (Figure IV.5). Even more significant for the present discussion was the fact that, according to chemical analyses, the Fuel-Containing Masses (FCMs or "lava" as it is commonly referred to) located in the lower regions of the reactor building contain none of the materials thrown into the reactor in the attempt to smother it – rather, they have a material composition similar to that of a mixture of corium, the Lower Biological Shield (LBS),* and other metal structures formerly located beneath the

---

as shown by the "bathtub" curve, and especially the final sharp drop in releases] were results of specially adopted measures [Accident Management Actions] that led to the binding of fission products into more stable chemical forms."

[25] U.S.S.R. State Committee on the Utilization of Atomic Energy, Volume I: General Material, 39-40.

[26] "The [accident management] measures adopted by the Governmental Commission significantly diminished direct contact of the damaged [!] reactor core with the atmosphere and prevented the spread of the melted nuclear fuel beyond the bounds of Unit-4. The over 5000 tonnes of various materials thrown *into* the reactor created the needed insulating plug over the reactor." [emphasis added, translation from Ю. В. Сивинцева, В. А. Качалова, 57.]

[27] For descriptions of bore sample collection and general research within the Sarcophagus see (1) *Техническое Обоснование Ядерной Безопасности Объекта "Укрытие"*, Под редакцей группы в составе: С. Т. Беляев, А. А. Боровой, Ж. Г. Волков, А. Ю. Гагаринский, Н. Е. Кухаров, Г. А. Шароваров, В. Ф. Шикалов, Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, 1990, (2) *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие»*, Чернобыль, Украина; Минск, Беларусь: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, Институт радиоэкологических проблем при АН Беларусь, 1992.

* In architectural-engineering jargon, the Soviets typically use the term "scheme" to indicate a major component of a system. In the this case, the Lower Biological Shield is oftentimes referred to as *Scheme OR*, while the Upper Biological Shield is referred to as *Scheme E* (hence its nickname "Elena"). For clarity,

core.† (The LBS, containing serpentine – a hydrous magnesium silicate $3MgO{\cdot}2SiO_2{\cdot}2H_2O$ or $Mg_6[Si_4O_{10}]{\cdot}[OH]_8$, cast iron-pebble filler-material, and stainless steel coolant piping surrounded by stainless steel plating, is the only structure in the vicinity that contains substantial quantities of magnesium – traces of which are found in the FCMs.)[28]

In addition to chemical analyses, detailed examination of video clips of the damaged reactor taken from a helicopter two to three days after the accident clearly show that the infamous red-glowing mass of (presumably) burning graphite** is located away from the shaft of the reactor in the area just to the east of the southern spent fuel pool on the level of the Central Hall. Little is visible of the reactor shaft itself because it blocked by a significant amount of severely damaged "upper water & steam communication piping" (i.e., coolant piping) and the Upper Biological Shield (UBS) is positioned almost vertically on its side blocking most of the shaft. Finally, visual investigations conducted later showed that the vast majority of materials thrown into the reactor area formed a huge pile approximately 8–12 meters high partially covering the opening to the southern spent fuel pool – precisely where the "burning" mass was seen†† (See Figures IV.5 – IV.7). Apart from the

---

the term *Scheme* will be substituted with *Component*; so, for example, the Lower Biological Shield will be referred to as *Component OR*.

† See Chapter V.3, "The State of Nuclear Fuel Located Within *Shelter*."

28 *Техническое описание конструкции реактора РБМК-1000*, a reference book for training RBMK operators. See also the construction plans and blueprints Гострой СССР, Чертежи ВНИКИЭТа, Москва, Ноябрь 1976, Октябрь 1979.

** Given the fact that the roof of Unit-4 was covered with a large amount of asphalt-like (bitumen) material, an argument has been put forth that it wasn't graphite at all that was seen burning – producing the red glow – but rather a large quantity of asphalt that collapsed into the Central Hall together with the roof. Unfortunately, this is impossible to verify because the Central Hall area, and especially the pile of debris over the spent fuel pools, has not yet been investigated. See also N. Shteinberg, J. Joosten, and S. Routchkine, "Fire at Chernobyl-2," *Nuclear Engineering International*, (April 1992): 23.

†† Serhij Vasyl'ovich Shirokov [private communication in Kiev on 29 March 1993] flew over the destroyed reactor building twice: on May 1st and on May 5th (on the 6th and 10th days following the accident.) According to Shirokov, on May 1st it was quite difficult to see clearly into the area of the Central Hall because "thick, white" smoke was continuously billowing out, the unsteady motion of the helicopter made it difficult to get a fix on objects, and to avoid extreme exposures to the helicopter's crew the hover period was quite short. However, he asserts that on May 1st the red glow in vicinity of southern spent fuel pool was still visible, and a faint glow from the area of reactor shaft could also be seen. Other smaller "glows" were visible through holes in the roof of the turbo-generator hall created by debris ejected during the explosion(s) that burned or melted through the roof. These "glows" were presumably chunks of core material that had not completely cooled.

Figure IV.5

Cross Section (Looking North) of the Damaged Chornobyl Unit-4
Reactor Building and Sarcophagus

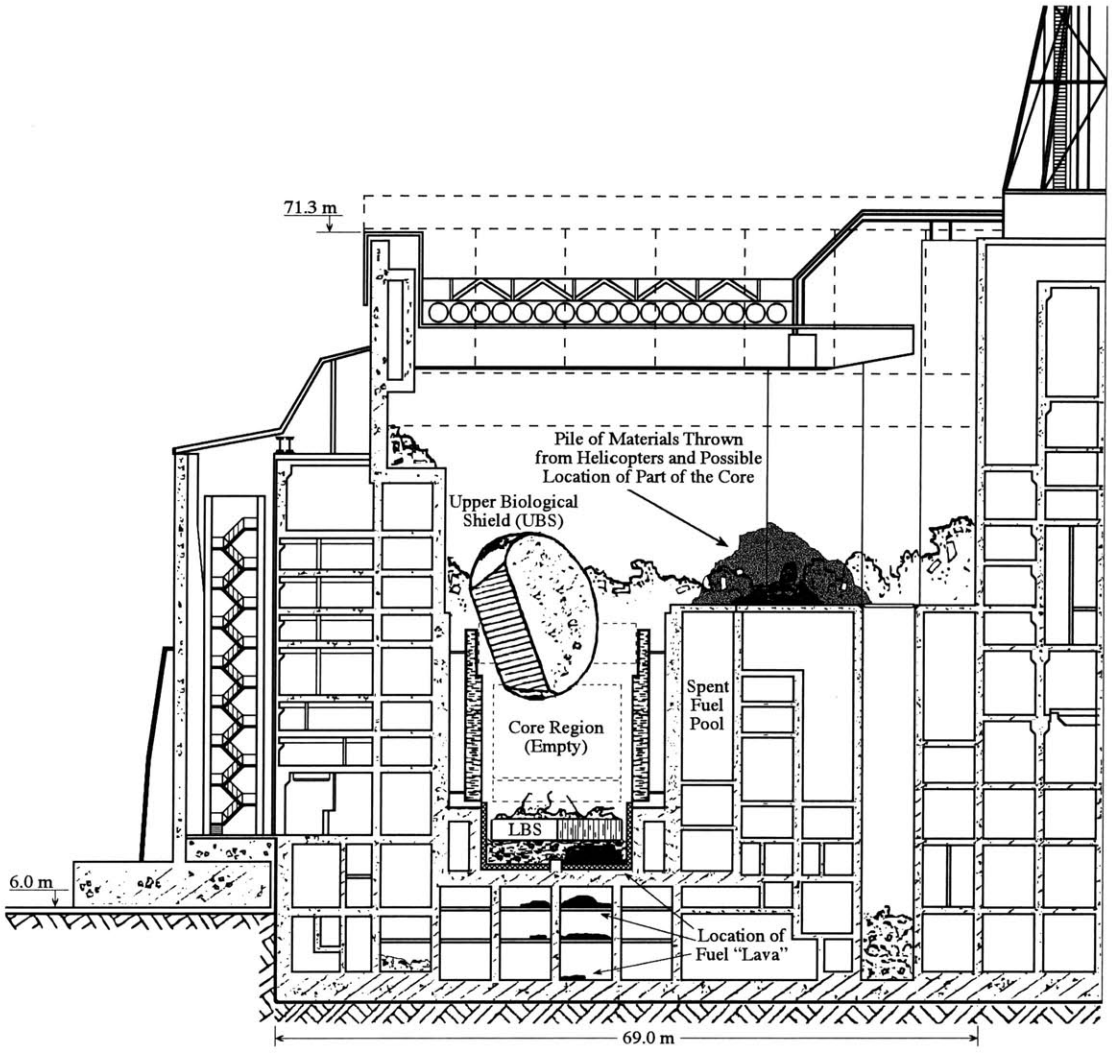


Figure IV.6
Schematic of the Central Hall Area and Sarcophagus at Level 35.5 m

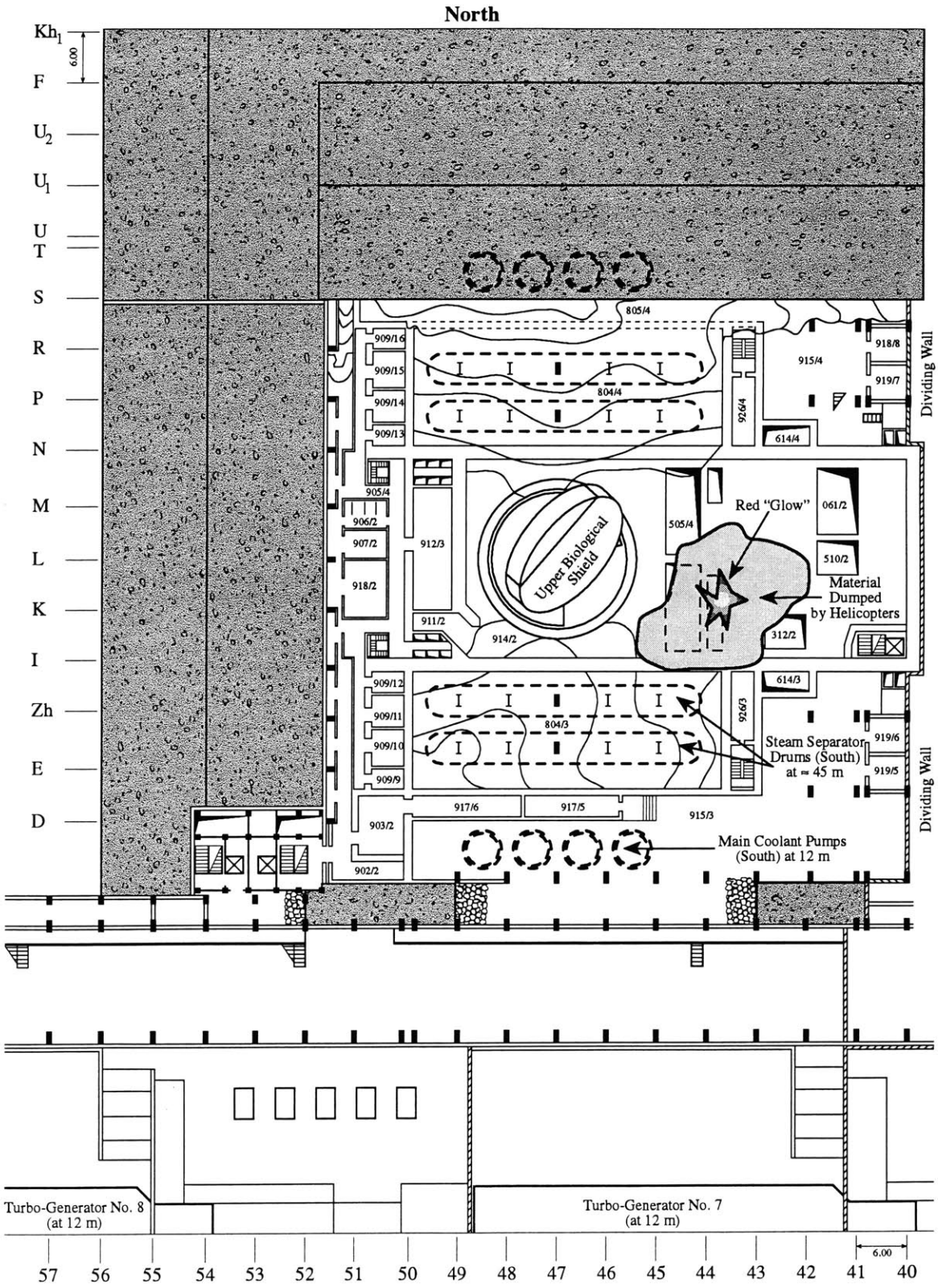
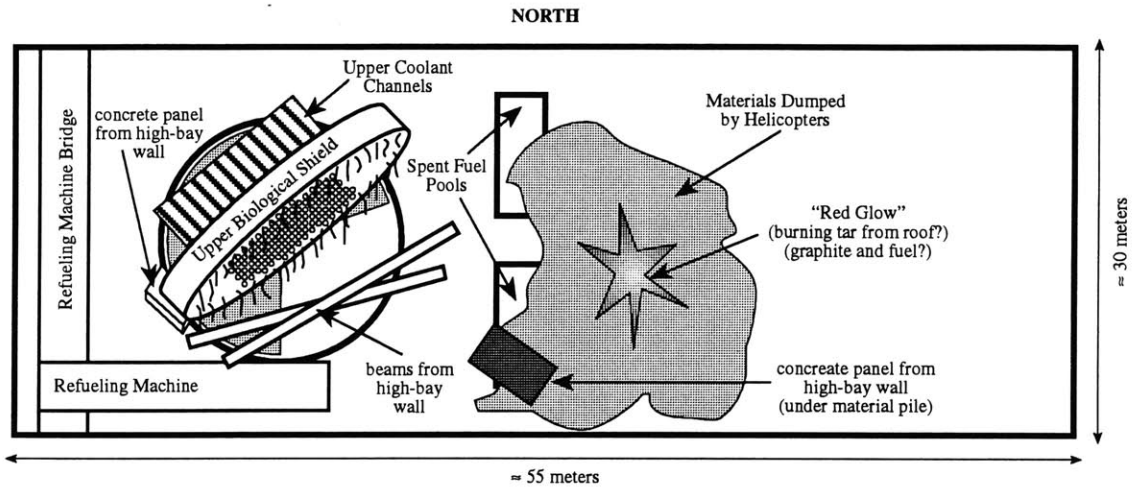


Figure IV.7

Schematic of the Central Hall Showing the Location of Materials Dropped from Helicopters



fact that accurate bombing of a small target from 250–300 meters in a highly radioactive environment made the task of the pilots extremely difficult, dispatch commands were radioed from an observer either on the roof of the Prypjat's Communist Party Executive Committee building (*Miskvykonkom*) or from the hotel *Polissja* in the city[29] – three kilometers away and facing into the sun for the first half of the day.[30,31] Evidently the heli-

[29] Read, Piers Paul, op. cit., 107, 123. Aside from general air traffic control for the helicopters, it would have been impossible for the observer on the roof to guide the helicopter to the correct position above the reactor because he was over three kilometers away.

[30] Personal conversations (September 24–28, 1992) with Konstantine Pavlovich Checherov, *Complex Expedition* scientist, and Vadym Vasyljovych Hryshenko, Head Construction Engineer for Units 5 & 6 called up to manage accident management actions. Actually, the dispatcher acted more as an air traffic controller for the dozens of helicopters engaged in the operation. There were no direct commands given to drop the material – only the crew members could see what they were targeting. The general command seems to have been to hit the "red glowing mass." Hindsight notwithstanding, one wonders why, instead of having commands radioed from a man three kilometers away (who obviously could not see whether the bags of materials were hitting the intended target), another helicopter hovering at 1500 – 2000 meters above the destroyed reactor could have been safely used to issue the same commands and would have proved much more effective.

[31] Air Force Major General Antoshkin was told, "*...well after midnight on April 27th...* everything depends on you and your helicopter pilots now, general. The crater has to be sealed off tightly with sand, from above." By the time a suitable landing pad was established and enough men were rounded up to collect sand from the banks of the river into bags, the first bombing runs did not begin until sometime during the morning of the April 27th, or possibly one and one-half days after the accident. [emphasis added, Grigori Medvedev, 179, 181; Piers Paul Read, 107–109.]

copter crews, in an effort to smother the blaze, aimed for the burning mass – missing the reactor shaft completely. It was not until 1990–91 that the Soviets reported the fact that few if any bags of materials had fallen on top of the core.[32,33,34,35] It is clear that the Soviets knew this quite early on,[36,37] or at least could have deduced it from aerial photographs over the destroyed reactor. As supporting evidence for the renderings in Figures IV.5 – IV.7, Figure IV.8 is one of these photographs – taken directly over the reactor about two months after the accident. Clearly visible is the UBS hanging inside the reactor shaft, and the large pile of material thrown in the area of the southern spent fuel pool. Figure IV.9 is another photograph of the Central Hall area clearly showing no pile of materials (contained in large canvas and plastic bags) covering the UBS or the core shaft.

---

[32] A. A. Borovoi, "Post-Accident Management of Destroyed Fuel From Chernobyl...," 15. It is unclear why, given this information, the IAEA in its *International Chornobyl Project* report continued to claim that the reactor had been covered with this material.

[33] Боровой, А. А., "Внутри и Вне «Саркофага" Припринт, Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, (1990): 6.

[34] "Between 1986 and 1989, unsuccessful attempts were made to find traces of lead in rooms below the reactor, the washing tank [Pressure Suppression Pool], the steam distribution duct [corridor], the room under the reactor [Sub-Reactor Region], etc. Only three years after the accident (1989), after many search attempts, was it realized that the problem posed could not have been solved, or at least only partially. [¶] Under the most optimistic assumptions, only a small part of materials could really have been dumped in the reactor pit. Most formed mounds up to 15 meters high in the reactor control room [Central Hall]. Similarly, it was impossible to block all channels taken by air to escape from the reactor pit, in other words create a suitable filtering layer." Belyayev, Spartak T., Alexand[e]r A. Borovoy[i], and I. P. Bouzouloukov, "Technical Management on the Chernobyl Site: Status and Future of the 'Sarcophagus'," in *Nuclear Accidents and The Future of Energy: Lessons Learned from Chernobyl: Proceedings of the International Conference in Paris, France, April 15–17, 1991*, by the European Nuclear Society (ENS), Paris, France: European Nuclear Society, 1991, 27.

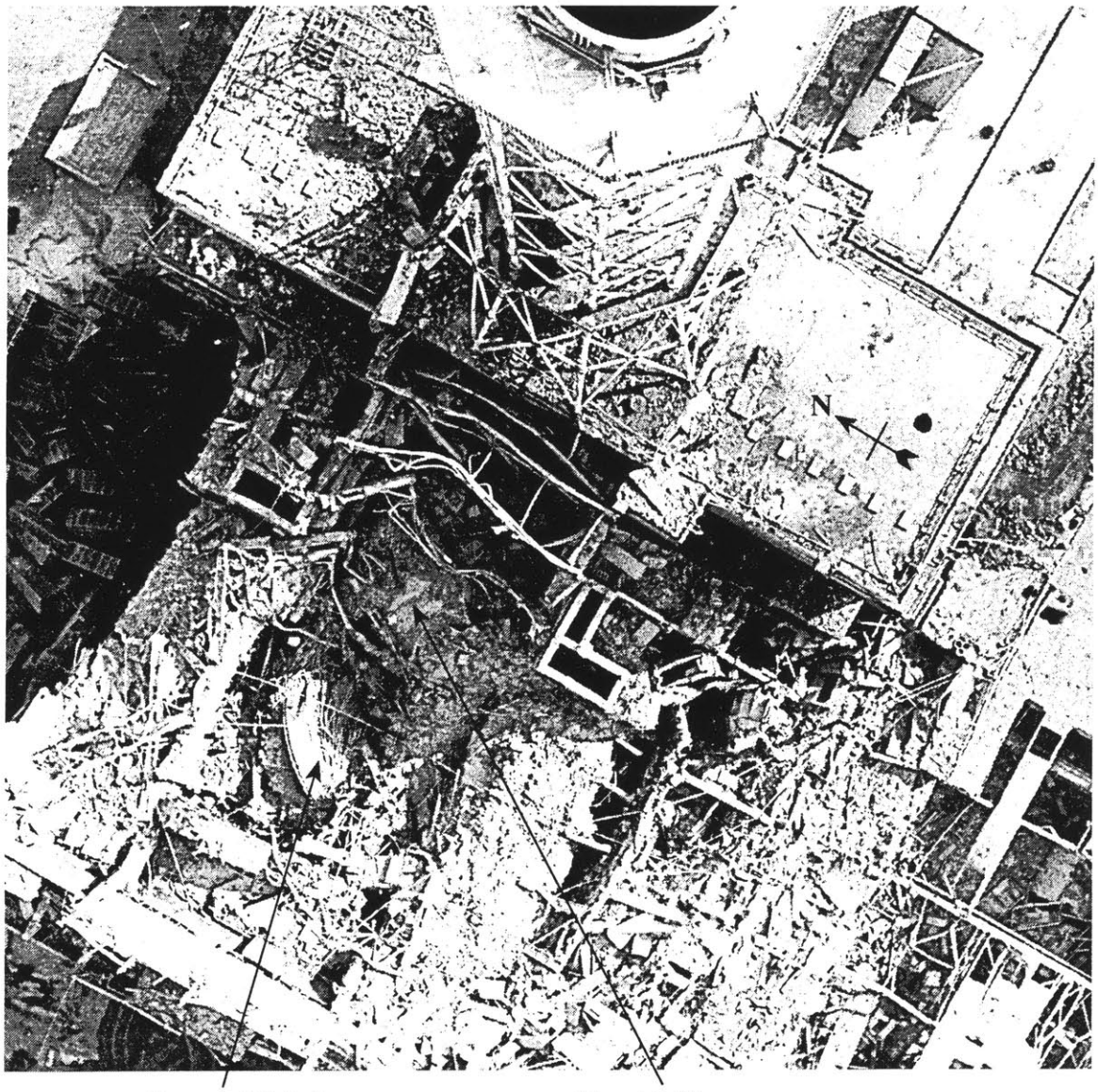
[35] Interestingly, in a 1991 NOVA documentary (originally Horizon/BBC) entitled *Suicide Mission to Chernobyl*, without realizing its implications the same claim is also made: "... the military attempted to bomb the reactor with neutron-absorbers and other chemicals. Several pilots flew straight through an invisible plume of radioactive particles – and died soon after. Despite their valiant efforts, *almost no neutron absorbers got into the core.*" [emphasis added]

[36] Interestingly, in testimony given by V. Ya. Prushinsky, chief engineer of USSR Division of Nuclear Energy, states, "On May 4th, I few over the reactor in a helicopter with Academician Velikhov. After studying the destroyed reactor building from the air, Velikhov admitted that he did not know how to bring the reactor under control. He sounded quite worried. And this was after 5,000 tons of assorted materials had been dumped into the gaping hole left by the nuclear blast." [Grigori Medvedev, 182–183.]

[37] As further evidence that the dumped material had not hit the intended target until it was too late, "Still, in the fading light of the evening [of May 6th], a last run by a helicopter over the reactor showed a small but bright spot of red in the crater... The next day [May 7th] a further eighty tons of lead were dropped into the reactor, after which the luminescence ceased." [Read, Piers Paul, op. cit., 141.] From this account it is unclear what or where the "small but bright spot" was, and contradicts radiochemical analyses (see Part II) that indicate essentially no lead is found in samples of solidified corium.

Figure IV.8

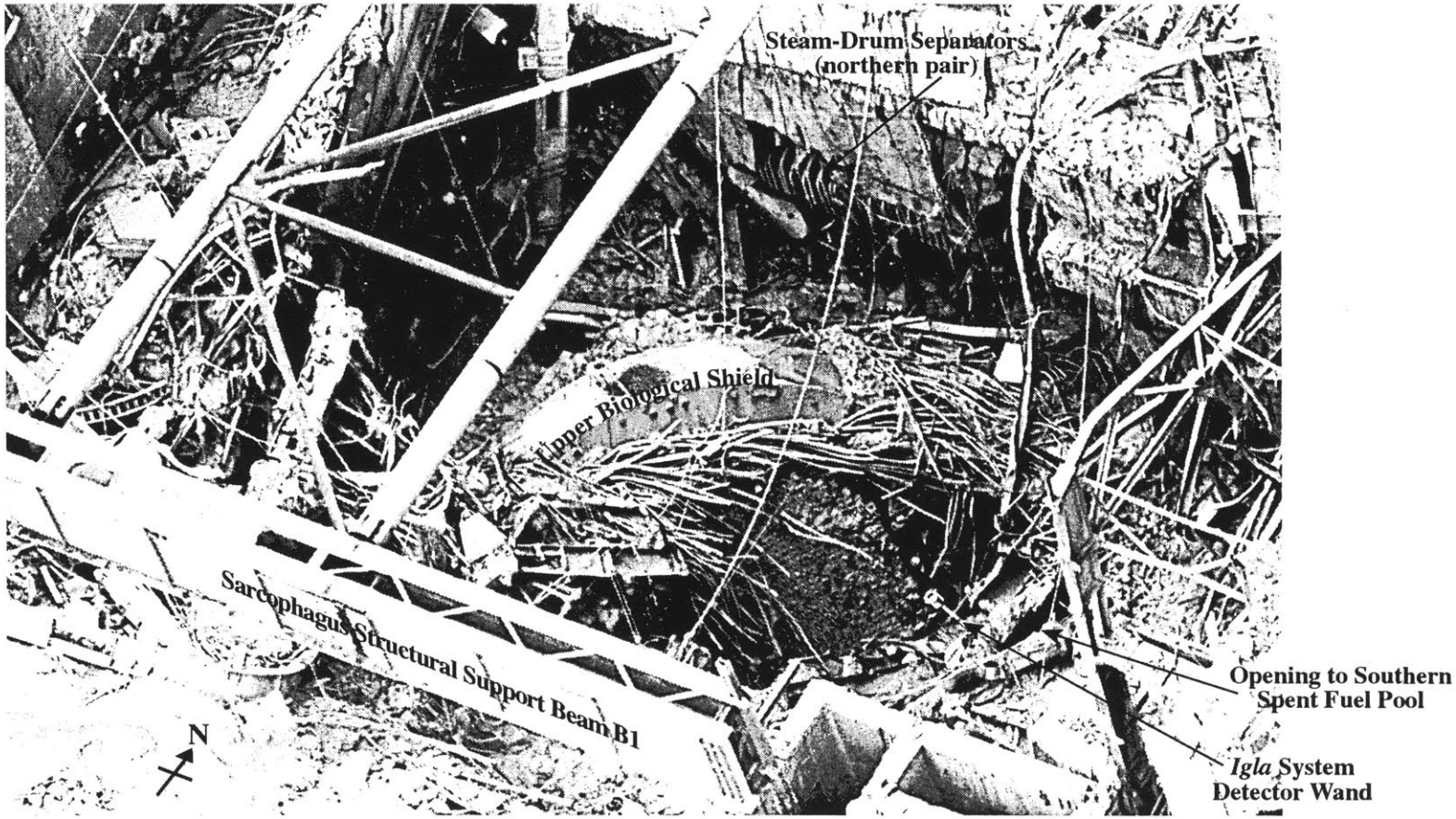
Photograph of the destroyed Chornobyl Unit-4 reactor building in July 1986 as viewed from directly above the reactor shaft in the Central Hall Area.†



† Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

Figure IV.9

Photograph of the Upper Biological shield (USB) viewed from the south-by-southeast taken in September 1986. (Pressure channels along the periphery of the USB remain while those in the middle have clearly been severed flush with the surface.) Note the absence of any bags of materials covering the UBS and surrounding structural debris, the gaping hole in front of the UBS leading downward into the core shaft, and the hole over the Southern Spent Fuel Pool.†



† Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

IV.3.2.2. (Liquid) Nitrogen Purge of the Core Region

Based on a May 1st decision by the Governmental Chornobyl Commission, beginning early on May 6th[40] the Soviets started to "purge the core with nitrogen" by pumping it (using the station's compressor) under the core through the "lower piping communication" (coolant channels) under the reactor to eliminate air ingress, to provide cooling for the core, and to prevent further oxidation (burning).[41,42] According to Medvedev, *"liquid* nitrogen was pumped... into all the spaces around the reactor vault," and that, "a cloud of cold nitrogen [gas] rose around the reactor. This proved to be an effective remedy. The temperature of the lower part of the reactor began to fall. At the same time, the air drawn by the chimney effect through the reactor core was gradually replaced by nitrogen, which suppressed the graphite fire... The fire began to die out."[43] A number of other sources also credit this action with having fulfilled its intended purpose.[44,45,46,47] Unfortunately,

---

[40] "On May 5, a cold nitrogen inlet system was located in the space under the reactor pit in order to provide additional cooling and to reduce the oxygen concentration." Ibid. Although the purging system may have been installed, the nitrogen did not arrive until 1:00 A.M. on the 6th of May – almost exactly 10 days after the accident and just after the end of the Active Phase. [Read, Piers Paul, op. cit., 140.]

[41] U.S.S.R. State Committee..., 39–40. Note that here (as the primary source material) liquid N_2 is not explicitly mentioned; although in Ю. В. Сивинцева и В. А. Качалова, 84, it is specifically stated that the reactor was cooled with *liquid* nitrogen. This is also the case in INSAG-1 (46) and the IAEA's International Chornobyl Project *Международный Чернобыльский Проект: Технический Доклад* (88, 90) which references other sources including INSAG-1.

[42] In what appears to be an indication of just how much emphasis was placed on *liquid* nitrogen as a working fluid, Valerij Legasov is alleged to have proposed, "Why not pump it [nitrogen] in to freeze the earth beneath the foundations, drive out the oxygen and smother the fire?" [Read, Piers Paul, op. cit., 139.]

[43] Zhores Medvedev, *The Legacy of Chernobyl*. New York: W.W. Norton and Company, (1990): 60.

[44] S. N. Begichev, A. A. Borovoi, E. V. Burlakov, A. Ju. Gagrinsky, V. F. Demin, I. L. Khodakovsky, and A. A. Khrulev, "Radioactive Releases Due to the Chernobyl Accident," *Presented at the International Seminar on Fission Product Transport Processes in Reactor Accidents*, May 22 – 26, 1989, Dubrovnik, Yugoslavia, (1989): 9.

[45] INSAG-1, 39.

[46] U. S. Nuclear Regulatory Commission, comp, *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250), Washington, DC: U.S. Government Printing Office (1987): 6-3 — 6-8.

[47] *Международный Чернобыльский Проект: Технический Доклад*, 88–89. Based upon the above references, this report states that (translation), "... members of the Governmental Commission decided to begin pumping *liquid* nitrogen into region underneath the reactor." Moreover, whereas the INSAG-1 report hypothesizes on the scenario of the Active Phase, The *International Chornobyl Project* report is more affirmative in its analysis, "In the next five days [April 27 – May 1] the rate of release decreased to a minimum – approximately six times less than the initial release. During this stage of the accident, *the decrease in the release rate was achieved on account of measures taken to quench the burning graphite and on account of the cooling of the core.* [emphasis added] These measures, including the dumping of 5000 tonnes of boron carbide, dolomite, clay, and lead into the core from helicopters provided filtration for the radioactive substances being released from the core." (90) And yet this appears to contradict a different conclusion reached on the previous page, "By May 6th the temperature of the [reactor] vault began to fall, the reasons

as with the material dumping to smother the core, this scenario does not fully reflect the reality of events during the Active Phase.

By all indications,[48] the original intent ot the May 1st decision was to pump *liquid* nitrogen into the core shaft to cool the core and to limit oxidation.[49] An order went out to bring as much liquid nitrogen to the station as soon as possible; and by May 6th (at 1:00 A.M. – almost exactly 10 days after the accident and just after the end of the Active Phase)[50] the first tanker-trucks were arriving on the scene. Two N_2 and O_2 make-up stations, to service the needs of Units 1 & 2 and Units 3 & 4 separately, were located on the territory of the power plant, along with a compressor station just to the northeast of Unit-1 (Figure IV.10.) In addition, several large N_2 storage tanks were located close to the

---

for which to this day remain unknown. Possibly, this came about thanks to the action of the boron carbide and sand, and possibly due to the burning away of graphite or the further melting of the fuel which then took on a "safer" [more stable?] configuration."

There are more inconsistencies in this report. For example, on page 88 we read (translation), "Part of the problem had to do with the fact that no plan had been prepared in advance in the event of an accident with such large-scale and prolonged releases of radioactive substances. For example, during the first few days after the accident, when the Governmental Commission was stationed in Prypjat, its members had neither respirators nor individual dosimeters. ¶ At the station itself, automatic means for external dosimetry control were lacking..." Yet on the following page, "By the beginning of May, monitoring above [the reactor] began with the help of helicopters. *By August* [emphasis added], special detectors (diagnostic buoys) were able to be placed in the debris of the core close to the Upper Biological Shield... These detectors measured gamma radiation, thermal conductivity and thermal conductivity, air temperature, and convection currents." Despite the shortage of lack of dosimeters at an operating nuclear power station (not to speak of special thermometers and heat detectors capable of withstanding radiation fields upwards of 10,000 Rad/hr), the report continues, "By May 1st, the temperature of the core began to increase, which possibly arose as a result of fission product decay heat within the *sealed* [?!] reactor." [emphasis added]

Not only could the temperature of the core not be established to any degree of accuracy during the Active Phase, but even if the temperature could be measured on May 1st, one cannot immediately draw the conclusion that the temperature was *decreasing* before that – especially since the core was neither sealed nor covered at all. It is more than likely that the temperature of the core, if not increasing during the first five days, was at least staying more or less constant.

[48] Much of the discussion that follows is summarized from a private conversation with Vadym Vasyljovych Hryshenko, (October 13, 1992.) Because the Governmental Commission files are still under lock and key, this scenario can by no means claim to be definitive – although it is presumably the most accurate to date.

[49] Morris Rosen (at the time of the accident Deputy Director of the Division of Nuclear Safety in the IAEA's Department of Nuclear Energy and Safety), based on Soviet information, stated that "other measures being taken to bring the situation under control include the use of *gaseous* nitrogen from containers of *liquid* nitrogen introduced to the access area, to maintain an inert atmosphere in the reactor area and to assist in cooling." ["Chernobyl – The IAEA Visit," Nuclear Engineering International, (June 1986): 3]. It is not clear what was meant by 'access area' nor how gaseous nitrogen could provide effective cooling or displacement of oxygen in a reactor building the size of Chornobyl Unit-4 which dimensions approximately 70 x 70 x 70 cubic meters on a side. There is actually much information in this article (which the Soviets provided] that is untrue or could not have been known so early after the accident given the extreme conditions in the area of Unit-4.

[50] Read, Piers Paul, op. cit., 140.

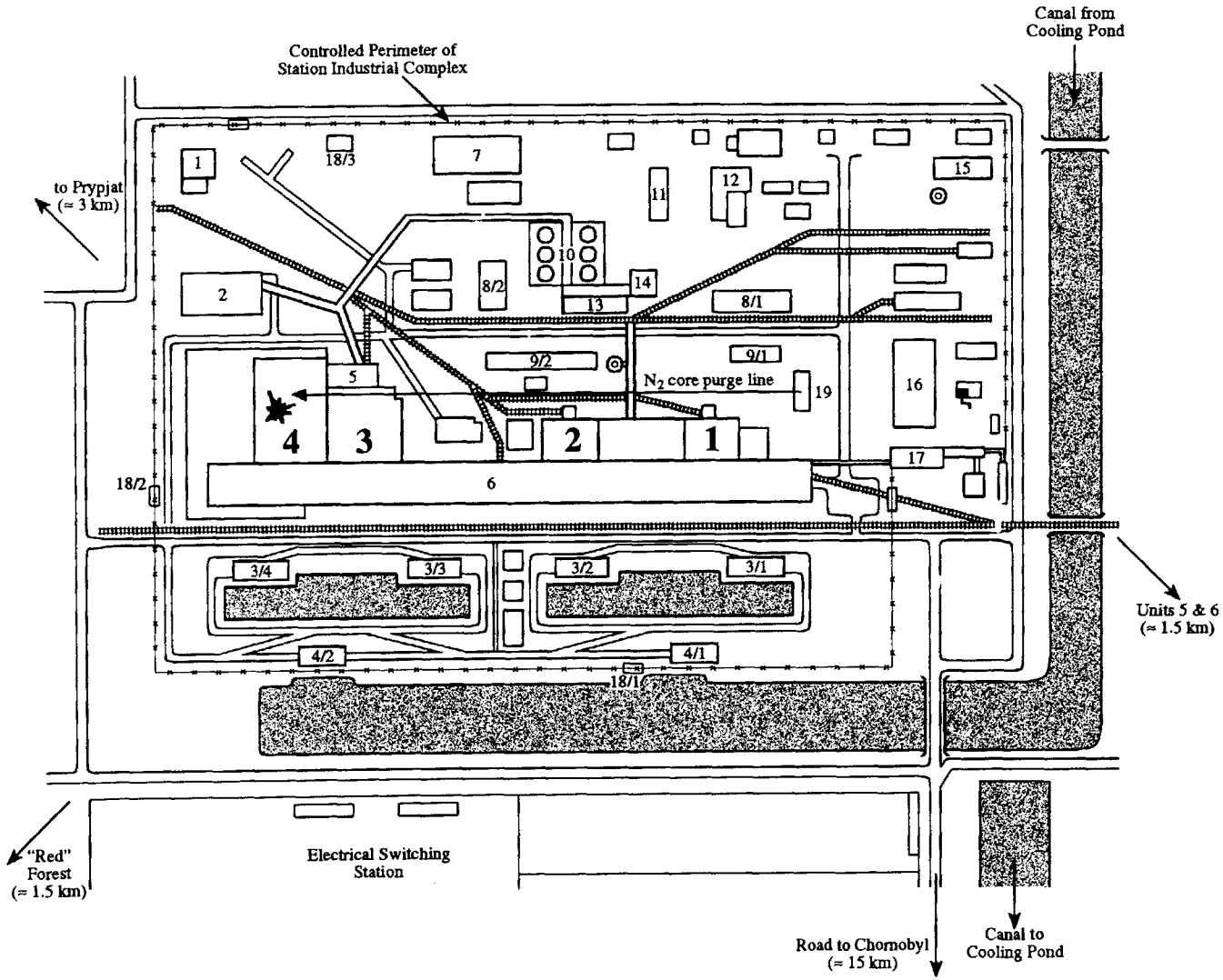


Figure IV.10

Map of the
Chornobyl Nuclear Power Station
(4 x 1000 MWe RBMKs)
(1.0 cm = 50 m)

1 Spent Fuel Storage Building
2 Liquid Waste Repository
3 Condensor Circulation Pumps
4 Canal Cooling-Water Pumps
5 Emergency Core Cooling System (ECCS), Unit-3
6 Turbo-Generator Hall
8 x 500 MWe Turbo-Generators
(total length = 750 m)
7 Tar/Asphalt Preparation & Supply
8 Diesel Emergency Power
9 Liquid N_2 and O_2 Makeup & Storage
10 Liquid & Low-Level Waste
11 Transport Cleaning & Garage
12 Storage & Equipment
13 Waste Water Processing
14 Waste Gas Containers
15 Construction Boiler / Generator
16 Administration Building
17 Visitor Center and Main Entrance
18 Security Entrances
19 Compressor Station

western wall of Unit-4, but because of debris from the explosions and high radiation fields in that area, this supply was unusable. The objective was to take advantage of the 500 m^3/hr-capacity compressors to pump *gaseous* nitrogen approximately 400 meters along existing 150 mm piping to the east face of Unit-3.[51] At this point, several walls (starting from the east side of Unit-3 and continuing through a number of rooms and Corridor 001 at Level -1.0 m) were to be drilled through to assemble another 200 meters of piping that would carry nitrogen further along until just before the western wall of Unit-4. Here the pipes would be directed upward to the 2nd floor of the Pressure Suppression Pool into which the nitrogen was to be released.

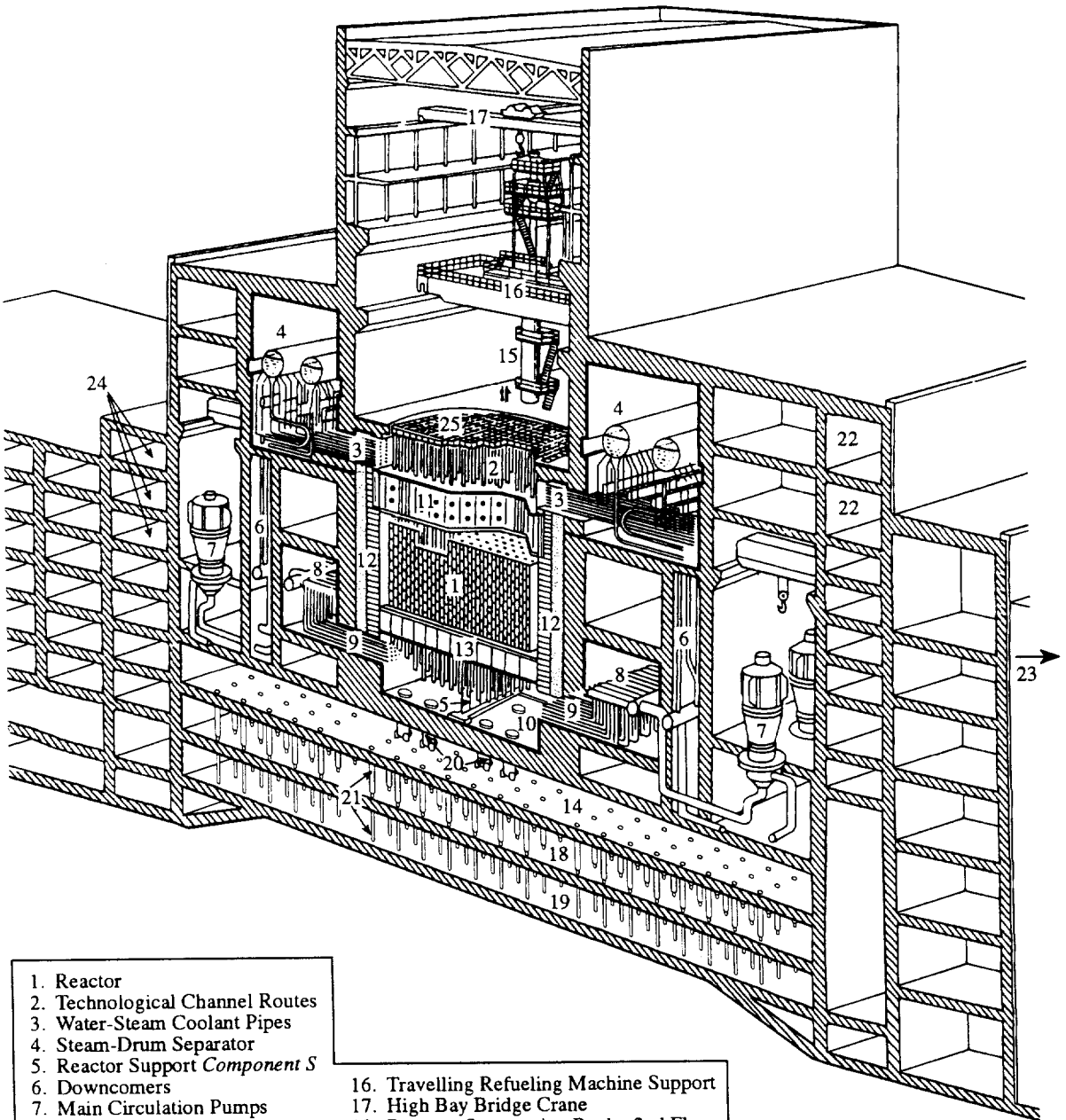
The decision was made to pump in the hope that the *gaseous* nitrogen would eventually snake its way through steam distribution piping on the 2nd floor of the Pressure Suppression Pool, through the Steam Distribution Corridor, up through the Sub-Reactor Region, and into the core to displace the oxygen and thus quench the fire (see Figure IV.11 for a visual reference.) Presumably this operation was carried out. However, the pumping itself was not started before 1:00 A.M. on May 6th, i.e., after the Active Phase when, for all intents and purposes, the major part of the crisis was over. In fact, "Little of it [liquid nitrogen] was used, however, because after twenty-four hours even Legasov realized that the operation was a waste of time."[52] By this time, the core had melted through the Lower Biological Shield and flowed into the lower regions of the reactor building where it "froze" (Figure IV.12.) Of course, at that point the nitrogen would have had no effect on the core. Moreover, a tremendous amount of nitrogen was needed considering that the free volume of air for the Pressure Suppression Pool alone under nomi-

---

[51] The 500 m^3/hr pumping rate appears low by approximately an order of magnitude. A typical U.S. liquid nitrogen trailer-truck can pump 650,000 ft^3 to ambient in about two hours or at a rate of 9,200 m^3/hr. Given the 3700 m^3 volume of the Pressure Suppression Pool, the volume of gaseous nitrogen would be sufficient. However, whether this would have displaced the oxygen in the area of the core is strongly dependent on the displacement efficiency, which in turn is strongly dependent on geometric factors. Since the core area and surrounding areas were heavily damaged and there was a strong updraft from the fires, without more information it is difficult to conclude that even *gaseous* nitrogen purging would have been effective – even if the pumping had started before the end of the Active Phase (see ahead).

[52] Read, Piers Paul, op. cit., 140.

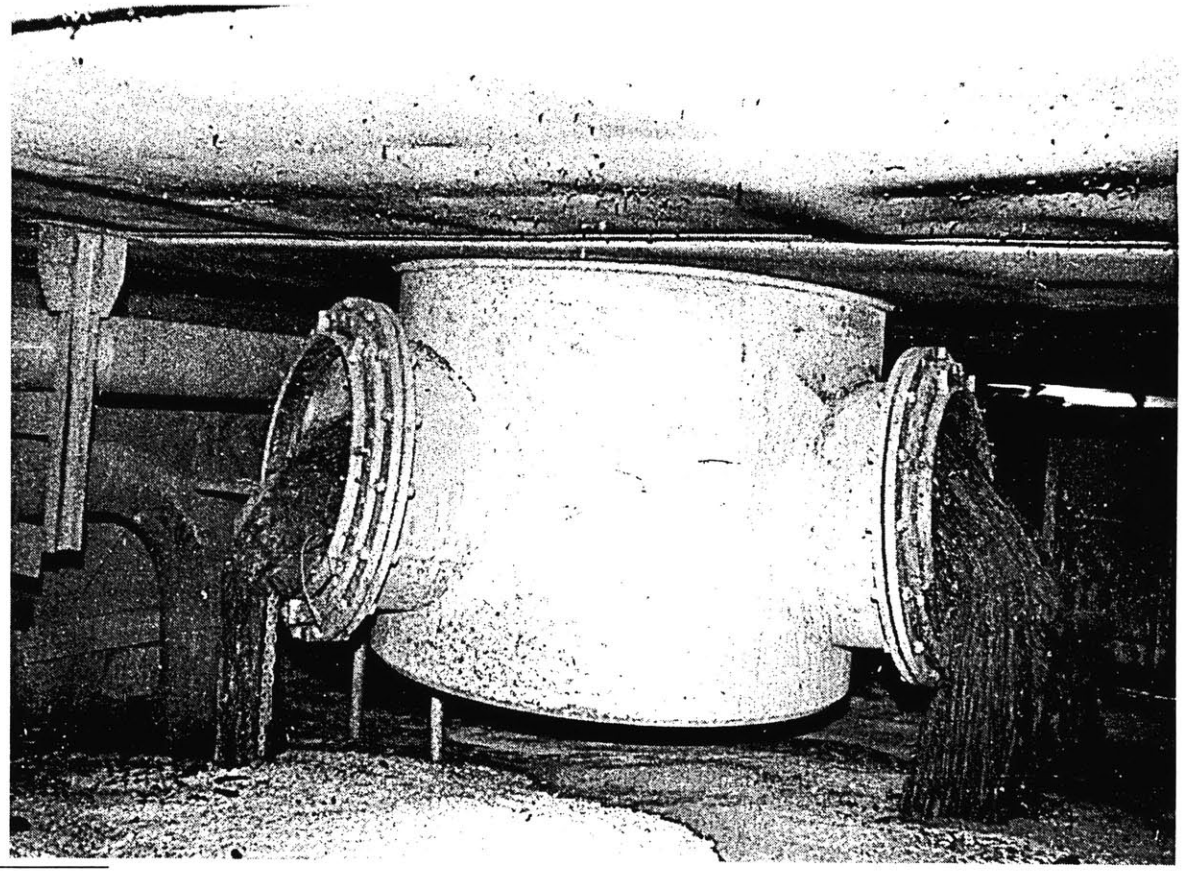
Figure IV.11
Sectional View of a Chornobyl Unit-4



1. Reactor
2. Technological Channel Routes
3. Water-Steam Coolant Pipes
4. Steam-Drum Separator
5. Reactor Support *Component S*
6. Downcomers
7. Main Circulation Pumps
8. Group Dispensing Headers
9. Water Coolant Pipes
10. Sub-Reactor Region
11. Upper Biological Shield
12. Lateral Biological Shield
13. Lower Biological Shield
14. Steam Distribution Corridor
15. Refueling Machine
16. Travelling Refueling Machine Support
17. High Bay Bridge Crane
18. Pressure Suppression Pool – 2nd Floor
19. Pressure Suppression Pool – 1st Floor
20. Steam Distribution Headers
21. Steam Distribution Pipes
22. Dearator Systems
23. To Turbo-Generator Building
24. Location of ECCS
25. Removable Channel Service Blocks

Figure IV.12

Photograph showing one of three Steam Distribution Headers (SDH – part of the Accident Pressure Relief System) with waterfall-like formations of frozen corium. This seems to indicate that by the time the corium had melted through the Lower Biological Shield and reached the headers, it was in a very viscous, molasses-like state able to solidify very rapidly. (Note that at more than 1000°C the yield strength of stainless steel is significantly lowered, and that its melting point is in the range of 1300 – 1700°C.) Note also that the header (as well as other structural components of the lower regions of the reactor building) suffered relatively little damage from the corium. (Particularly intriguing is the chain hanging from the header's left outlet together with the corium flow.)



† Photograph courtesy of Alexander Alexandrovich Borovoi of the Inter-Branch Scientific & Technical Association "Shelter."

nal conditions is 3700 m^3 – this is especially true given the fact that the N_2/O_2 : 28/32 = 0.875 mass ratio is quite inefficient for oxygen displacement.[53] In addition, later investigations have shown that, besides the very heavy damage suffered by areas immediately adjacent to the reactor which would permit nitrogen gas to filter out of the building thus further reducing the effectiveness of the core purge, the Lower Biological Shield (weighing approximately 1200 tonnes-equivalent) had descended four meters, crushing all the piping beneath it, and itself was heavily damaged from fuel having melted through it.[54] It appears, therefore, that any attempt to pump nitrogen through the structural debris as suggested in the Soviet report would have proved futile.[55] Why the Soviets reported in Vienna that this method was a major contributor to successfully *cooling* the core and arresting the release of radioisotopes without positive confirmation is unknown.

IV.3.2.3. Water Release from the Pressure Suppression Pool[56]

Soviet engineers became aware that the approximately 5,000 tonnes of material thrown into the heavily damaged the central hall threatened to compromise the structural integrity of the reactor support* and possibly push the molten core into the lower regions

---

[53] U. S. Nuclear Regulatory Commission, comp, *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250), Washington, DC: U.S. Government Printing Office, (1987): 2-46.

[54] Боровой, А. А., Г. Д. Ибраимов, С. С. Огородник, В. Д. Попов, К. П. Чечеров. "Состояние IV Блока ЧАЭС и Ядерного Топлива, Находящегося в Нём (По Результатам Исследований 1988 – 1989 гг)." Припринт. Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, 1990.

[55] Interestingly, Taras Plokhyj and Nikolai Steinberg, according to Piers Paul Read, "... from the beginning, both thought this an absurd idea. If the explosion had been contained within the structure, it might have made sense, but because the whole unit had been ruptured, all the nitrogen would escape into the open air. [Read, Piers Paul, op. cit., 139.] Does this imply there was little water in the PSP while the reactor was operating – making the pressure suppression system ineffective in the event of a design-basis accident? Was the water used to supply the feedwater pumps in the futile attempt to cool the core? Did it leak out as a result of damaged suffered by building structural components from the initial explosions?

[56] The Pressure Suppression Pool consists of two floors of water and air filled chambers with telescoping steam bubbler tubes (225 per floor) penetrating the floor between the two floors. The nominal water depth is 1.2 m, and the total water and air volumes on the two floors is approximately 3200 m^3 and 3700 m^3 respectably. The Pressure Suppression Pool, as with the Steam Distribution Corridor above it, is rated at a design pressure of 0.25 MPa (0.36 psig). [NUREG-1250, 2-43 – 2-46.]

* Again, it is unclear when the Soviets would have realized that the material wasn't being thrown into the reactor shaft but rather off to the side to smother the "red glow." In addition to the influence fear may have had on judgement, one can understand why helicopter pilots and their crews (who were unfamiliar with the layout of the Central Hall and the location of the reactor shaft) were unable to differentiate the location of the "red glow" from the location of the reactor shaft. This is especially true given that smoke was billowing out from the Central Hall and debris from the explosion obscured visibility. However, if it is the

of the reactor building – creating, as it were, an *assisted* "China Syndrome" situation. It was reasoned that if the molten fuel were able to penetrate into the lower regions of the reactor building, where the Pressure Suppression Pool and its 3200 m^3 of water were located,[57] the interaction of the fuel with water would generate a tremendous amount of steam that in turn would lead to enhanced releases of radionuclides into the environment.† (Actually, "passages and air vents of the basement" also became flooded with water from broken auxiliary feed pipes used to supply water, albeit unsuccessfully, to the destroyed reactor during the first day after the accident.[58]) During the night of May 3–4,[59] sometime before excavation design work for the flatbed heat exchanger began,[60] three volunteers (A. Ananenko, V. Bespalov, and B. Baranov)[61] in diving suits managed to open slide or gate valves, while fire brigade pumps were used to drain the pool. "It took until May 8th [2–3 days after the Active Phase] for the task to be completed, by which time some 20,000 tonnes of highly radioactive water had been pumped out."[62] The water was first pumped into Corridor 001 on the northern side of the basement of the reactor building,

---

case that reconnaissance teams of investigators and people managing the AMAs flew over the destroyed reactor during the Active Phase (assuming they were familiar with the layout of Unit-4), one wonders why the concern of "compromising the structural integrity of the reactor support" was raised.

[57] Interestingly, after a reconnaisance in the early hours of May 2nd, it was found that the 2nd (upper) floor of the Pressure Suppression Pool had no water, while the 1st (lower) floor contained only about 200 cubic meters of water. [Read, Piers Paul, op. cit., 134.]

† This is in contrast to western accident management principles which call for flooding a damaged reactor with as much water as possible until the situation is stabilized, i.e., the presence of great quantities of water is seen as beneficial to mitigating the consequences of severe accidents. Note, however, this assumes the presence of a containment building and filtration systems that would retain steam-generated releases. Chornobyl had no containment building, and water supply systems and the building itself were destroyed.

[58] Read, Piers Paul, op cit., 134–137, provides an account of the draining of this area of the reactor building. This task was completed (after a thirty-hour operation) by midnight May 7th – two days after the end of the Active Phase. Considering that the molten corium turned to a pumice-like substance only on the first floor of the Pressure Suppression Pool (See Chapter V), the "draining of the basement" detailed here must have taken part in other regions of the vast basement of Unit-4.

[59] Personal conversation with Vadym Vasyljovych Hryshenko, October 13, 1992. According to testimony by G. A. Shasharin, "On May 4th we found the gate valve which had to be opened in order to drain water from the lower part of the suppression pool. There was little water in it. We looked into the upper pool through the hole of the reserve passage and found it empty." [Grigori Medvedev, 203.]

[60] NUREG-1250 (7-20) reports that this occurred on the night of May 6–7, i.e., *after* the Active Phase of the accident was over – obviously confusing the draining of the Pressure Suppression Pool with the draining of other regions of the the basement that had become flooded as a result of the fruitless attempt to provide feedwater to the reactor in the earlier hours after the accident.

[61] Marples, David R. *Chernobyl and Nuclear Power in the USSR*. New York: St. Martin Press, 1986, 157.

[62] Zhores Medvedev, 58–59.

and later transferred to a liquid waste repository on the station grounds.[63] However, not all the water was drained from the basement and "fresh" water, in the form of precipitation, constantly enters the basement. According to a 1992 Soviet report, approximately 600 m^3 of radioactive water (a considerable amount that today remains a major issue in plans for the construction of a new sarcophagus) is still located within the sarcophagus.[64] Also, because the lava that did encounter whatever water was left in the Pressure Suppression Pool, it turned into a hard, pumice-like substance – pieces of which actually floated away from the main pile spreading contamination throughout these lower areas.

IV.3.2.4. Sub-Foundation Flat-Bed Heat Exchanger

Still another action taken to avert a possible "China Syndrome" was the construction of a makeshift flat-bed heat exchanger (initially designated to employ liquid nitrogen as the working fluid)[65] underneath the Unit-4 building's foundation. It was reasoned that the planned 25 tonnes per day of liquid nitrogen would keep the soil frozen at a temperature of -100 °C – providing not only a stronger support for the building's foundation, but also cooling the foundation to hopefully arrest the interaction of molten core with concrete. The decision to begin construction was taken early on in the accident when little was known about the condition of the core or how extensively damaged the lower regions of the reactor building, while construction was supposedly completed in late June. Table IV.2 provides a design schedule for the planned version of the heat exchanger.

By all accounts the heat exchanger was built, but its working fluid was water and it wasn't completed until the end of June – approximately eight weeks after the end of the Active Phase.[66] The initial design called for the entrance to an access tunnel to be located on the north side of the spent fuel storage building (refer back to Figure IV.11) where the

---

[63] Private conversation with Vadym Vasyljovych Hryshenko, op cit.

[64] *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие»*, 42.

[65] NUREG-1250, 7-20 as referenced to INSAG-1, 46. The heat exchanger was affectionately called the "samohon (moonshine) still" by construction workers because of its shape and function.

[66] Much of this discussion is based on a private conversation with Vadym Vasyljovych Hryshenko, October 13, 1992, and a number of people who took part in the excavation work.

construction and mining crews would be partially shielded from the most contaminated areas surrounding the destroyed Unit-4. This idea was quickly abandoned – partly because the spent fuel storage building was located too far away (it would take too long to reach the intended mark below the core), and partly because the foundation had a vault-like shape running east-to-west, i.e., the tunnel from the north would have to be deeper and not completely horizontal. Construction on the access tunnel was started about two to three days *after* the end of the Active Phase from the east side of Unit-3, while work on the heat exchanger itself began on June 3rd and completed on June 28th.[67]

Table IV.2[68]
Design and Construction Schedule for the Chornobyl Unit-4
Reactor Building Sub-Foundation Flatbed Heat Exchanger

Goal / Task	Organization(s) Responsible	Scheduled Completion
Heat Exchanger Plate Feasibility Study and Validation	1) PO-VNIPIET† 2) Kurchatov Institute of Atomic Energy	May 15
Bore Hole Soil Freezing Design	1) USSR Ministry of Transport Systems Construction	May 20
Horizontal Tunnel Design	1) USSR Ministry of the Coal Industry	May 20
Heat Exchanger Plate Design	1) Atomic Power Design and Construction 2) USSR Ministry of the Coal Industry 3) Power Systems Construction 4) Hydro-Station Special Design	May 20
Cooling Water Supply System Design	1) PO-VNIPIET 2) Kurchatov Institute of Atomic Energy 3) Hydro-Station Design	May 25
Complete Design Implementation and Appraisal	1) Atomic Power Design and Construction 2) USSR Ministry of Coal Industry Equipment 3) Hydro-Station Special Design 4) Hydro-Station Design	May 30
Final Recommendation for Exploitation	1) PO-VNIPIET 2) Hydro-Station Design	May 30

† PO-VNIPIET – The Industrial Association – (All Union) Scientific Research and Design Institute of Power Engineering; Vladimir Aleksandrovich Kurnosov, Director

[67] Ю. В. Сивинцева и В. А. Качалова, 97. This section of the book contains more detailed information on the heat exchanger and other accident mitigation efforts.

[68] Ю. В. Сивинцева и В. А. Качалова общие редакторы, *Чернобыль: Пять трудных лет*, Москва: Издат, (1992): 338.

While design work was being completed on the heat exchanger, the 168 meter access tunnel was excavated. A two meter diameter tunnel was dug with ribbed ceiling supports making its working diameter approximately 1.8 meters (refer to Figure IV.13.) After the tunnel was completed, excavation continued for another 30 meters to the west, after which the tunnel split to the north and to the south into 1.5 meter diameter "arms" each extending 15.4 meters. The height of the shafts was extended to 2.5 meters where the top ran flush with the bottom of the reactor building's foundation. When this set of "arms" was excavated, 100 mm diameter coolant tubing sheathed with a thin plate of graphite was assembled and installed along with reinforcing iron rods 25 mm in diameter running horizontally and vertically separated by a distance of 100 mm. Heat detectors were placed flush against the building's concrete foundation as well as in other locations, and concrete was poured in to strengthen and protect the plate and to act as a major barrier to corium if it breached the building's foundation. Moving back to the east, other sets of arms were thus excavated for the next sections of the heat exchanger. After the 30 m x 30.8 m x 2.5 m cavern and heat exchanger were completed, more concrete was poured to make the plate an massive integrated object.[69] After the tunnel had been sealed and pressure and leakage tests were conducted with the water working fluid, the project was abandoned.[70] Although a commendable attempt, with hindsight it proved ineffective because, as mentioned earlier, later investigations revealed that large quantities of corium cooled quickly in the lower regions of the reactor building approximately 9–10 days after the accident – causing relatively little damage to piping and other structural materials.

---

[69] Ibid.

[70] Private conversation with Vadym Vasyljovych Hryshenko, op cit.

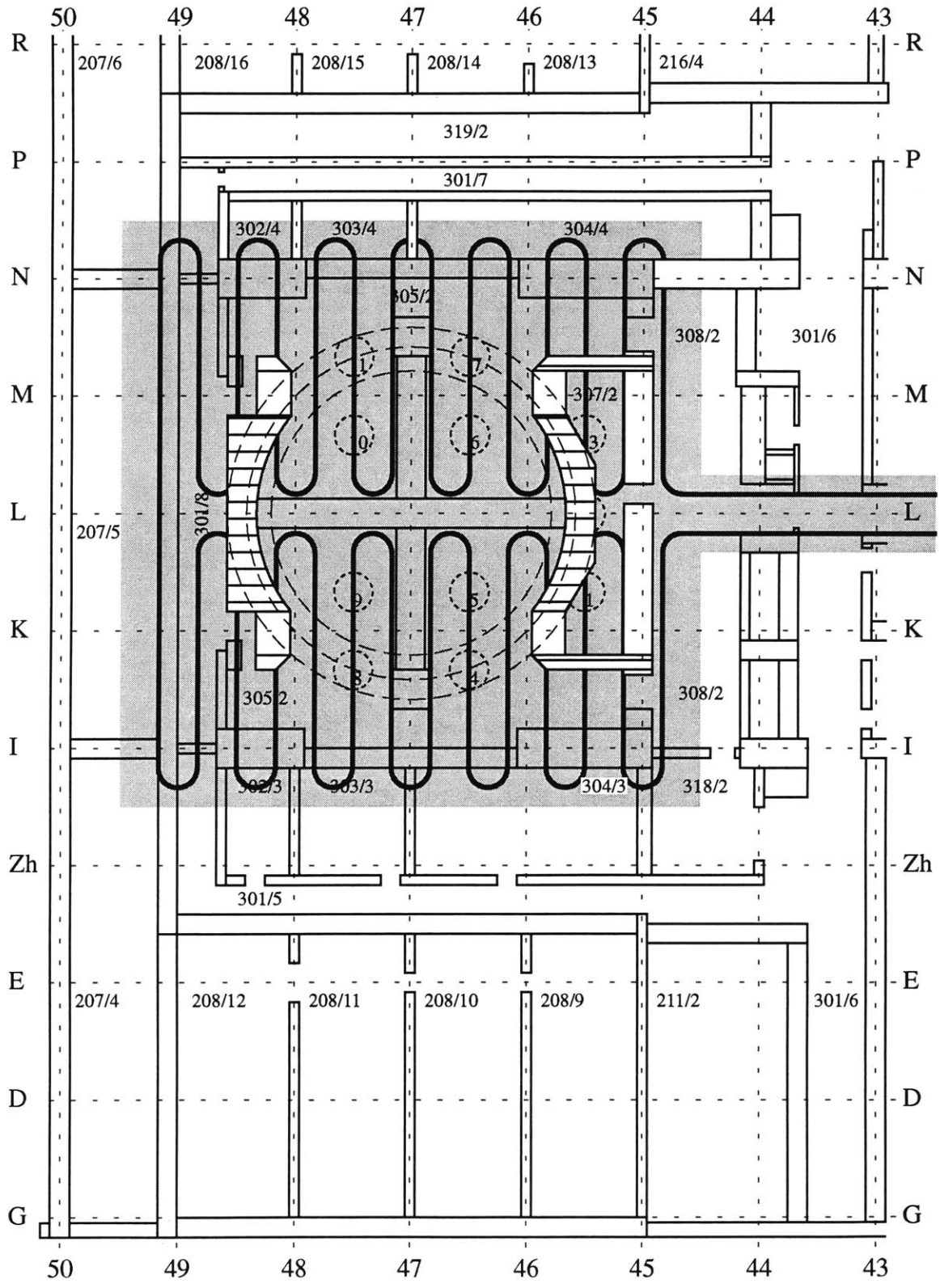


Figure IV.13
Level 9.00 m: Sub-Reactor Region

Top-View Schematic of Chornobyl Unit-4
Sub-Foundation Flatbed Heat Exchanger

KEY

Level 9.00 m
Scale: 1 inch = 8 meters
Distance between axes: 0.75 inch = 6 meters

IV.3.3. Reassessment of Active Phase AMAs

The AMAs taken at Chornobyl during the first few days following the accident were generally ineffective – although well-intentioned.† The first attempt to supply water to the core from emergency auxiliary feed pumps to quench the core debris was apparently unsuccessful and quickly abandoned.[71] The subsequent steps, namely the dumping of various materials into the reactor building to smother the fire, supplying nitrogen to bring down the temperature in the core space and to reduce the oxygen concentration in the air, construction of a flat heat exchanger beneath the foundations of the reactor building, and release of water from the pressure suppression pool, either were not fully implemented as reported (as in the case of nitrogen purging), failed to cover the reactor core (in the case of material dumping) – apparently because the main goal was to stop the burning (which was visible) and not to cover the core (which was partially hidden from sight by piping and debris), or were not completed during the Active Phase of the accident (in the case of the makeshift flat heat exchanger beneath the reactor building which was not completed until the end of June 1986.) Moreover, once the corium-lava ate through the Lower Biological Shield, it had lost most of its heat energy in the melting process, and the decay heat had decreased significantly. In addition, the solidus of the corium-LBS mixture had increased (because the materials of the LBS and surrounding structures had complicated the chemistry) therefore decreasing further its ability to interact significantly with surrounding materials.* The lava then flowed downwards (along existing piping of the Pressure Relief System and openings in the damaged building structures caused by the explosions) and eventually into the pressure suppression pool – all along the way solidi-

† A number of my colleagues in Russia and Ukraine have argued that despite the heroic efforts of the helicopter crews, the firefighters, and other workers on the ground, these actions were unwarranted. They assert that an accident containment and mitigation effort ostensibly portrayed as one of the most difficult and heroic engineering tasks ever undertaken, in reality may best be categorized by ineptitude and a reckless desire to conceal the extent of the accident on the part of people in charge. Hindsight notwithstanding, rather than proceeding with a "siege mentality" to mitigate the consequences of the accident, careful thought should have been given before any actions were taken.

[71] U.S.S.R. State Committee..., 40.

* Eutectic materials form readily during severe accidents and can lower melting or freezing temperatures by several hundred degrees.

fying in mid-flow producing interesting stalactite-like formations and clogging piping but causing relatively little damage. A summary of AMAs undertaken during the Active Phase is shown in Table IV.3 and Figure IV.14.

One interesting consequence of the fact that the corium-LBS did little damage to surrounding structures in the lower regions of the reactor building (especially considering the AMAs were ineffective and the burning/melted core fell into a more stable state with no human intervention) is that the infamous "China Syndrome" now seems a much less likely occurrence – even for an accident as severe as Chornobyl. This has important implications for western safety concerns – namely, it may be possible to avoid a China Syndrome altogether at western nuclear power installations by designing a relatively simple, low-volatility material bed to "catch" ejected corium (in the already very unlikely event of a pressure vessel failure) and have it interact with the bed material to form a quickly-solidifying mixture. (Note that a typical 1000 MWe western PWR or BWR have a UO_2 fuel load of approximately 75 and 115 tonnes respectively – as compared to the RBMK-1000 with a 190.3 tonne UO_2 fuel load where, for the case of the Chornobyl accident, about 135 tonnes flowed into the lower regions of the reactor building.) If designed properly and combined with the western practice of flooding the corium with as much water as possible, the corium would chemically bind into a more stable state – reducing the pressure and contamination burden on the containment building.†

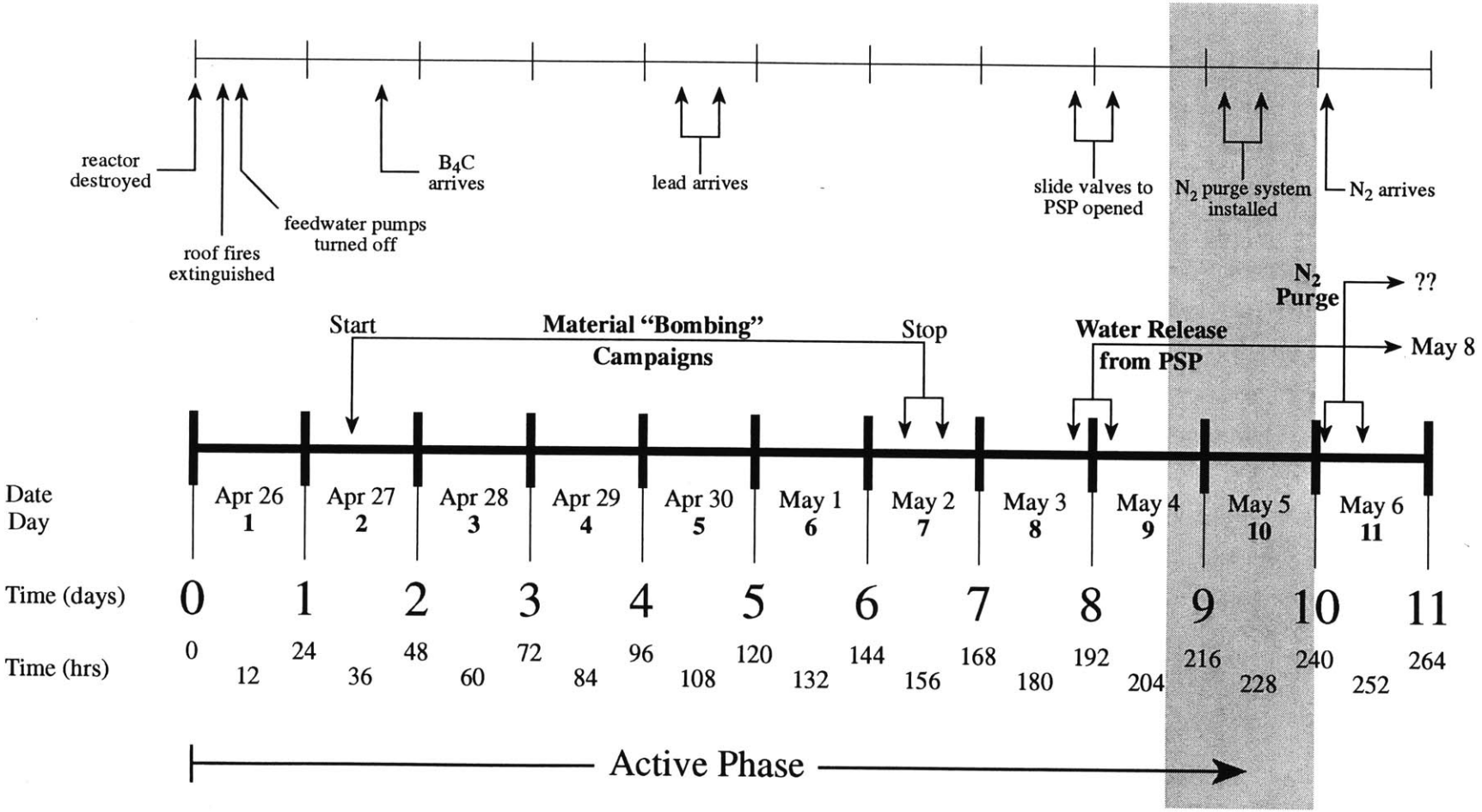
On a more somber note, the results of these investigations seem to support earlier western far-field source term estimates that indicated significantly more volatile radionuclides were released into the environment than reported by the Soviets at Vienna in

† Such "core catchers" have actually been designed and some even patented in the West. One such example is "Core-Catcher for Nuclear Reactor Core Meltdown Containment," by Michael J. Driscoll and Frank L. Bowman (U.S. Patent #4113560, September 12, 1978). A more recent reference is C. W. Forsberg, E. C. Beahm, and G. M. Parker, "Core Melt Source Reduction System (COMSORS) to Terminate LWR Core-Melt Accidents," *Proceedings of the 2nd International Conference on Nuclear Energy (ICONE-2),* San Francisco, CA, (March 21-24, 1993). See also, Ronald Allen Knief, *Nuclear Engineering: Theory and Technology of Commericial Nuclear Power*, 2nd Ed., Washington, D.C.: Hemisphere Publishing Group, (1992): 403.

Table IV.3
Summary of Accident Management Actions
Taken During the Active Phase of the Chornobyl Accident

Date and Time		Days	Action and Reasoning
Saturday, April 26	≈ 01:24	0	Accident – destruction of Unit-4 reactor
Saturday, April 26	01:30 – 06:30	0 – 0.25	Fire fighters extinguish blazes started by ejected core materials – mainly on the roofs of the auxiliary buildings, Unit-3, and the Turbine-Generator Hall
Saturday, April 26	morning	0.25 – 0.5	Feedwater pumps turned off – found ineffective apparently because piping to core destroyed
Saturday, April 26	> 15:00	> 0.75	Official recognition of what had happened and extent of damage, decision taken to begin material "bombing" campaigns
Sunday, April 27	≈ 10:00	≈ 1.4	Start of material "bombing" campaigns
Sunday, April 27	at night	≈ 2	Arrival of Boron Carbide
Wednesday, April 30	during day	≈ 4.5	Arrival of Lead
April 30 – May 1		4 – 6	Apparent ebb in releases followed by increase in releases to the end of the Active Phase
Thursday, May 1	during day	≈ 5.5	Decisions made to set up system to "purge the core with [ostensibly with *liquid*] nitrogen," and to design a sub-foundation heat exchanger to mitigate against a possible "China Syndrome"
Friday, May 2	during day	≈ 6.5	Temporary halt to material bombing until after the Active Phase – feared that building support structures compromised that could initiate an "assisted" China Syndrome or steam explosion if reactor core driven into the Pressure Suppression Pool
May 3 – 4	at night	≈ 8	Divers open slide valves to drain water from the Pressure Suppression Pool
Monday, May 5		9 – 10	Nitrogen-purging system installed
Monday, May 5		≈ 10	Peak of releases observed followed by rapid and significant drop
Tuesday, May 6	≈ 01:00	≈ 10	First tanker-trucks arriving with liquid nitrogen. Soon afterwards gaseous nitrogen started to be pumped into 2nd floor of the Pressure Suppression Pool
Tuesday, May 6		10 – 11	Releases drop to more than three orders of magnitude less than during the initial ten days – this signals the end of the Active Phase
Thursday, May 8		≈ 13	20,000 tonnes of highly radioactive water from the Pressure Suppression Pools had been pumped out and into Corridor 001
Tuesday, June 3		≈ 28	Construction start for subfoundation, flat-bed heat exchanger
Saturday, June 28		≈ 64	Completion of construction and testing of sub-foundation, flat-bed heat exchanger

Figure IV.14
Summary of Accident Management Actions



August 1986. If indeed a major portion of the core was exposed virtually uncovered for approximately nine days (releasing more radioactivity into the environment than previously thought), the significantly increased incidences of children's thyroid cancers now occurring in Ukraine and Belarus seem to substantiate the conjecture that they were a direct result of the Chornobyl accident. More importantly, this strongly obligates the current Russian government to release data and other information contained in the files and records of the former Soviet Governmental Commission on Chornobyl. (The source term problem as well as a review of the reliability of the Soviet data presented at Vienna will be considered in Chapter VI.)

At the Vienna IAEA conference in August 1986 the Soviets stated they had to choose one of two options to mitigate the releases: (1) Either "localize the focus of the accident by filling the reactor shaft with heat discharging and filtering materials," or (2) "Allow combustion processes in the reactor shaft to end naturally."[72] As is clear now the burning core and the release of radionuclides during the Active Phase of the accident, in fact, stabilized themselves – despite Soviet actions and claims to the contrary. From the point of view of the safety of personnel assigned to implement AMAs during the Active Phase, the Soviet claim that "...decisions made [to mitigate the consequences of the accident] were primarily the right ones,"[73] seems correct. However, the actions required to consumate them were not properly carried out.

Given this new information, western assessments of the effectiveness of AMAs must themselves be reassessed.[74] For example, the IAEA's INSAG-1 report states, "The accident management actions taken at Chornobyl *were, generally, quite successful*... [the] dumping [of] materials into the reactor well..., supplying nitrogen to bring down the temperature in the core space and to reduce the oxygen concentration, and the construc-

---

[72] U.S.S.R. State Committee..., 40.

[73] U.S.S.R. State Committee..., 41.

[74] James Varley, in a *Nuclear Engineering International* article, "Who Was to Blame for Chernobyl? – INSAG's Second Thoughts"(May 1993: 51), concludes that the Soviet delegation's suppression of information vital to understanding the causes and consequences of the accident, "... now looks more like a matter of deliberate deception."

tion of a flat heat exchanger beneath the foundations of the reactor building, *stabilized the situation at an early stage* (about nine days after the initiating power surge) of the accident [emphases added]."[75] This appears to be another indication that the West was partly deceived by the Soviet delegation in Vienna.

[75] INSAG-1, 43. Another rather premature assessment of the accident in general is, "The Chornobyl-4 accident generally was judged to identify no significant new lessons for the nuclear power industry outside the USSR." [Knief, *Nuclear Engineering*, 466.]

CHAPTER V

A DESCRIPTION OF THE SARCOPHAGUS "SHELTER" AND STATE OF UNIT-4 AND ITS NUCLEAR FUEL: A POSTMORTEM

V.1. The Sarcophagus *"Shelter"*

V.1.1. Construction and General Description*

The Chornobyl Unit-4 post-accident containment structure – in Ukrainian dubbed *Ukryttja* or *"Shelter"* but commonly referred to as the "sarcophagus" (Figures V.1a & V.1b) – was completed in November 1986. The sheer size of this containment (constructed upon the ruins of the destroyed reactor building) built in extremely hazardous working conditions (necessitating the use of unique and remote construction methods in very high radiation fields) in the short time span of six months, make it an unique accident clean-up and isolation achievement. After considering eighteen different project variants, scientists and engineers chose a design which would take advantage of the remaining reactor building's foundation and superstructure.[1] The benefits of their decision were significantly lower costs and high speed of construction. There were, however, also disadvantages: lack of information on the structural integrity of the reactor building, remote methods for pouring fresh concrete did not always permit observation and review of work, and in a number of cases high radiation fields made welding key containment components impossible. As a result of these construction difficulties, two essential deficiencies exist and continue to threaten the integrity of *Shelter*: (1) it is unknown how strong are the supports

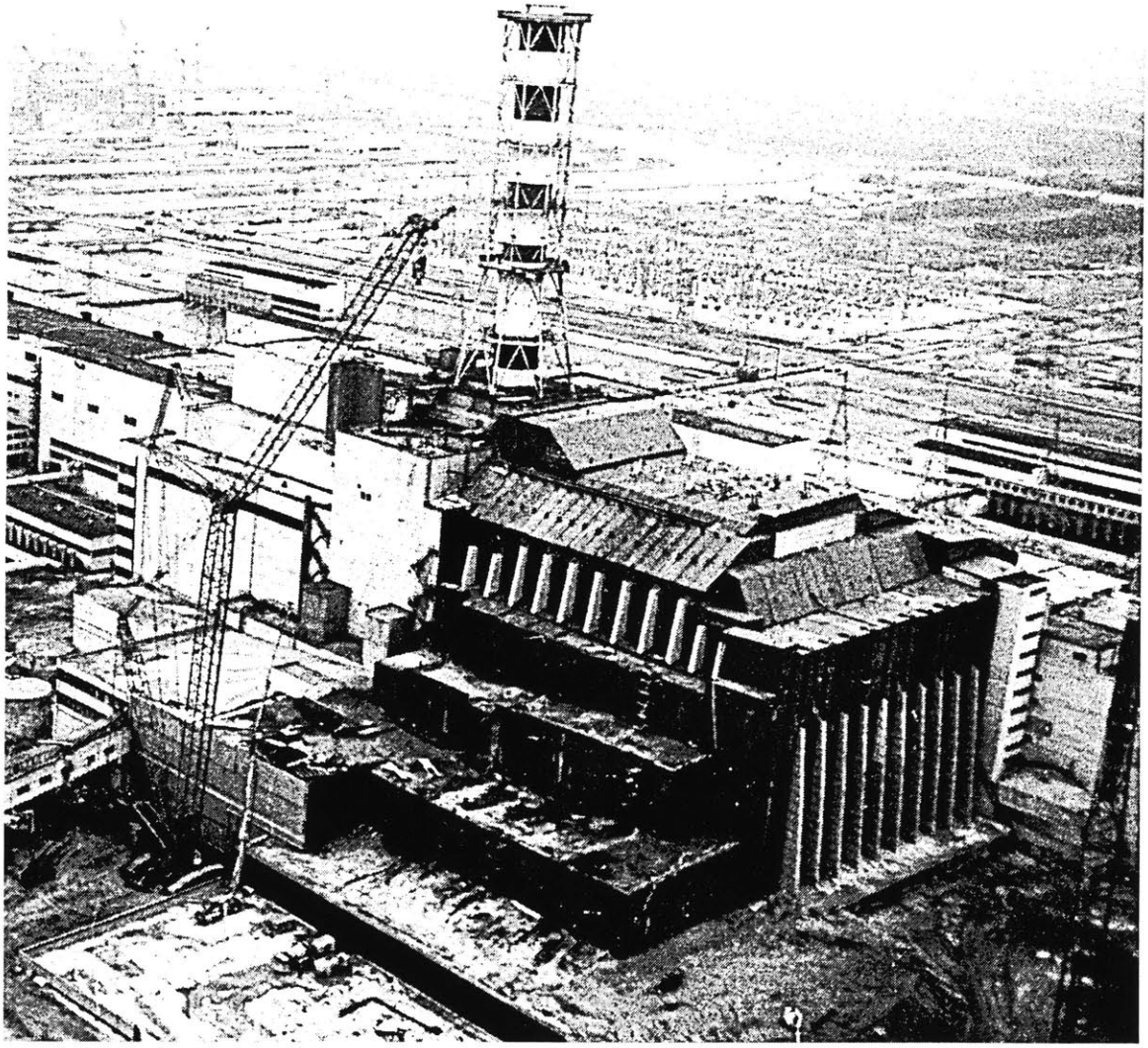
---

* A fairly extensive account of accident mitigation and clean-up efforts can be found in Ю. В. Сивинцева и В. А. Качалова, общие редакторы, *Чернобыль: Пять трудных лет: Сборник материалов о работах по ликвидации последствий аварии на Чернобыльской АЭС в 1986–1990 гг.* Москва: ИЗДАТ (1992). Included is a good synopsis of the contruction of the sarcophagus.

[1] Kurnosov, V. A., Bagryanskii, V. M., and Moiseev, I. K., "Entombment of Chernobyl' Unit-4," *Atomic Energy*, Vol 64, No. 4, (April 1988): 301. (translation)

Figure V.1a[2]

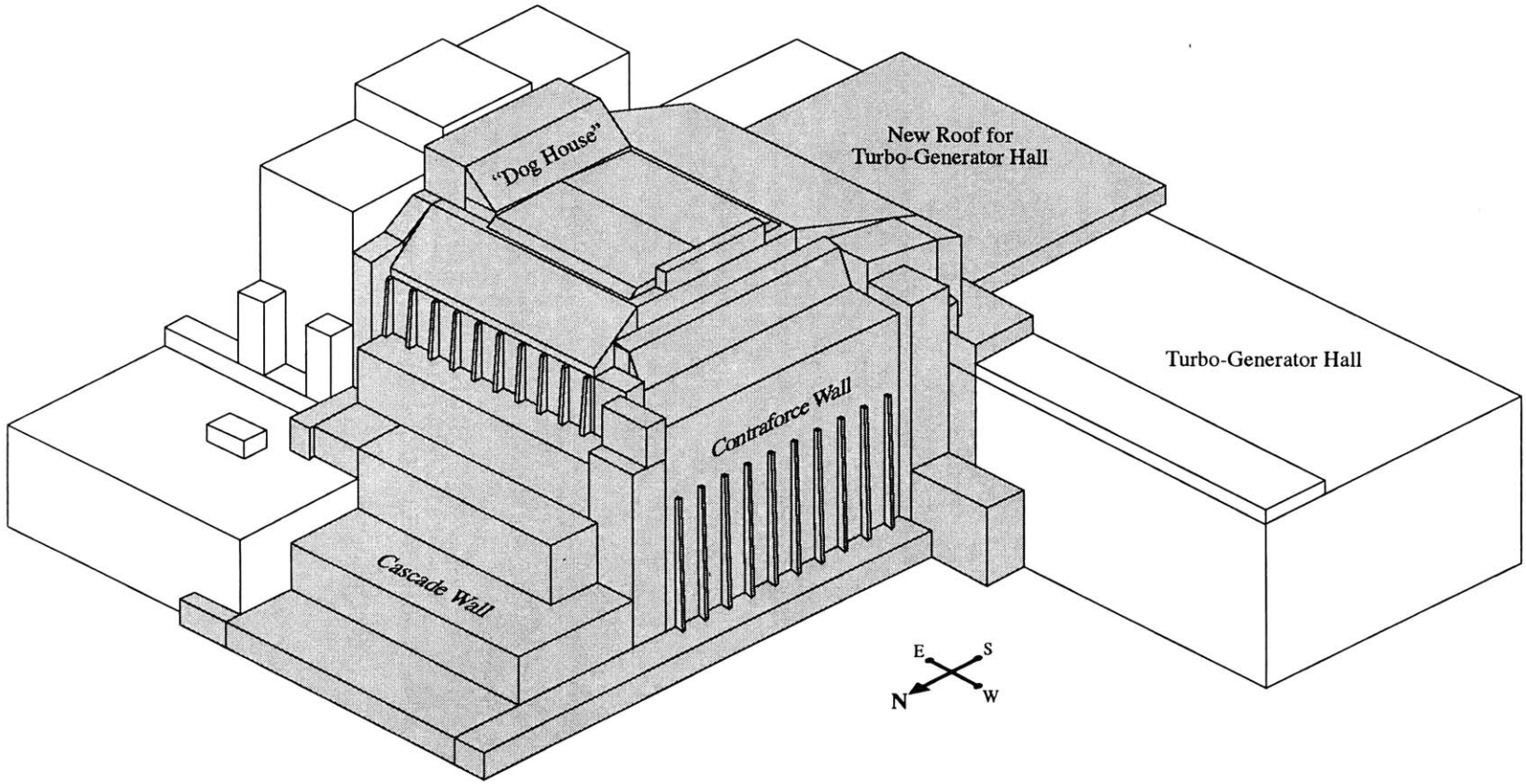
Photograph of the nearly completed Chornobyl Unit-4 Sarcophagus "Shelter" in November 1986 as viewed from the northwest.



[2] Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

Figure V.1b

General View of the Chornobyl Unit-4 Sarcophagus "Shelter"



that buttress the upper sections of the structure, and (2) openings and breaks in the walls and the roof of *Shelter* are estimated to total about 1200 m^2.[3] These deficiencies may lead to serious consequences and hazards (discussed below) if not addressed in the near term.

During the construction of *Shelter* a great deal of so-called "fresh" concrete flowed into the lower sections of the damaged reactor building that made it difficult or impossible to enter many areas for a structural support review and for investigations of the remains of the reactor.[4] On the other hand, part of the remains of the reactor core that melted and flowed into the lower regions of the reactor building (the corium or so-called Lava-Like Fuel-Containing Materials – LFCMs)† were covered with layers of concrete – making it easier gain entrance into other areas that otherwise would have been impossible because of high radiation fields.

During 1987-91, scientists, engineers, construction specialists, and other members of the *Chornobyl Complex Expedition* of the Kurchatov Institute of Atomic Energy, con-

---

[3] "According to Nikolai Shteinberg, head of Ukraine's atomic energy regulatory agency, *Derzhatomnahljad*, who was chief engineer at Chornobyl for the first 10 months after the accident: 'From an engineering standpoint, no one can tell you what will happen to the sarcophagus in the next half-hour.'" [Chrystia Freeland, "Waiting for the Next Chornobyl," *The Financial Times of London*, No. 32,043, Week 16, (April 21, 1993): 20.]

[4] One of the most persistent myths surrounding the construction of the sarcophagus is that it was intended to be a solid, hermetically-sealed structure of concrete and steel. One Soviet preprint (internally published) actually calls it "the concrete cube 'sarcophagus'" [Векслер, Л. М., В. К. Попов, "Авария на Чернобыльской АЭС и её уроки (1986 – 1990)," (припринт) Москва, Россия: Институт атомной энергии им. И. В. Курчатова, (1990): 27.] This myth was first propogated in the Soviet press and naturally later made it into the western press. The amounts of concrete *claimed* to have been used to construct the sarcophagus range from 300,000 to 410,000 cubic meters. However, if one simply takes the cube root of these values, the dimensions of a pure block of concrete with these volumes would be in the range of 66.9 to 74.3 meters on a side! This is larger (and certainly taller) than the current sarcophagus – which is mostly empty space (see Figures V.5b and V.6b) even if one considers the reactor building itself. The actual amount of concrete used was approximately 161,000 cubic meters – a great deal of which leaked through holes in the reactor building out onto the immediate grounds of the station. See the following references:

(a) Ацуми Коди (Асахи), «Хотя зарплата высока – трудности с набором кадров,» в Г. Малкин (составитель), *Ядерный след*, Москва: Энергоатомиздат, (1990): 47.

(b) «Нет ничего, что бы побредило народу,» Александр Коваленко и Юрий Рисованный, *Чернобыль – Каким его увидел мир*, Киев: Издательство ЦК ЛКСМУ «Молодь», (1989): 88.

(c) Zhores Medvedev, *The Legacy of Chernobyl*, New York: W.W. Norton and Company, (1990): 80.

(d) Harold Denton, "The Causes and Consequences of the Chernobyl Nuclear Accident and Implications for the U.S. Regulation of Nuclear Power Plants," *International Energy Seminar on, "Chernobyl: The Implications for Nuclear Power and the International Nuclear Regime,"* Johns Hopkins Foreign Policy Institute, Washington, D.C., (July 9, 1986): 10. as referenced to Richard Masters, "Chernobyl Has Less-Than-Expected Impact on Orders and Future Plans," *Nuclear Engineering International*, (June 1987): 28.

† As opposed to simply FCMs (Fuel-Containing Materials) which may include dust or micro particles, fuel assemblies, reactor building structural members impregnated with fuel particles, etc.

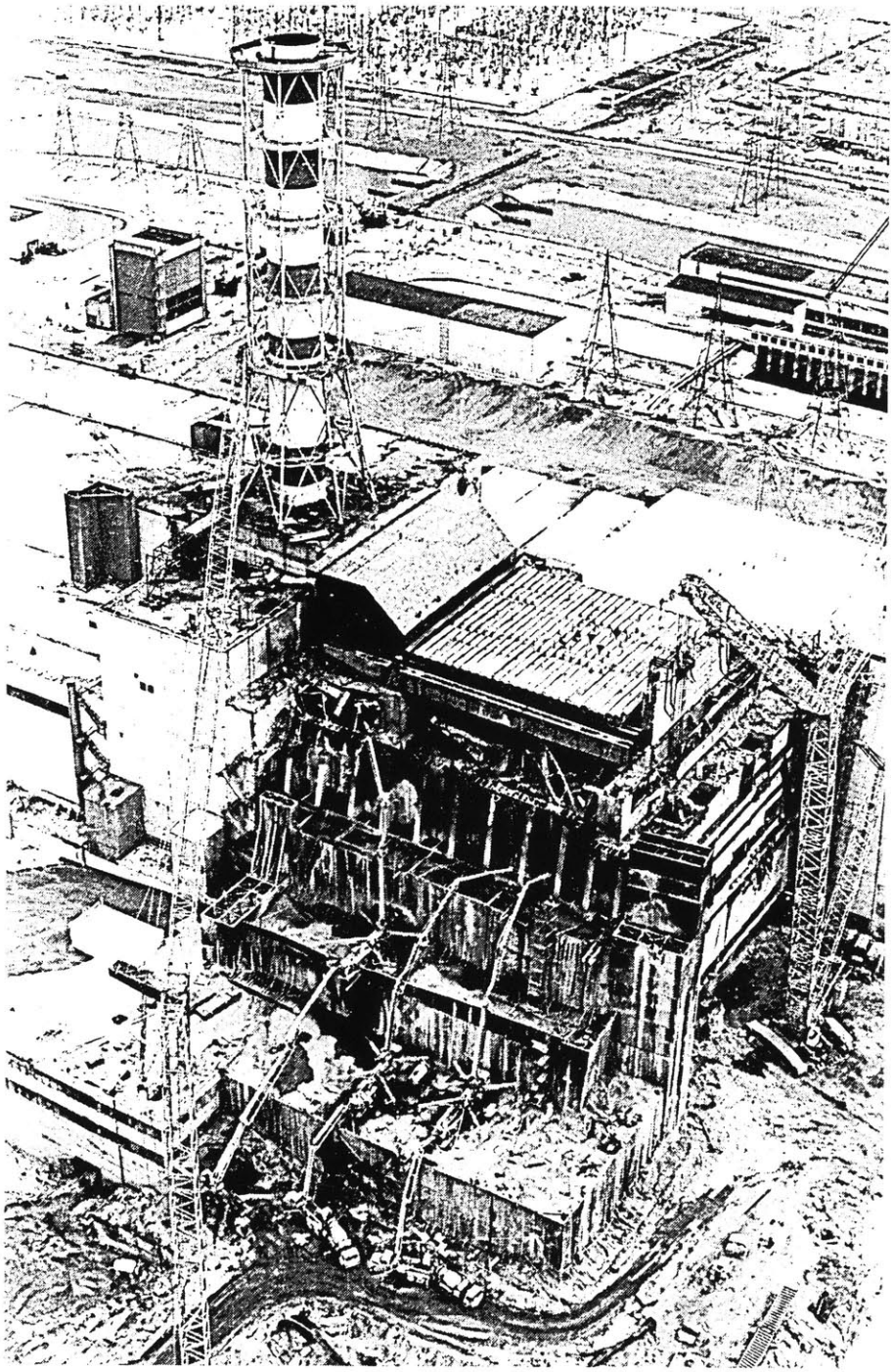
ducted much scientific and investigative research into the location and state of the nuclear fuel remaining within the sarcophagus. The FINISH system for continuous surveillance of the Fuel-Containing Materials (FCMs) was created to support the work of the *Complex Expedition.* during the same period, strengthening of internal structures and supports (particularly those which suffered significant damage during the accident) was carried out. Soon after the collapse of the Soviet Union, all scientific, construction, and technological work at the sarcophagus site fell under the direction of the Ukrainian Academy of Sciences's *Inter-Branch Scientific & Technical Center "Shelter."* Day-to-day maintenance and surveillance of *Shelter* is carried out by the governmental enterprise "Object *Shelter*."

The containment structure *Shelter* can be described briefly as follows: The east side consists of the so-called "dividing wall" which separates the 3rd block from the 4th, and is constructed as a combination of existing building walls and newly erected walls or concrete filler. The north side of the building is defined by the "cascade wall" (seen in Figures V.2 – V.3b) – filled with concrete, boxed radioactive materials collected from the roof and surroundings, building debris, and structural metals – is in the form of very large cascading steps. These steps conform more or less to the building debris and eventually rise to meet the upper levels of the former high bay area of the reactor's Central (Service) Hall. The western wall (Figures V.3a & V.3b) is relatively intact and is lined on the inside by a buttressed concrete shielding wall one meter thick and 45 meters high, and on the outside by large steel contra-force panels 6 x 45 meters weighing approximately 92 tonnes apiece.[5] The upper parts of *Shelter* rest upon three main metallic support beams B1, B2, and the so-called 160 tonne "Mammoth Block" (Figures V.4a & V.4b). The western supports for beams B1 and B2 is served by a reinforced concrete wall about one meter thick. This wall has a number of serious cracks and is tilted slightly toward the west. During the construction of *Shelter*, direct inspection of this wall was impossible – the only sources of information of its integrity were photos taken from helicopters flying

[5] Kurnosov et al, 301.

Figure V.2a[2]

Photograph of the sarcophagus and construction of the northern "Cascade" Wall in early October 1986. The concrete delivery booms were used to pump concrete to a height of approximately 55 meters.



[6] Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

Figure V.2b

Top-View Schematic of the Chornobyl Unit-4 Sarcophagus "Shelter"

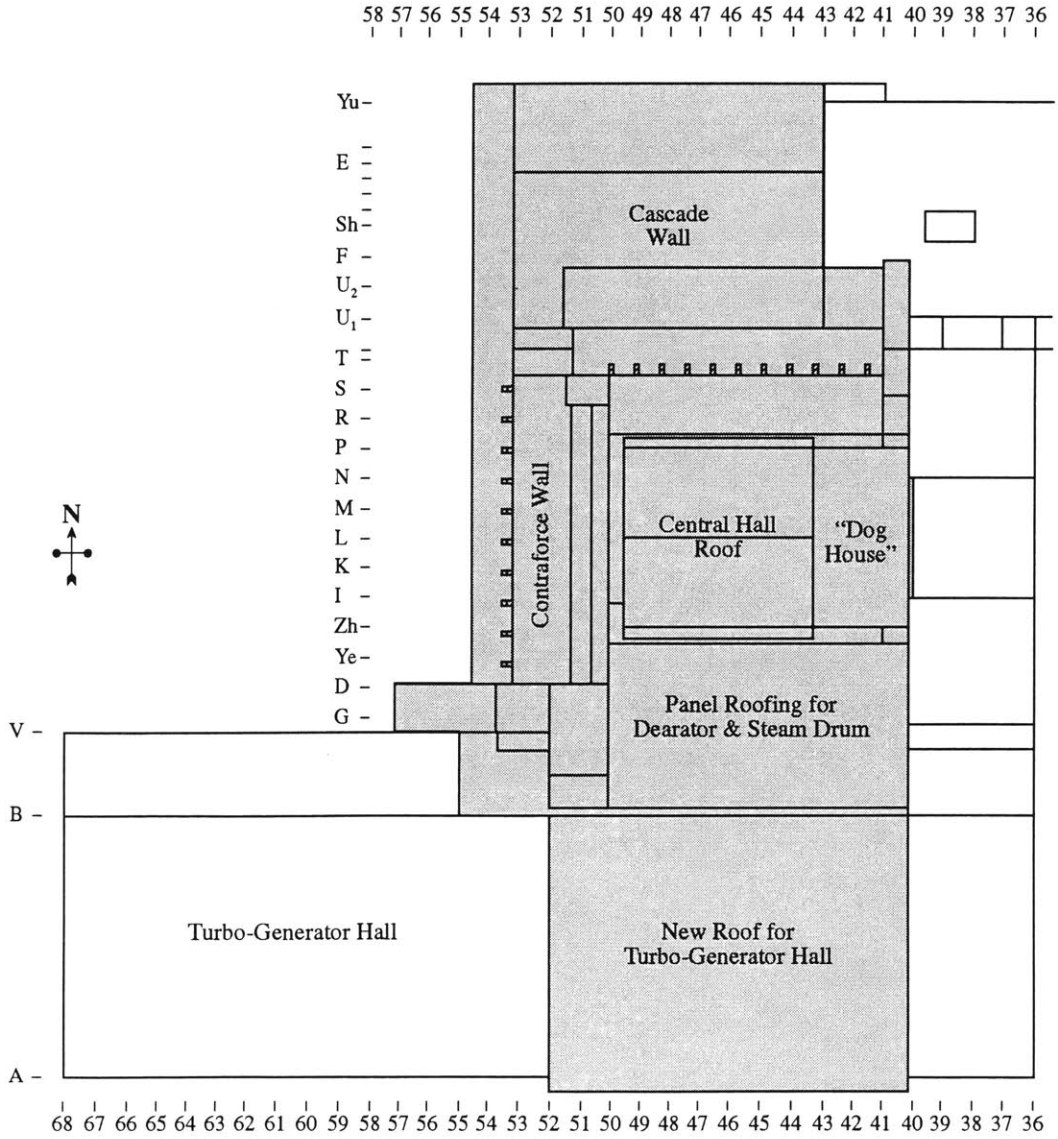
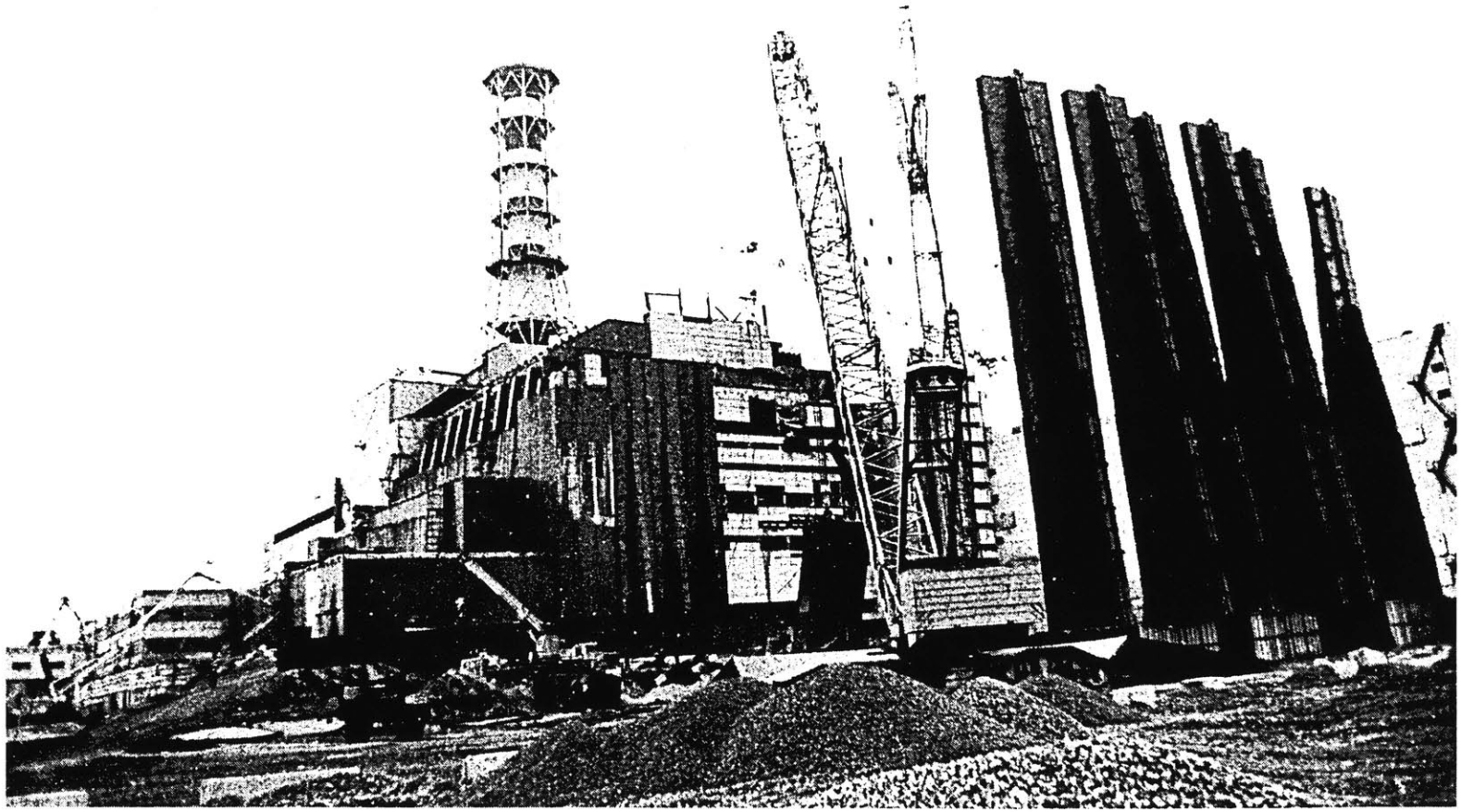


Figure V.3a[7]

Photograph of the 92-tonne Contraforce Wall panels before installation in October 1986.



[7] Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

Figure V.3b

Chornobyl Unit-4 Sarcophagus "Shelter"
Silhouette Along Axis 47
(Coordinates of Corners Given in Meters
With Respect to Level 0.0 m and Axis L)

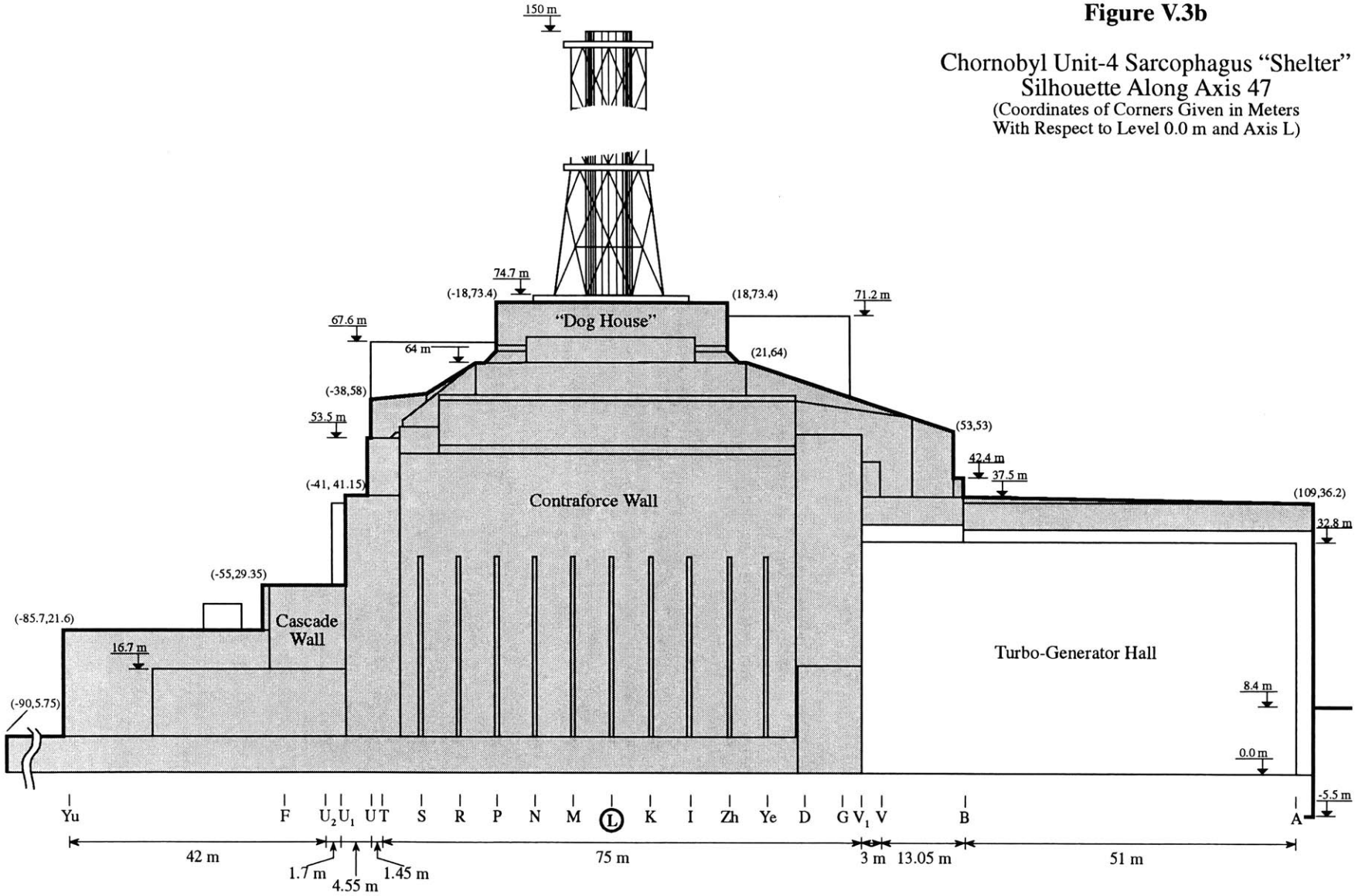
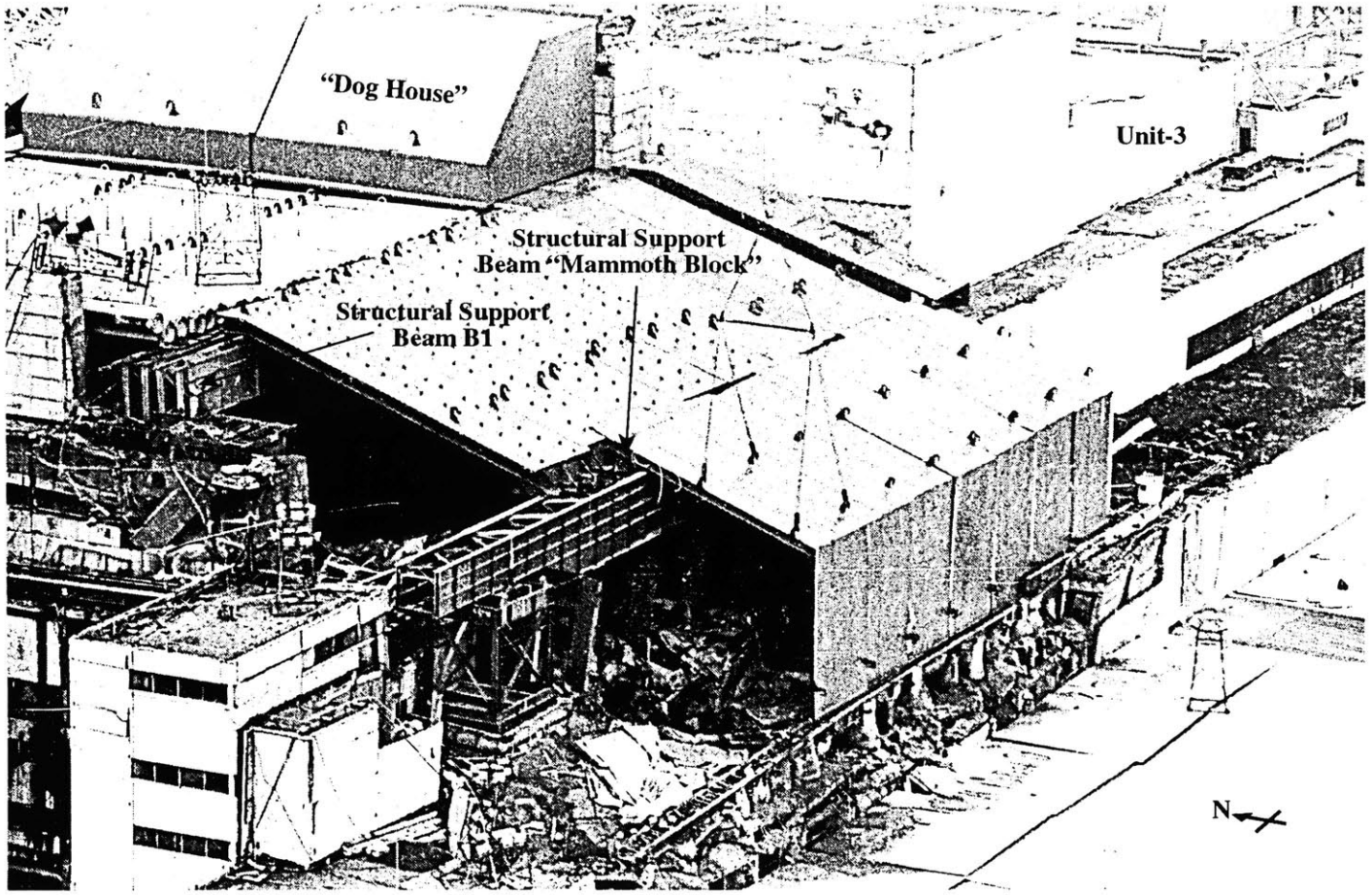


Figure V.4a[8]

Installation of roofing panels with a partial view of the "Mammoth" Block. Note the one meter-thick reinforced concrete structural support members inclined away from vertical.

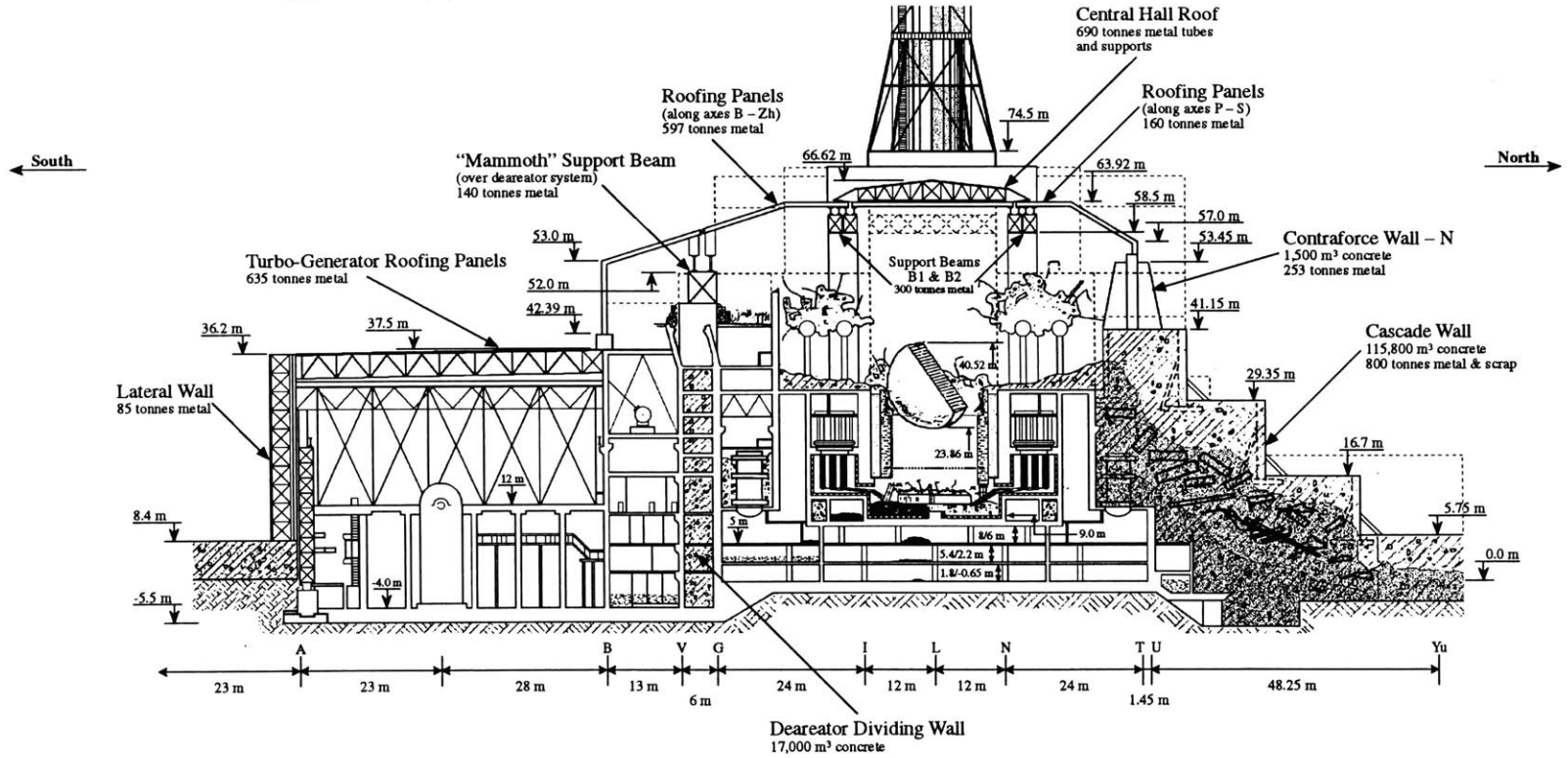


[8] Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

Sarcophagus Component	Metal Mass (t)	Concrete Volume (m³)
Central Hall Roof	690	–
Roofing Panels – Axes P-S	160	–
Roofing Panels – Axes B-Zh	597	–
Roofing Panels – Axes 41-43	145	–
Roofing Panels – Axes 50-53	158	–
Turbo-Generator Hall Roofing Panels	635	–
Turbo-Generator Hall Lateral Wall	85	–
Support Beams B1 & B2	300	–
"Mammoth" Support Beam	140	–
Contraforce Wall – N	253	1,500
Contraforce Wall – W	1,037	3,700
Contraforce Wall – W Foundation	–	17,500
Cascade Wall	800	115,800
Deareator Diving Wall	–	17,000
Dividing Wall – Axis 41	–	5,510
	5,000	**161,010**

Figure V.4b

Schematic of the Chornobyl Unit-4 Sarcophagus "Shelter"
(North-South Cross-Section along Axis 47)



approximately 250 – 300 meters from it. Before beams B1 and B2 were placed onto it, an effort was made to strengthen the wall with fresh concrete, but at that time it was unclear whether this procedure served its intended purpose. On the eastern part of the damaged building the beams rest upon ventilation shafts which appear not to have suffered major damaged (Figures V.5a & V.5b). Upon beams B1 and B2 are laid a series of steel pipes upon which in turn was built a steel-paneled roof. Support for these steel panels on the southern side is served by the 70 meter long (54 meters of which is "free hanging" and unsupported) x 5.5 meter wide Mammoth Block which in turn rests upon two concrete columns.* These columns stand among the debris of the damaged building and were strengthened by remotely-poured concrete.[9]

Work in 1987–88 on strengthening internal structures that suffered heavy damage as a result of the accident have avoided, at least for the time being, an internal collapse that may have lead to further weakening of *Shelter*. No noticeable long term movements of internal structures have been observed – even though an earthquake registering 4.0 on the Richter scale occurred in May 1990 resulting in only a slight enlargement of currently existing cracks in supporting walls. This seems to attest to the fact that in general *Shelter* is a relatively strong structure able to adequately withstand normal loads. Visual inspection of the most difficult to reach eastern column-support of the Mammoth Block, conducted by an inspection team in 1991, showed that no serious flaws in this support exist – although it was noted that water was getting into *Shelter* through openings in the structure that could eventually weaken and wear away the base of this support.

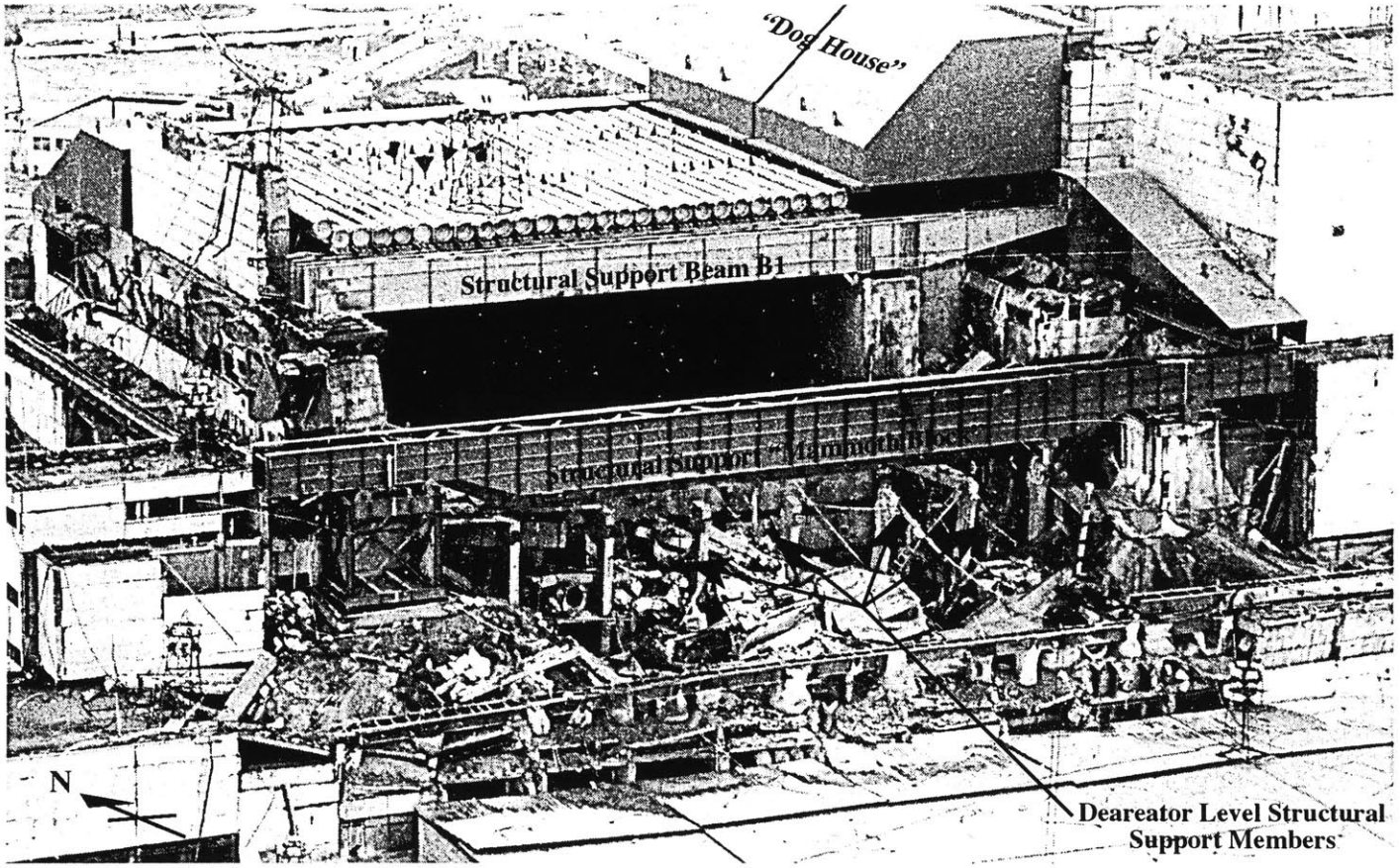
---

* There is a small inconsistency in the dimensions and mass of the Mammoth Block between those given by Kurnosov et al [Ibid., 302] (70 m long x 6 m tall x 2.4 m thick, 147 tonnes) and my review of the Sarcophagus construction plans (70 m long x 5.5 m tall x 2.4 m thick, 160 tonnes.)

[9] "Concrete Pumps for Chernobyl," *Nuclear Engineering International*, (December 1986): 3.

Figure V.5a[10]

Photograph showing damage to the southern areas of the reactor building. Note the "Mammoth" Block, Support Beam B2, Roofing Shielding Pipes, and the "Dog House."



[10]Photograph courtesy of Valentin Ivanovich Obodzinskij of the Kurchatov Institute, Moscow.

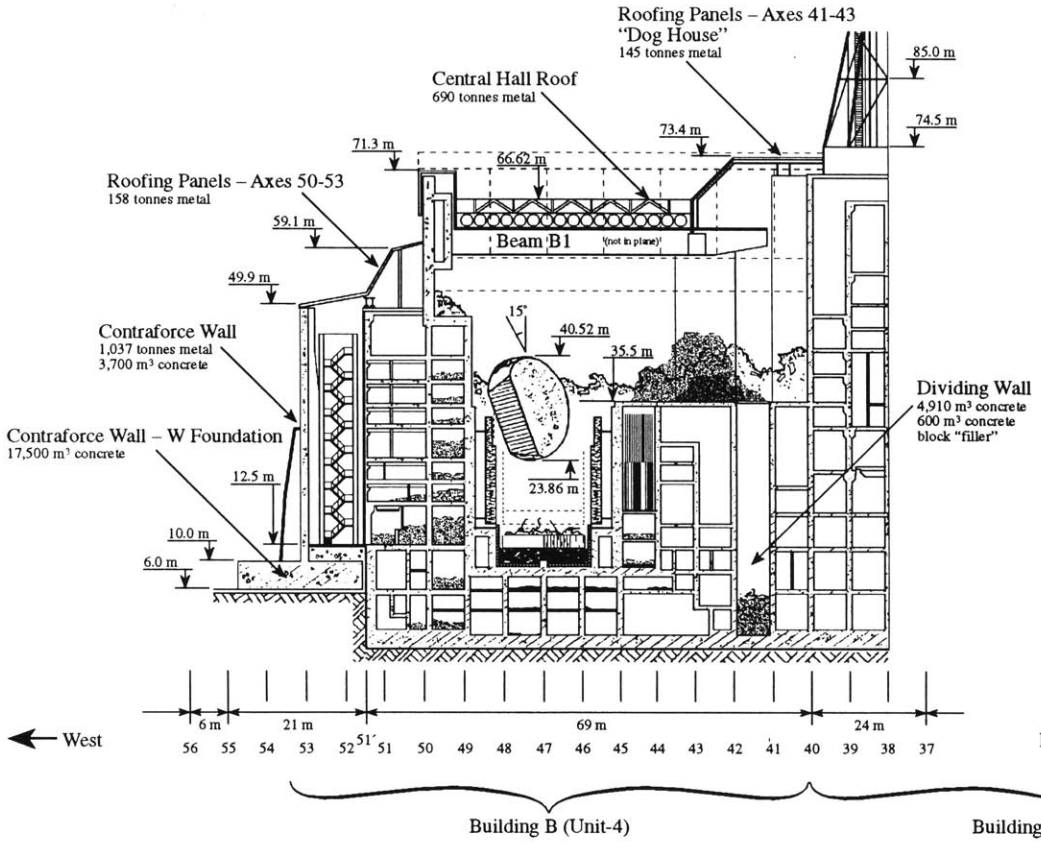


Figure V.5b

Schematic of the Chornobyl Unit-4 Sarcophagus "Shelter"
(East-West Cross-Section along Axis L)

Sarcophagus Component	Metal Mass (t)	Concrete Volume (m³)
Central Hall Roof	690	–
Roofing Panels – Axes P-S	160	–
Roofing Panels – Axes B-Zh	597	–
Roofing Panels – Axes 41-43	145	–
Roofing Panels – Axes 50-53	158	–
Turbo-Generator Hall Roofing Panels	635	–
Turbo-Generator Hall Lateral Wall	85	–
Support Beams B1 & B2	300	–
"Mammoth" Support Beam	140	–
Contraforce Wall – N	253	1,500
Contraforce Wall – W	1,037	3,700
Contraforce Wall – W Foundation	–	17,500
Cascade Wall	800	115,800
Deareator Diving Wall	–	17,000
Dividing Wall – Axis 41	–	5,510
	5,000	**161,010**

V.1.2. Radiation Hazards: Impact of *Shelter* Upon the Surrounding Environment

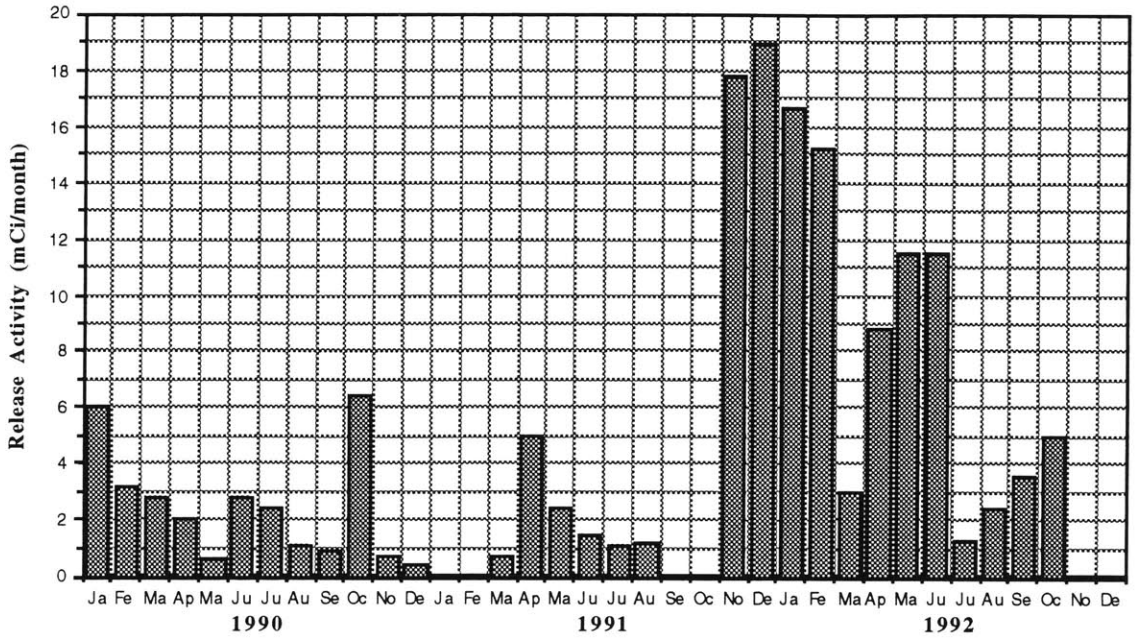
Rather than the collapse of the sarcophagus itself or the collapse of major portions of it (that could cause damage to the adjacent Unit-3 or threaten workers in the area), a more realistic threat is posed by the release of radionuclides into the surrounding environment. There are two ways by which radioactivity could be released into the environment: (1) the ejection of hot particles (dust) into the atmosphere through openings in *Shelter* if there is a collapse of internal structures within *Shelter*, and (2) the washing out of radionuclides by precipitation into the surrounding environment.

Dust suppression and the strengthening of supports internal to *Shelter* have so far averted potential threats posed by collapsing structures and the subsequent release of radioactive dust through openings in *Shelter*. In fact, for the period 1990-92, releases of any kind from *Shelter* were on an order of magnitude less than the normally permitted releases from a fully functioning RBMK (< 0.3 Ci/yr) based on Soviet standards.[11] (See Figure V.6.) However, the probability of the collapse of internal structures increases with time. In addition, because a gradual break-up of LFCMs is observed, the quantity of radioactive dust within *Shelter* is ever increasing – visual inspections and sample collection from the surfaces of exposed LFCMs have shown that they are losing their integrity (see section V.3.1.2.) Apparently, as decay heat generation decreases with time (and thus a decrease in the bulk temperature of the LFCMs), the material becomes less plastic (i.e., more brittle) as it cools. Additionally, on the microscopic level radioactive decay causes damage to the material matrix, and electric charges that collect on exposed surfaces (as ionization in the material takes place) give rise to electrostatic forces which in turn introduce stresses at the surface. As a consequence, the upper layers of the LFCMs are

[11] Borovoi, Alexandr Alexandrovich, "Post-Accident Management of Destroyed Fuel From Chernobyl: Technologies Used and Lessons Learned," Chornobyl, Ukraine and Moscow, Russia: International Atomic Energy Agency, (1990): 57–58.

Figure V.6[12]

Upper Limit of Total Radioactive Aerosol Releases from
Chornobyl Unit-4 Through Openings in the Sarcophagus



cracking.[13] This makes the LFCM surfaces increasingly susceptible to washout (from precipitation entering the sarcophagus) and to dust formation. Thus, the "dust release" component of an environmental threat appears to be increasing with time.

How hazardous is a potential ejection of dust in such a hypothetical case? Even the most pessimistic appraisals (i.e., those that postulate the greatest possible releases) con-

---

[12] According to an internal report [МНТЦ «Укрытие», *Подготовка и экспертная оценка исходных материалов для новой редакции ТОРБ Объекта «Укрытие»*, Чернобыль, Украина. (1992): 41], release data for January & February 1991 "is missing because during that period it was impossible to perform tasks at *Shelter* by members of the Complex Expedition *due to circumstances beyond their control.*" [emphasis added] More disturbing, however, is the absence of data for September & October 1991 and a very significant increase in releases immediately afterwards. The same report "hypothesizes" that the sticky film used to collect airborne contamination became contaminated with metallic debris from the roof of *Shelter*. It neglects to add that the reason for this contamination was an act of sabotage by one of the members of the Complex Expedition. [Private communications with researchers at Chornobyl.]

[13] See Богатов, С. А., А. А. Боровой, А. Н. Киселёв, Л. А. Обухова, К. П. Чечеров. "Оценка скорости эрозии топливосодержащих масс внутри «Саркофага» и характеристики образующихся частиц." Препринт ИАЭ-5434/3. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1991; and, Подготовка и совершенствование ТОРБ объекта «Укрытие» на основе оцененных баз данных по объекту и его влиянию на окружающую среду, Чернобыль, Украина: Академия Наук Украины – Межотраслевой научно-технический центр «Укрытие», (23.XII.1993): 91–94.

clude that with a major collapse of structures internal to *Shelter*, the ejection of dust from existing openings or cracks can pose a hazard only to those people working on the territory of the station. In fact, a "maximum" postulated accident defined by the complete collapse of the sarcophagus in the event of a strong earthquake or direct tornado encounter, would produce a radioactive plume and subsequent fallout that can be adequately appraised as local. Pessimistic predictions based on such a "maximum" accident suggest that a relatively thin (~1 kilometer wide) but somewhat long (on the order of a few dozen kilometers) plume could arise with contamination approaching dozens of Curies per square kilometer for Cs-137 and up to a few Curies per square kilometer for Sr-90 and plutonium.[14] Ejection of radioactive dust from *Shelter* is hazardous first of all because of possible contamination of the external environment by plutonium. For humans located within such a postulated plume, an insignificant rise in external exposure would be accompanied by an orders of magnitude increase in the concentration of plutonium hot particles in the air over that permitted by (former) Soviet standards.

The processes of water penetration into *Shelter*, and the flow of this water downwards through debris into lower regions of the reactor building (which gradually weakens the structure, washes out radionuclides from LFCMs, and carries away hot particles of fuel and dissolved forms of radionuclides) is less well understood and is discussed briefly in section V.3.1.3. The total gamma activity (the major contributor to which is Cs-137) of all waters lies within the range of tens of μCi/l to several mCi/l.[15] The problem of water migration to outside the bounds of *Shelter* is now being studied, but no conclusions have as yet been reached.

---

[14] Подготовка и совершенствование ТОРБ объекта «Укрытие» ..., 116–137.

[15] Подготовка и совершенствование ТОРБ объекта «Укрытие» ..., 94–102.

V.2. Remains of the Unit-4 Core Shaft and Adjacent Areas[16]

Investigations conducted from 1986 through 1989 showed that previous notions concerning the extent of damage within Unit-4 as a result of the accident, in most cases did not correspond to the actual state of the destroyed reactor. After a significant number of bore samples (about seventy) were taken of the core region, core-support area and sub-reactor region, steam-distribution corridor, and a number of other areas (Figure V.7), radiation field measurements were taken to determine which areas were safe enough to approach for closer inspection.[17] Visual inspections of these areas were then conducted either by remote-control visual aids (video-cameras, periscopes, or small robots), or, if approachable, directly by researchers armed with photo- and video-cameras. The following account details what was found within the reactor building of Unit-4. (Refer to Figures V.8 & V.9 and Figure III.11 for a visual reference and definition of abbreviations.)

The core of the reactor and the stainless-steel, hermetic pressure casing that contained the core, *"Scheme"* or *"Component" KZh*, are destroyed.** The Upper and Lower Biological Shields (*Components E and OR* respectively) have been displaced from their

---

[16] This section is based on extensive discussions with members of the Chornobyl research team as well as a detailed review and verification of a number of Soviet reports and preprints. Caution, however, is advised because inconsistencies in some of the sources and interpretations of researchers may not fully reflect a true descriptive account of the remains of Unit-4. The sources consulted are:

(1) Андерсон, Е. Б., С. А. Богатов, А. А. Боровой, Б. Е. Бураков, А. С. Евстратенко, А. П. Криницын, Э. А. Пазухин, А. И. Сурин. *Лавообразные топливо-содержащие массы объекта «Укрытие»*. Киев, Украина: Межотраслевой научно-технический центр «Укрытие» и Институт кибернетики имени В. М. Глушкова при АН Украины, Препринт 93-17 (1993).

(2) Киселёв, А. Н., А. Ю. Ненаглядов, А. И. Сурин, К. П. Чечеров. "Экспериментальные исследования лавообразных топливосодержащих масс (ТСМ) на 4-м блоке ЧАЭС (по результатам исследований 1986 – 1991 годах." Припринт ИАЭ-5533/3. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1992.

(3) Боровой, А. А., Г. Д. Ибраимов, С. С. Огородник, В. Д. Попов, К. П. Чечеров. "Состояние IV Блока ЧАЭС и Ядерного Топлива, Находящегося в Нём (По Результатам Исследований 1988 – 1989 гг)." Припринт. Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, 1990.

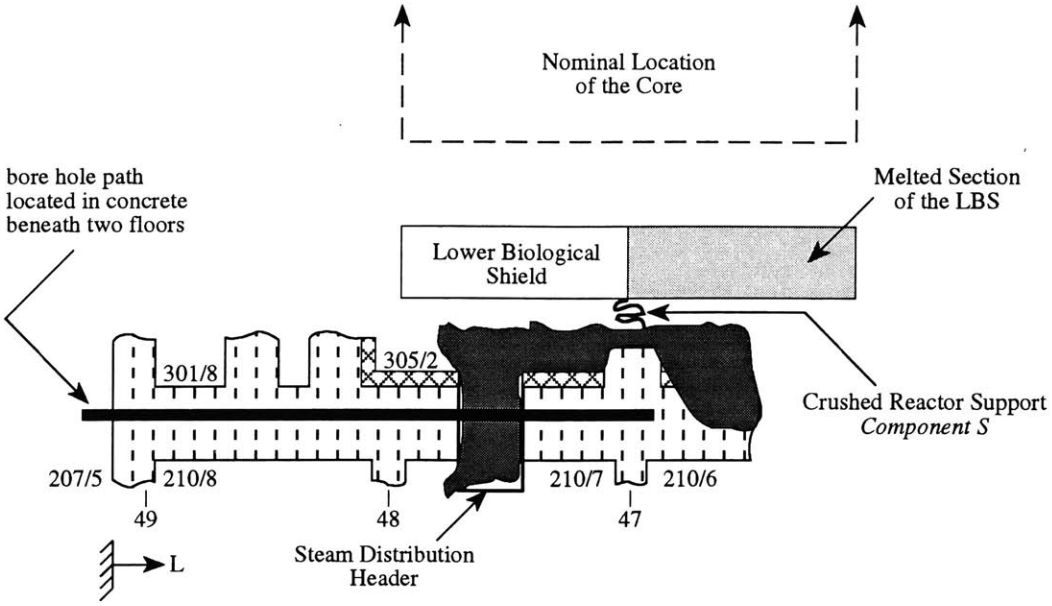
(4) *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие»*. Чернобыль, Украина; Минск, Беларусь: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, Институт радиоэкологических проблем при АН Беларусь, 1992.

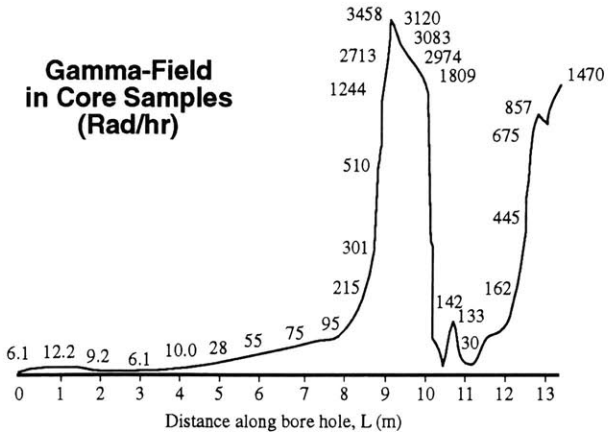
(5) Подготовка и совершенцтвование ТОРБ объекта «Укрытие» на основе оцененных баз данных по объекту и его влиянию на окружающую среду. Чернобыль, Украина: Академия Наук Украины – Межотраслевой научно-технический центр «Укрытие», 23.XII.1993.

[17] For a summarized account of remote methods employed to investigate Unit-4 see Borovoi, Alexandr Alexandrovich, Ivanov, Alexandr Ivanovich, and Sich, Alexander, "Use of Robotic Technologies and Remote Systems for Diagnostics and Research Within the Chornobyl Sarcophagus, *Proceedings of the ANS Fifth Toopical Meeting on Robotics and Remote Systems*, Knoxville, Tennessee, April 25–30, 1993.

** In architectural-engineering jargon, the Soviets typically use the term "scheme" to indicate a major component of a system. In the this case, the stainless-steel hermetic pressure casing that contains the core is oftentimes referred to by the shorter expression *Scheme KZh* from the Russian word *KoZha* or "skin."

Figure V.7
A Bore-Sample Drilling Schematic
(D = 112 mm, L = 13.37m, Viewed from the South)





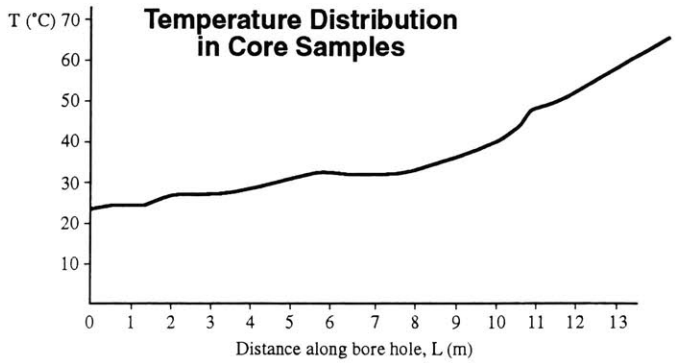


Figure V.8

Sectional view of Chornobyl Unit-4 in its current state. Approximately 71% of the initial 190.3 tonne UO_2 fuel load is now located in areas below the Lower Biological Shield. Note that virtually no fuel or graphite is found in the reactor shaft region. Also, an approximately one-quarter pie-shaped section of the LBS is missing – presumably taken up by the corium before it flowed into the lower regions of the reactor buildling, and which later cooled into ceramic glass-like and pumice formations.

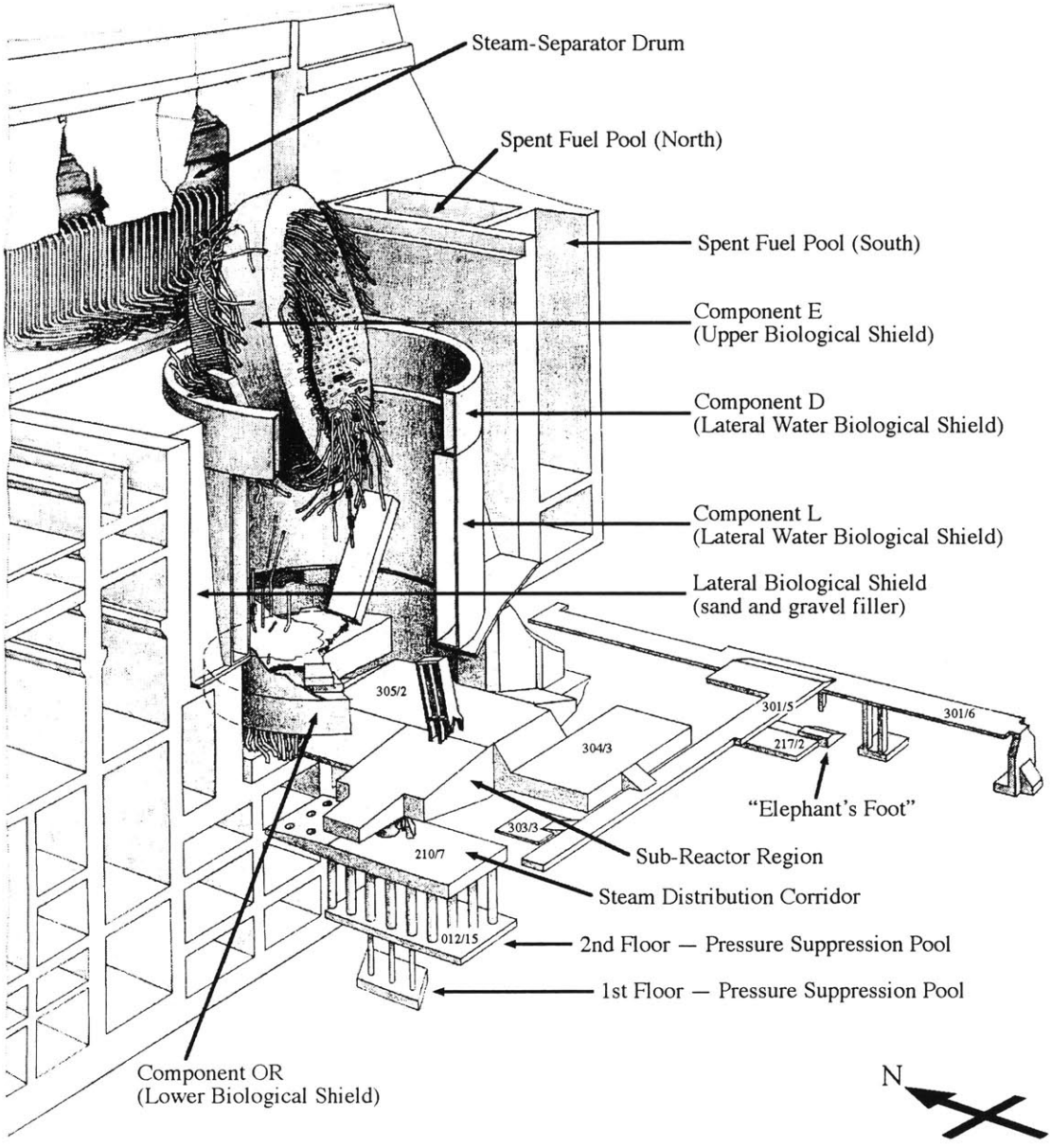
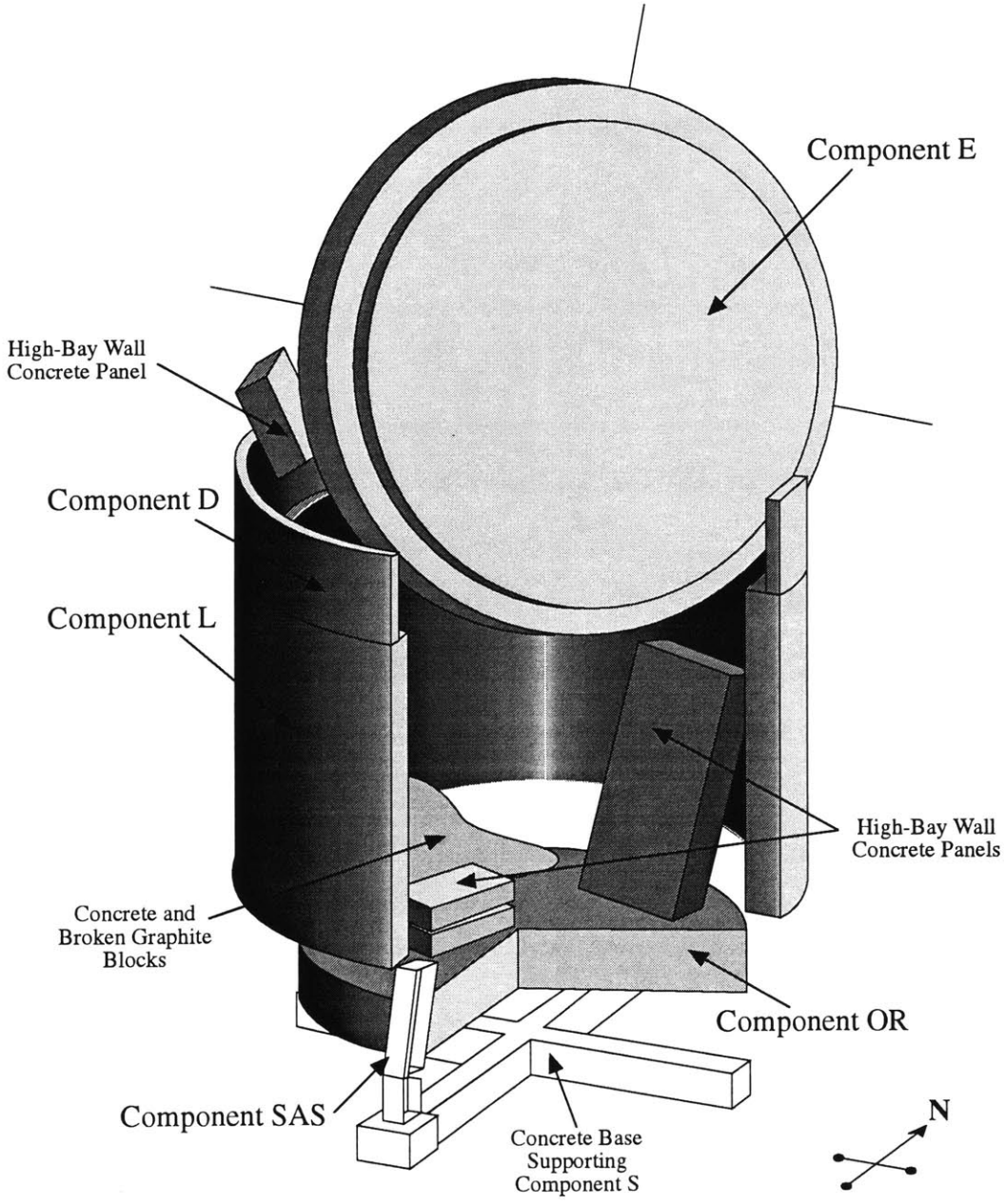


Figure V.9

Sectional Schematic of the Chornobyl Unit-4 Reactor Shaft



standard design positions. Cylindrical water tanks surrounding the core known as the lateral biological shields, *Component D* and *L,* remain more or less in their nominal positions. The 21.6 m x 21.6 m reactor shaft remains, as far as can be ascertained, intact with little if any of the sand and gravel filler material (between *Component L* and the shaft) missing.

Part of the reactor fuel and assemblies (in the form of Zircaloy pressure tubes containing fuel rods, individual pieces of fuel rods, broken or partially intact graphite blocks, granules of these, and dust) as a rule, are found in the upper regions of the reactor building. A significant amount of graphite blocks and some pieces of *Component KZh* were hurled onto the roofs of Unit-3 and the Turbo-Generator Hall. A small portion of the reactor graphite block pile along with the associated fuel assemblies are lying among debris and under concrete† on top of *Component OR.* The rest of the fuel is in the form of LFCMs located in the lower regions of the reactor building starting from below the current location of *Component OR.* The LFCMs are a combination of various structural materials (stainless steel, serpentine, graphite, etc.) that melted during the Active Phase of the accident, mixed with molten fuel, and flowed downwards into the lower regions of the reactor building to form varied types of frozen corium. *Component OR* itself was significantly damaged: besides descending approximately four meters (compressing the reactor support, *Component S,* accordion-style beneath it), a pie-shaped section (≈ 105°) of the southeast quadrant is conspicuously missing. *Component OR* is also tilted downward through an angle of approximately 10° in the direction of the missing section. It is not clear whether *Component S* collapsed as a result of the explosion, whether its yield point was lowered due to heating from the solidified but still quite hot corium (decay heat generation ten days, one month, and three months after the accident was 42 kWt/t U, 24 kWt/t U, and 12 kWt/t U respectively) that relocated to Room 305/2 after the Active Phase, or a combination of both.

† This is the so-called "fresh" concrete poured into the reactor building during the construction of Shelter-I.

Component E (together with the remains of approximately forty upper coolant channels (UCCs), moderator coolant or fuel & instrumentation channels – so called technological channels (TCs), and fragments of reinforced concrete support-structures) is suspended on its side by the walls of the reactor shaft approximately 15° from vertical. On the northeast side of the shaft it rests upon the upper portion of *Component D*, while on the southwest side it rests upon a large fragment (approximately 2 m x 3 m x 1.5 m) of reinforced concrete and steel panel pinned against *Component D*. This panel was later determined to be part of the lower bay wall on the south side of the central hall from approximately Level 45 m which supported the fueling machine and provided shielding for the steamdrum separators located adjacent to the reactor hall in Rooms 804/3&4.†† Virtually the entire space between *Component E* (normally its upper face) and *Component D* on the northwest side is filled in with heavily damaged stainless steel coolant pipes (which connect the UCCs to the Zircaloy core pressure tubes) and tangled UCCs. Driven in between these coolant pipes are reinforced concrete blocks about two cubic meters in volume. Apparently, these blocks were at one time part of the same wall from where the panel pinned on one side beneath *Component E* (see above) originally came. The central section of the (formerly) lower face of *Component E* (which corresponded to Level 28.5 m) is stripped of its TCs – approximately fifty percent of the core's total channels are cut off at flush with the surface. A small number of severely damaged TCs surrounding the stripped central section on the periphery of *Component E's* bottom face remain dangling from it. The number of these that are fuel or control channels as opposed to moderator coolant channels (MCCs) at this time is not known. From within the core region at Level 24.6 m one can see approximately forty badly damaged channels dangling from what is now the lower part of *Component E.* The bottom edge of *Component E* (which is inside

†† Still unanswered remains the question of how pieces of these high-bay wall panels managed to fall to the bottom of the reactor shaft. One credible explanation is that hydrogen generated early during the accident may have accumulated and detonated in the steamdrum separator chambers – blowing parts of the wall in toward the Central Hall. Another hypothesis is that pressure waves from the steam explosion may have reflected into the steamdrum separator chambers along the water-steam coolant channel paths also blowing out parts of the wall.

the core region) is at Level 25.0 m and the top edge (which is clearly seen from the Central Hall extending out of the core region) is at Level 43.0 m – placing the geometric center of *Component E* five meters above its normal position before the accident.

The core region, rather unexpectedly, turned out to be practically empty. Lying in a pile on top of the northeastern upper face of *Component OR* and on both sides of *Component KZh* (in the space between the remains of *Component KZh* and *Component L,* and between the remains of *Component KZh* and the center of *Component OR*) are graphite blocks, eight MCCs oriented vertically and still connected to *Component OR,* a reinforced concrete panel approximately five meters wide (apparently also once forming part of the walls of Room 804/4) that is blocking from sight the northern "emergency alignment" support (*Component NAS*) and resting at a sharp angle (≈ 70° from horizontal) and pressing MCCs into *Component L.* Lying horizontally in the southwest quadrant of *Component OR* are two reinforced concrete panels, one on top of the other, with dimensions approximately 1.2 x 3.5 x 1.0 meters. On the northwest section of the upper face of *Component OR* there is also a pile of graphite blocks, but these are covered somewhat with "fresh" concrete (that seeped in through the damaged wall of Room 804/4 during the construction of *Shelter-I's* "Cascade Wall" in the fall of 1986) approximately up to Level 16 m. A space of about one meter between the bottom of *Component L,* the upper remains of *Component KZh,* and the layer of concrete on *Component OR* remains.

The southeast section of *Component OR* (roughly along the reactor central Axes 47 and L) no longer exists.* It is without a doubt that this section (together with its associated LCCs, stainless steel coolant pipes, and support structures) melted. There is evidence to support this close to the area where the section should be: visible metal structures are

---

* At this point, it seems odd that the Soviets came to the following conclusion in August 1986 at Vienna: "The lower slab of the reactor shaft [Lower Biological Shield] had been preserved and fuel was localized mainly (roughly 96%) in the reactor shaft an[d] in compartments of steam water and lower steam service lines [Lower Coolant Channels]." [U.S.S.R. State Committee on the Utilization of Atomic Energy (comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Part I: General Material,* report presented at the International Atomic Energy Agency Expert's Meeting, Vienna, (August 25–29, 1986): 42.]

either partially melted or warped from heating, the part of *Component OR* to which its "melted" section should be attached shows signs of some burning and a melting process having taken place, and the top of the southern "emergency alignment" support for *Component L* (*Component SAS*) is tilted 15° toward *Component OR* and burned halfway through approximately in the middle.

Component OR descended approximately four meters straight down from its normal position, crushing *Component S* beneath itself.** On both sides it also crushed and pulled smoothly downward with itself the lower coolant channels (LCC) that are now resting upon the corner of the upper cover for Rooms 302/3&4, 303/3&4, and 304/3&4. (Refer to Figures V.10 – V.14 for schematics of rooms and locations of the corium in the lower regions of the reactor building.) Normally the LCCs enter the space under the reactor (the upper space designated as the Sub-Reactor Region, the lower space as Room 305/2) horizontally from the reinforced "strong boxes" (Rooms 404/3&4) that protect the group dispensing headers (GDHs). The LCCs that descend vertically from the GDHs before horizontally entering the Sub-Reactor Region are relatively undamaged; and one may walk through Rooms 404/3&4 (on top of concrete which seeped in during the construction of Shelter) as during a routine inspection. *Component NAS* remains in its normal position; while in front of it (looking toward the center of *Component OR*) the lower section of the cylindrical wall, *Component KZh,* descended together with *Component OR* and is more or less intact for 1.5 meters vertically up to its first thermal expansion compensators.

Located a small distance from the graphite blocks under the bottom part of *Component L* and pressing against south-eastern edge of the circular wall of *Component L* (whose steel surface is torn or burned-through) is a reinforced concrete fragment ap-

---

** It is now known that *Component OR* (the Lower Biological Shield) descended four meters not as a result of the initial explosions, but rather because of decay heat (≈ 50 kWt/t UO_2 at 10 days after the accident) from the approximately 75 tonnes of melted fuel that to this day remain in the Sub-Reactor Region (Room 305/2) surrounding the mettalic reactor support structure, *Component S*. This support thus soon reached its yield point and under a load of approximately 800 tonnes (the remains of *Component OR* and other debris) smoothly descended four meters. [Private communication with several Kurchatov Institute researchers, September 1992.]

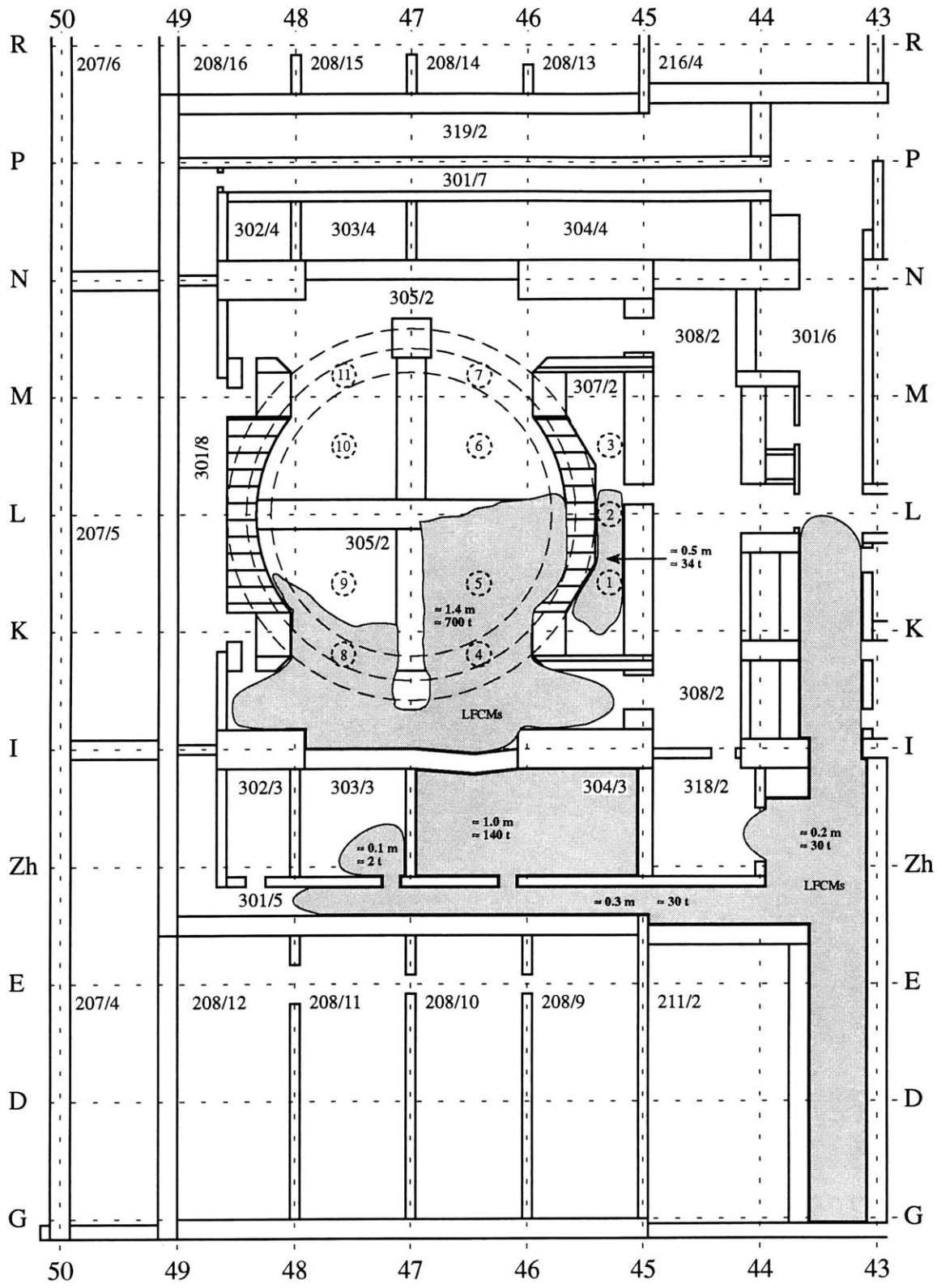


Figure V.10
Level 9 m: Sub-Reactor Region

Locations of Fuel Containing Masses in the Sub-Reactor Region and adjoining areas.

KEY

Level 9.00 m
Scale: 1 inch = 8 meters
Distance between axes: 0.75 inch = 6 meters

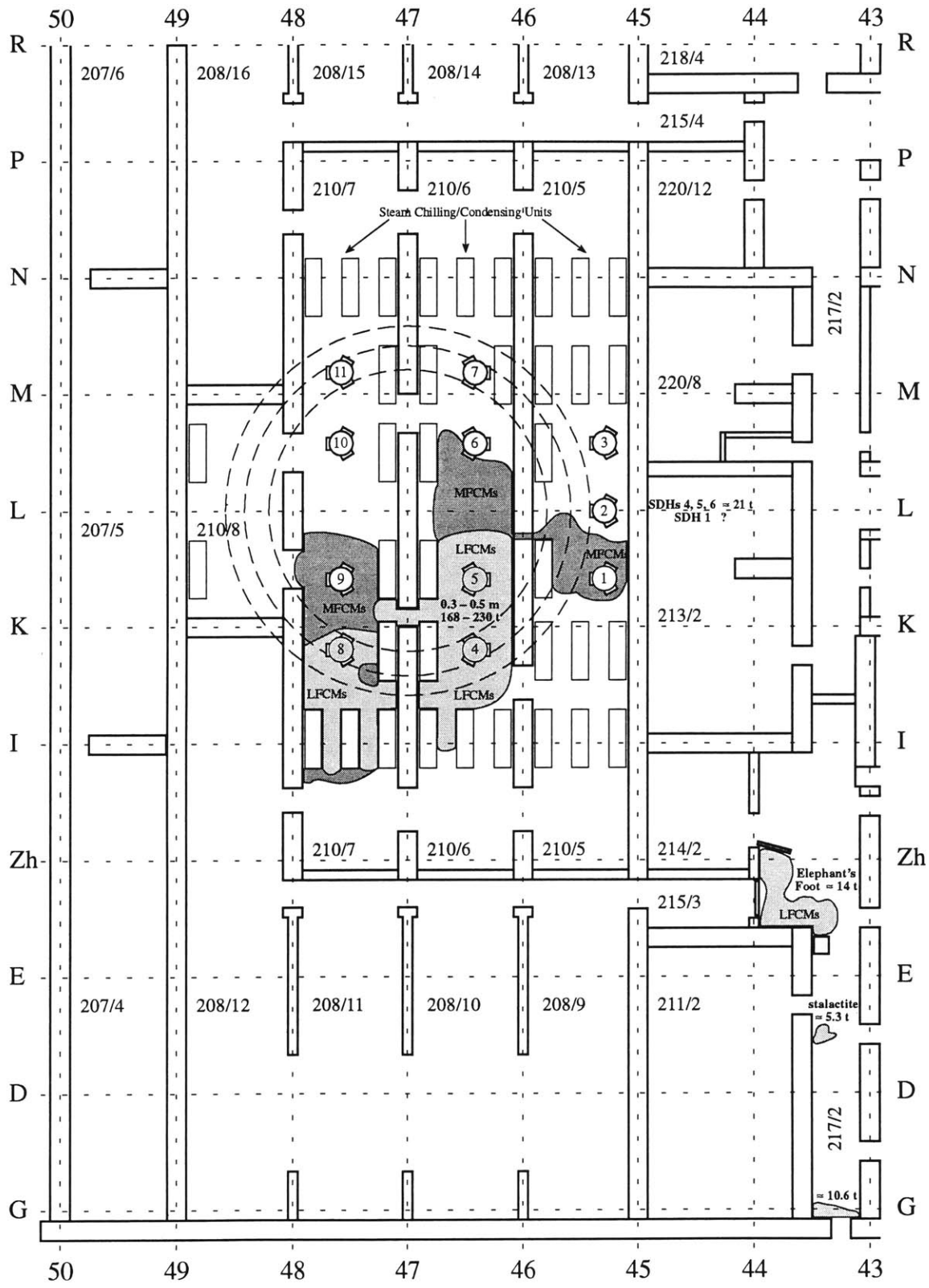


Figure V.11
Level 6 m: Steam Distribution Corridor

Locations of Fuel Containing Masses in the Steam Distribution Corridor and adjoining areas.

KEY

Level 6.00 m
Scale: 1 inch = 8 meters
Distance between axes: 0.75 inch = 6 meters

N

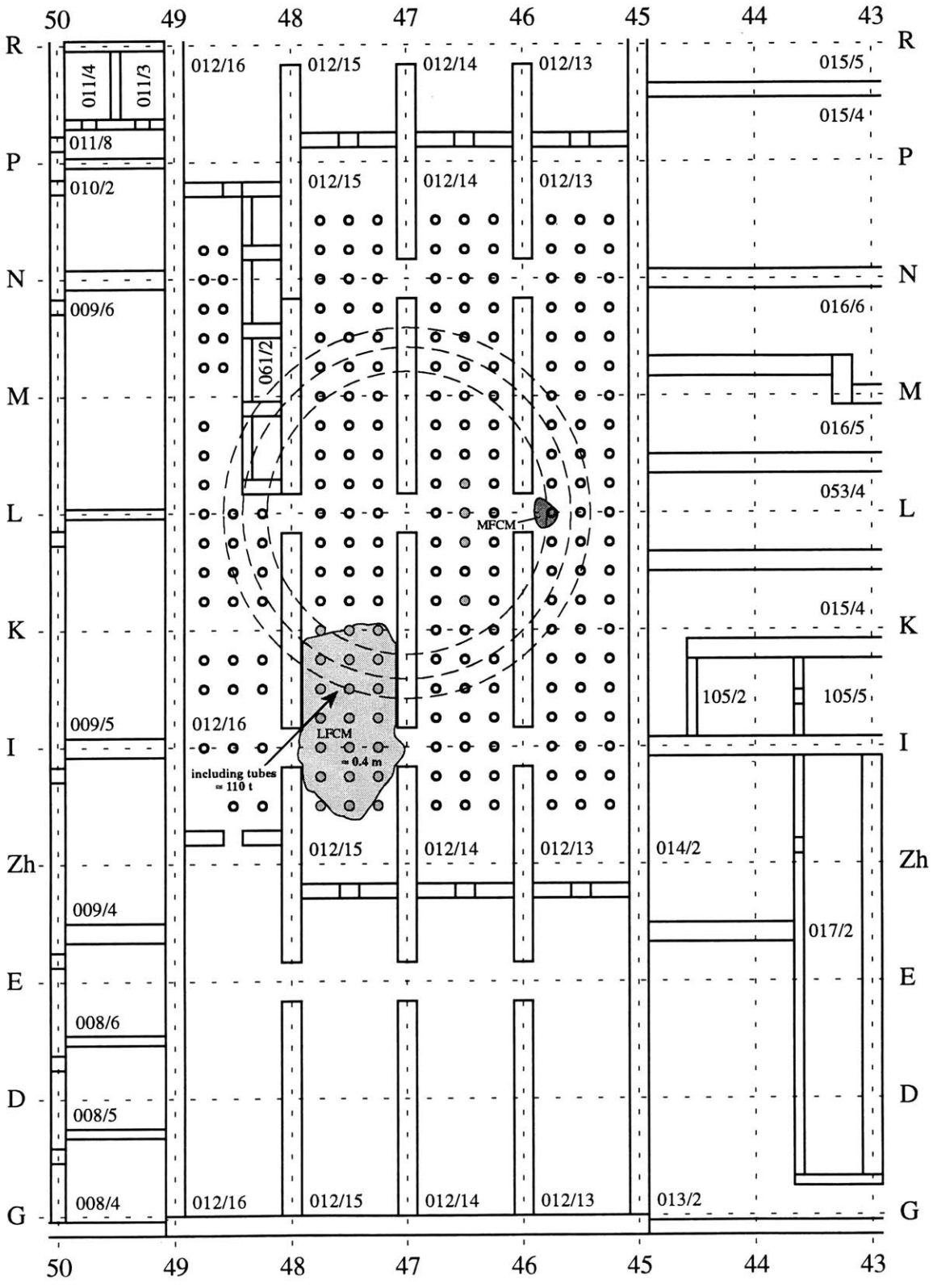


Figure V.12
Level 3 m: Pressure Suppression Pool – 2

Locations of Fuel Containing Masses on the second floor of the Pressure Suppression Pool and adjoining areas.

KEY
Level 3.00 m
Scale: 1 inch = 8 meters
Between axes: 0.75 inch = 6 meters

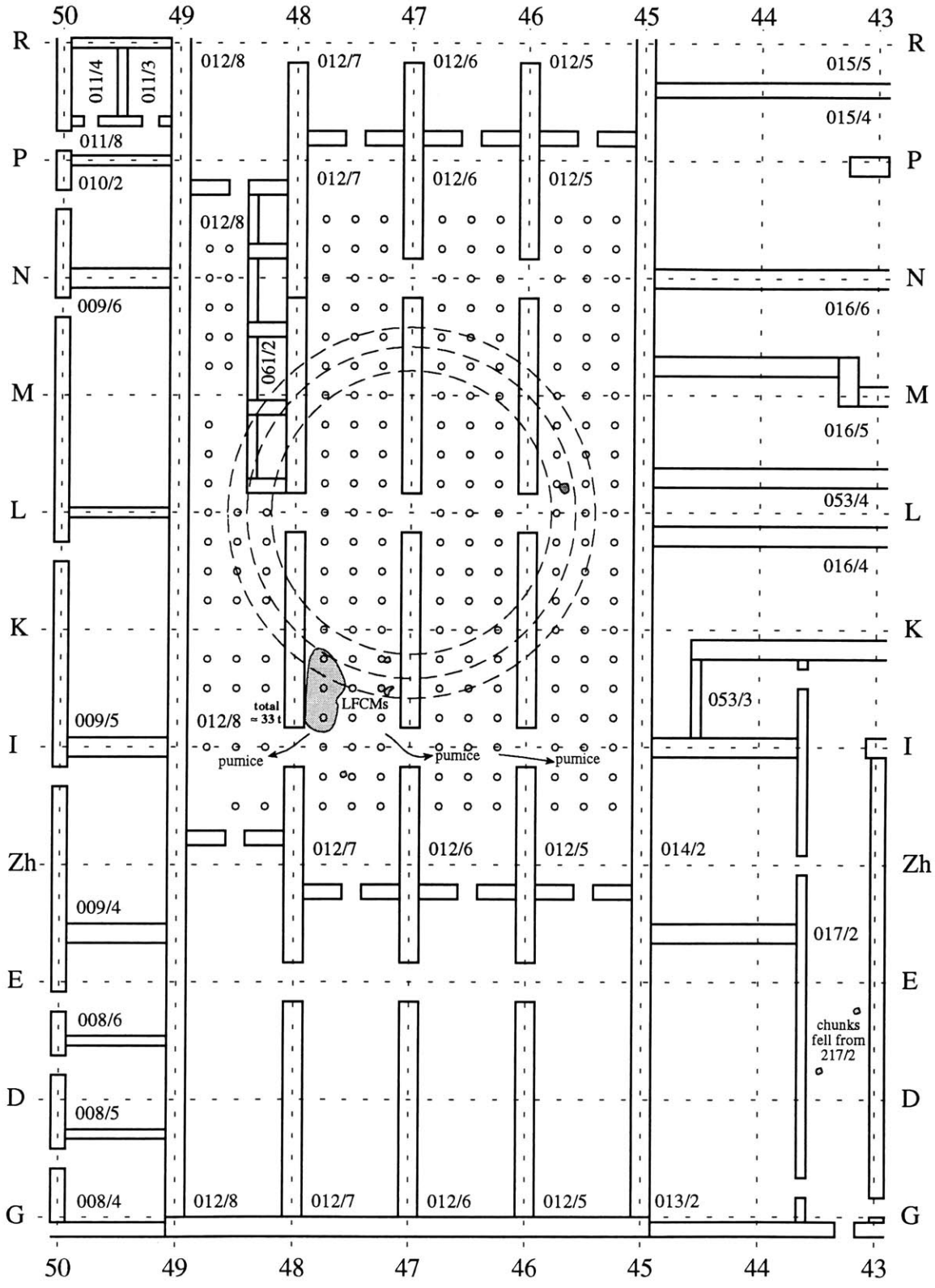
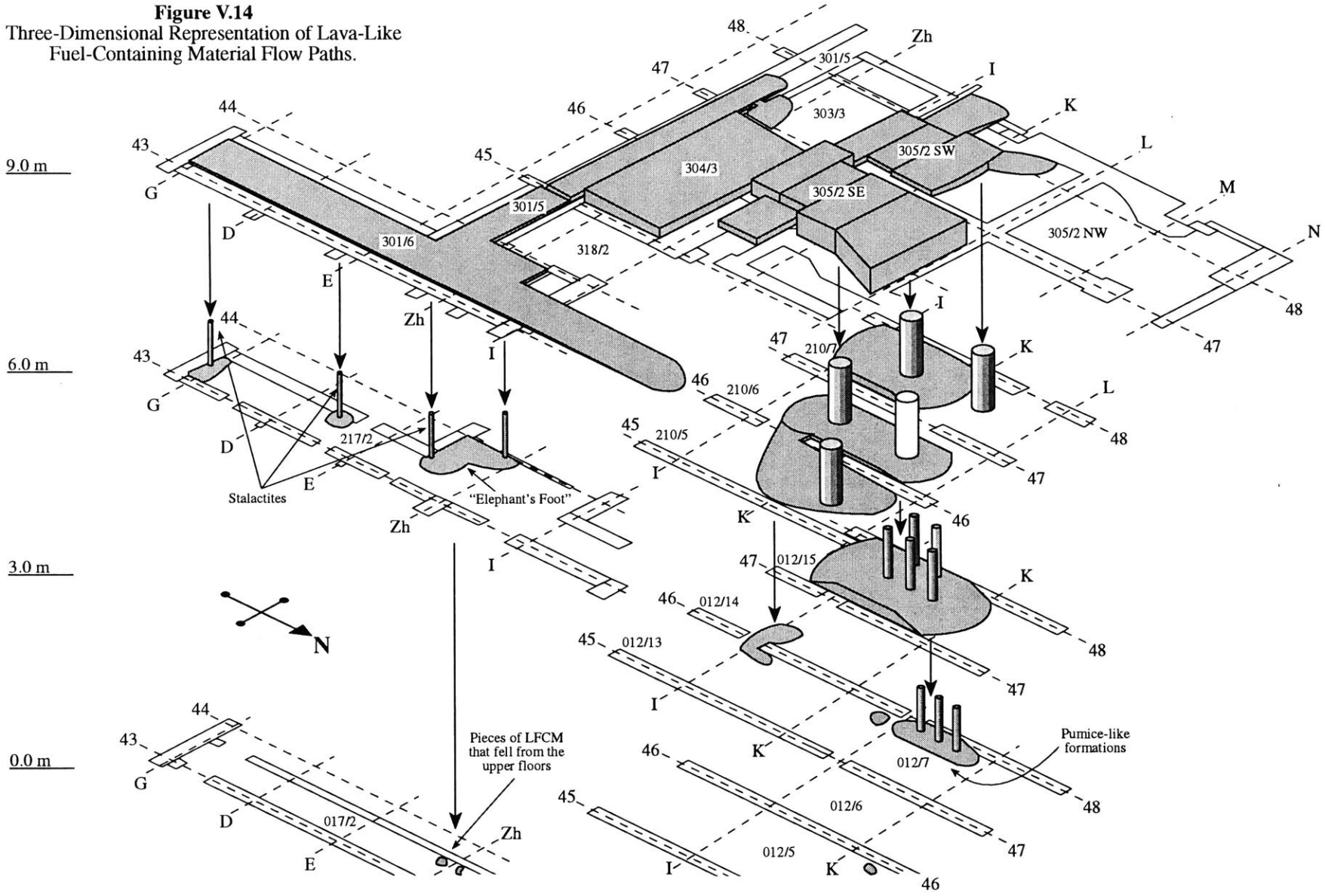


Figure V.13
Level 0 m: Pressure Suppression Pool – 1

Locations of Fuel Containing Masses on the first floor of the Pressure Suppression Pool and adjoining areas.

Figure V.14
Three-Dimensional Representation of Lava-Like Fuel-Containing Material Flow Paths.



proximately one cubic meter in volume with a rusted armature jutting out from it. Along the reactor's central east-west Axis 47 (between the *Component SAS* and the LCCs that drop almost vertically downward) is found a flattened stainless steel sheet approximately 8 mm thick. It is assumed this is from the wall paneling of the Sub-Reactor Region. In the south-eastern part of the Sub-Reactor Region on the LCCs (that are pressed against the wall of Room 304/3) lies a layer of gravel and metal (presumably serpentine and the cast iron-pebble thermal compensator-region filler†) that is partially covered with graphite blocks. In front of the southern gate leading into Room 308/2 (Room 305/2 ante-chamber), the very south-eastern part of the lower water communication pipes (that drop downward approximately to Level 12 m) is also filled in with gravel (presumably serpentine), that poured through the opened gates into room 308/2. This was subsequently covered with concrete in 1986 to Level 11.5 m. The Room 305/2 antechamber on the inner side of the pile of gravel is also covered with concrete to the same level. This concrete, judging from the flows, spread in the southeastern part of the Sub-Reactor Region from the north out from under the northern part of *Component OR.*

In the area of the intersection of Axes 46 and L a pink-colored metallic structure is standing almost vertically – either a column that toppled down from the central hall or a curled-up steel sheet. The steel paneling from the southwestern section of the wall of Room 307/2 is missing (either burned, melted, or torn away), and the wall has a blackened niche – possibly a puncture or a hole burned through from Room 305/2. The mettalic covering, upon which is located gravel and metal chunks, seems undamaged. Its color is pinkish with sooty discolorations appearing here and there. The stainless steel covering of the walls of Rooms 305/2 and 404/4 (which is normally separated from the

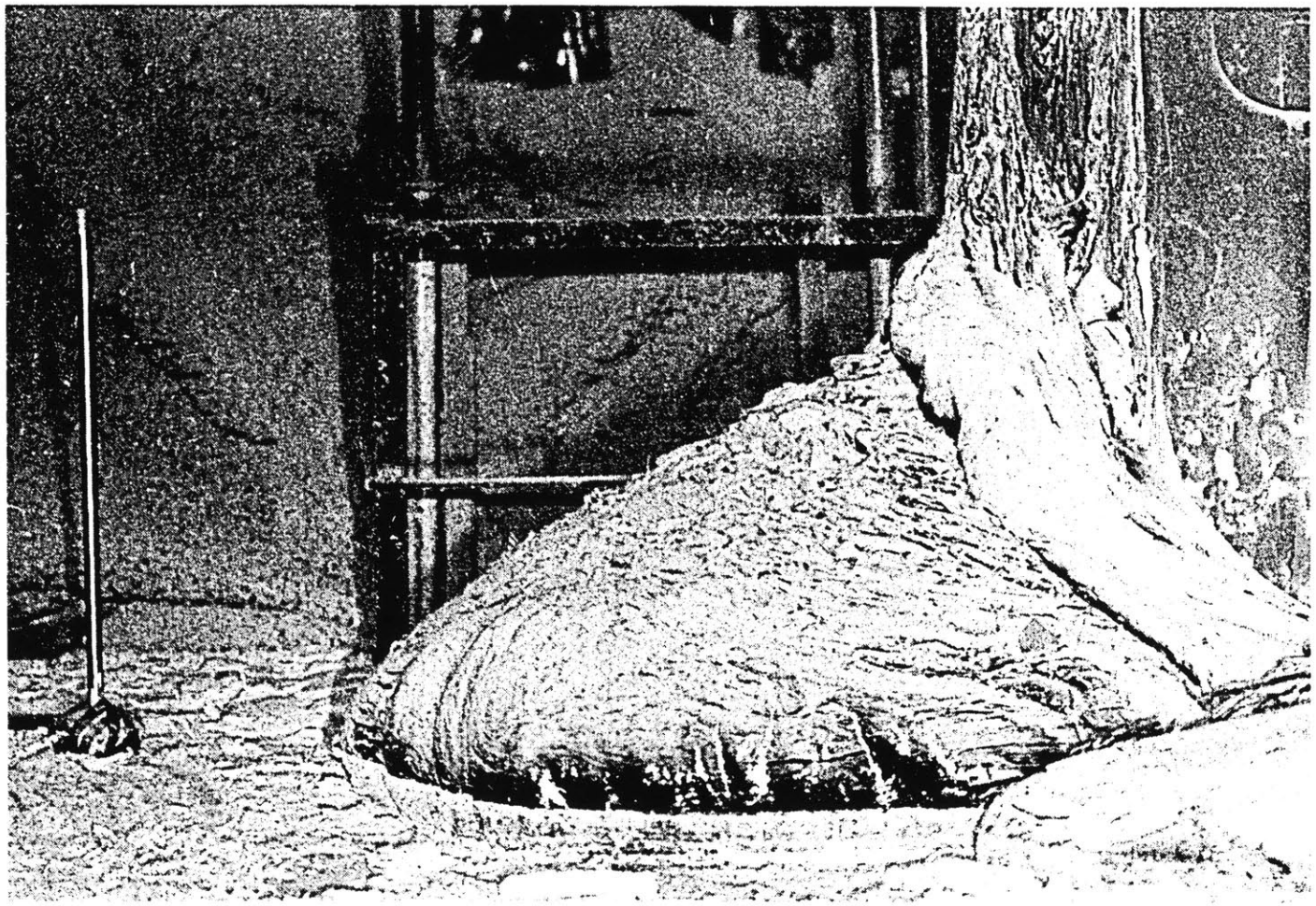
† Serpentine, a hydrous magnesium silicate $Mg_6[Si_4O_{10}]\cdot[OH]_8$ obtained from the naturally-occurring rock Serpentinite, fills the spaces between coolant tubes penetrating both the Upper and Lower Biological Shields in the form of course sand, pebbles, and small rocks. Serpentine's most significant and unique feature is that most of the water of crystallization is retained up to high temperatures on the order of 450 to 500°C. As a consequence, serpentine can be used in shielding applications where high temperatures may be involved. Nominally, approximately 617 tonnes of Serpentine is found in the Lower Biological Shield and its peripheral thermal compensator section.

concrete by industrial fiberglass insulation 30 cm wide) has been pressed into the concrete by a shock wave similar to that encountered during an industrial metal-stamping process – possibly the result of a hydrogen explosion. However, the light-green silicon-based paint covering the steel wall and rated to 1000°C remains seemingly unscathed. Group dispensing headers of the southern "strong box" (Room 404/3) for the lower water communication piping on the surface appear undamaged. However, in contrast to LCCs emerging into Room 305/2 from Room 404/4, the southern piping is pulled severely toward the direction of Room 305/2 and slanted 15°–20° from their nominal vertical orientation. As in Room 404/4 the covering above Rooms 617/4 and 617/3 (Room 706/3 & 706/4 containing the Group Dispensing Header control system "Tiber") has collapsed on top of the headers.

The lower part of the wall of Room 304/3 (between Axes 46 and 47) was separated (sheared) from the floor apparently as a result of the rapid redistribution (impact of ≈1000 tonnes) of the molten corium as it melted through the Lower Biological Shield. This permitted the corium lava to flow into this room filling it to a height of approximately one meter, then further on into Corridor 301/5 between Axes 48 and 44 to a maximum height of 0.5 meter, and finally filling Corridor 301/6 between Axes G and L. (Measurements taken in 1986 indicated a 7,000 and 11,000 R/hr exposure rate at these Axes respectively.) Concrete that poured in from the east and the west along Corridor 301/5 did not completely cover the FCM and left a 1.5 meter-wide patch exposed between Axes 45 and 46. Corridor 301/6 is today covered with a concrete layer two meters thick. Either through the electrical cable chase-way on the floor of Corridor 301/6 or through some other cavity or shaft, lava flowed downwards into Room 217/2 in the region of Axis Zh and a little further south in the region of Axis G creating the highly radioactive "Elephant's Foot" (Figure V.15) and stalactite-type formations (Figure V.16) whose lower parts are now covered with a concrete layer about one meter thick. Apparently, lava also

Figure V.15[18]

Photograph of the two-tonne accumulation of melted nuclear fuel dubbed the "Elephant's Foot."



[18] Photograph courtesy of Alexandr Alexandrovich Borovoi of the Inter-Branch Scientific & Technical Center "Shelter" of the Ukrainian Academy of Sciences, Kyjiv and the Kurchatov Institute, Moscow.

Figure V.16[19]

Photograph of a nuclear fuel "stalactite" located near the southern end of Corridor 217/2.

[19] Photograph courtesy of Alexandr Alexandrovich Borovoi of the Inter-Branch Scientific & Technical Center "Shelter" of the Ukrainian Academy of Sciences, Kyjiv and the Kurchatov Institute, Moscow.

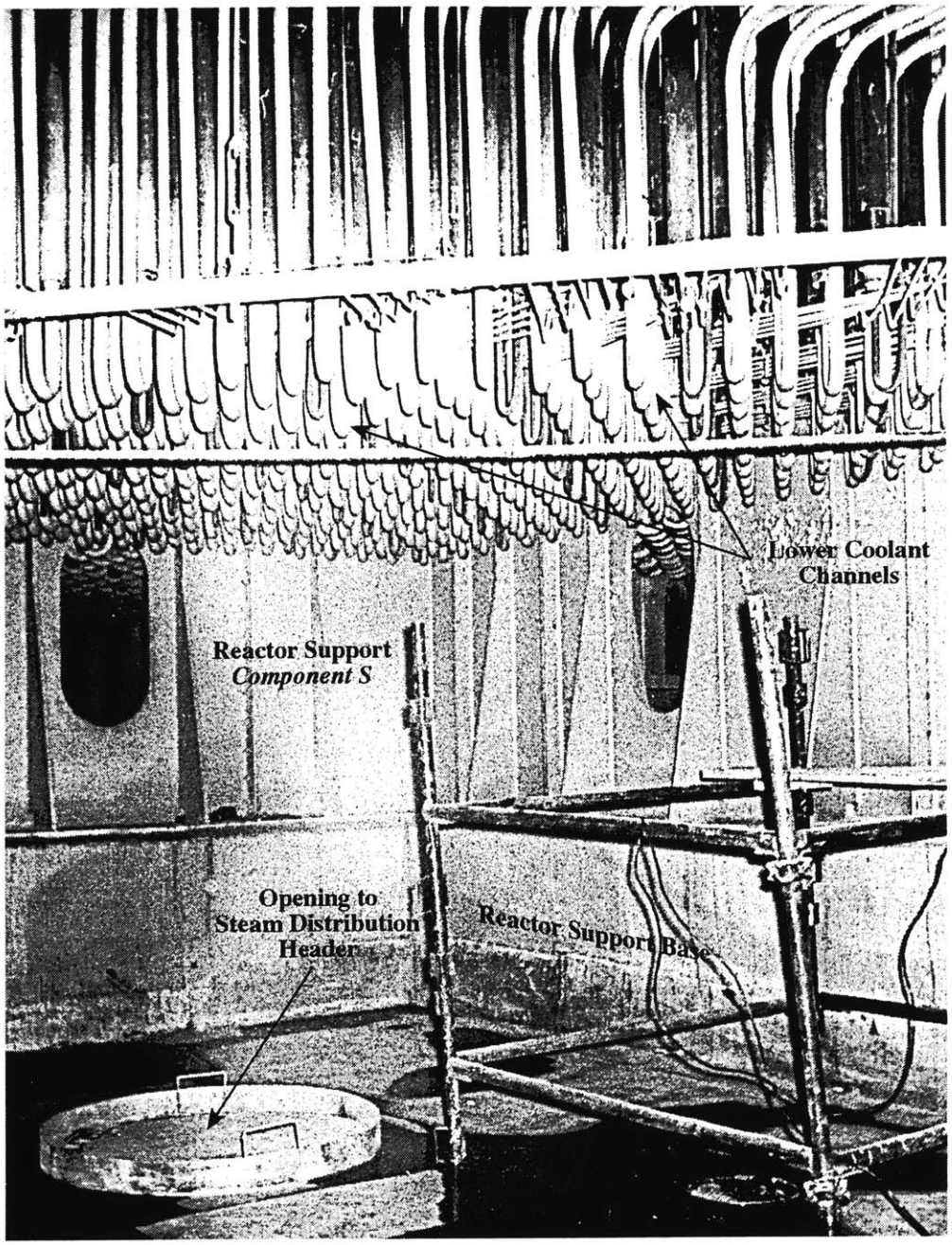
partially entered Room 303/3 either from room 305/2 or from Corridor 301/5. It has the same smoky appearance as LFCMs found in Rooms 304/3 and Corridor 301/5. The door of Room 303/3 flew off its hinges in an easterly direction, leaving an opening for concrete to flow in and cover the floor to a height from a few dozen centimeters at the southwestern corner to 1.6 meters at the entrance. Bore samples have shown that the southern labyrinth entrance into Room 305/2 from Room 301/8 contains no LFCMs.

The lower part of Room 305/2 and the southern strong box of the LCCs (Room 404/3) are filled with concrete to a much lesser extent. Concrete entered Room 404/3 through a doorway on the west at Level 17 m and Level 20 m from stairway 329/3 while it was being poured to strengthen the southwest column supports for the so-called "Mammoth" Block that supports the roof of *Shelter-I.* Concrete along the southern wall of Room 404/3 formed a 1.5 meter thick layer and further flowed into the southwestern part of Room 305/2 onto piles of graphite blocks, Zircaloy pressure tubes, and then downward along LCCs from Room 404/3 onto various metallic debris in the Sub-Reactor Region torn from *Component OR* and from the lower portions of Room 404/3. The concrete filled in the empty spaces of this pile of debris and covered it up to approximately Level 13 m at the southern wall. The southern labyrinth doorway from into the service corridor for Room 301/8 is completely filled with concrete – just as was the northern labyrinth doorway. It is impossible to see *Component OR* in the southwestern part of Sub-Reactor Region. At the same time, concrete flows entered Room 404/4 through a door on its west side from stairway 329/4 at Levels 17m and 20m. Also, concrete from upper doors at an abrupt forty-five degree angle entered in 404/4 and then entered Room 305/2. In the northwest corner of Room 305/2 the level of concrete almost reaches to Level 15 m. The doorway of the "labyrinth" leading from the Sub-Reactor Region into the service corridor for Room 301/8 is completely filled with "fresh" concrete.

After the initial explosions destroyed the reactor and the hot fuel had melted through *Component OR,* part of the molten fuel flowed from the Sub-Reactor Region downward

Figure V.17[20]

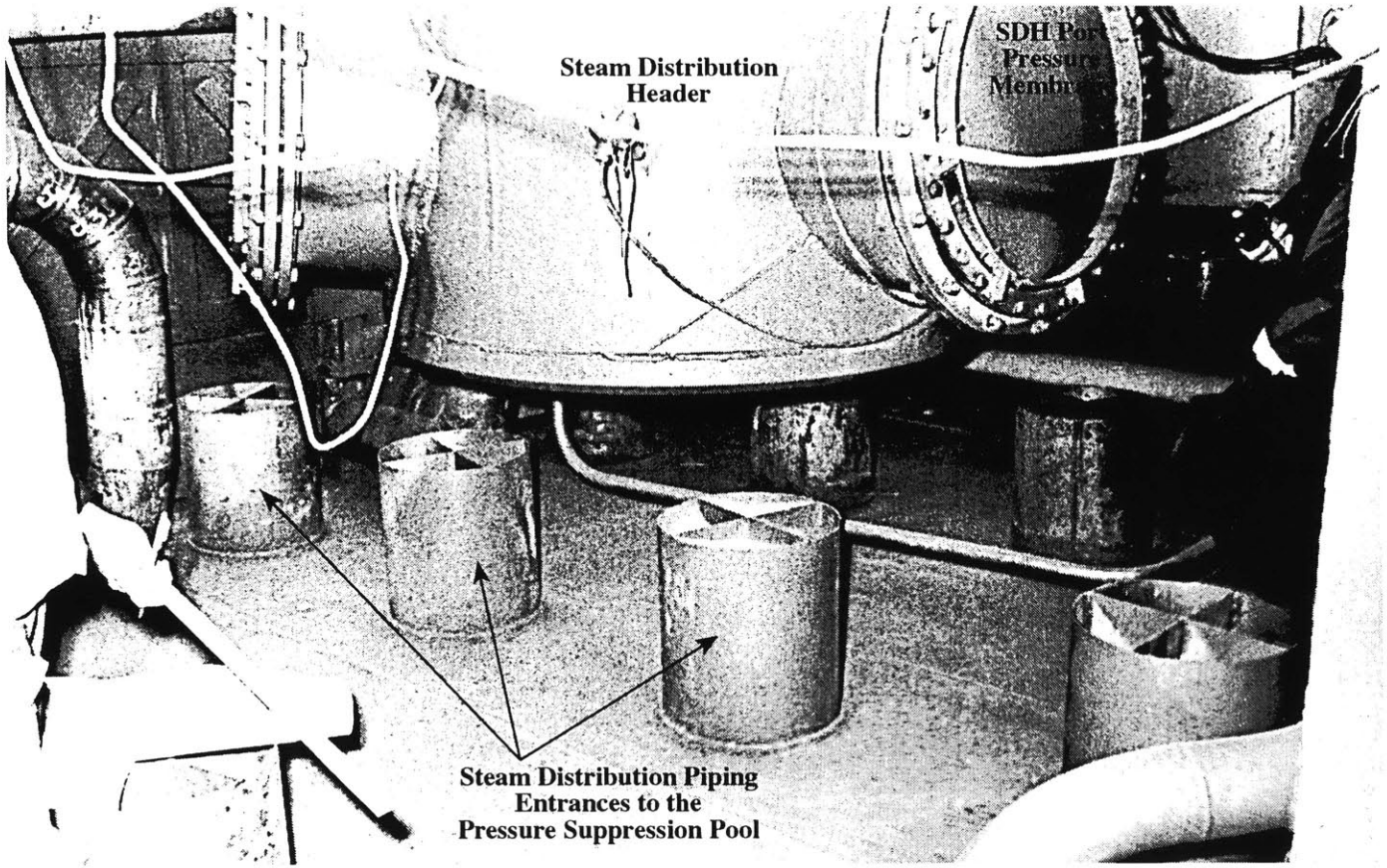
Photograph of one quadrant of a nominal Sub-Reactor Region (corresponding to Room 305/2) of a 2nd-generation RBMK-1000 (Chornobyl Unit-3). Clearly visible is the ribbed reactor support structure, *Component S*, and the one meter-tall reinforced concrete cross upon which it stands. At the top of the photograph are seen the Lower Coolant channels just below the Lower Biological Shield (*Component OR*) through which they enter the core. On the floor is seen one of the eleven one meter-diameter pressure membrane-covered ports to the Steam Distribution Headers located on the floor below.



[20] Photograph courtesy of Viktor Danilovich Popov of the Inter-Branch Scientific & Technical Association "Shelter."

Figure IV.18[21]

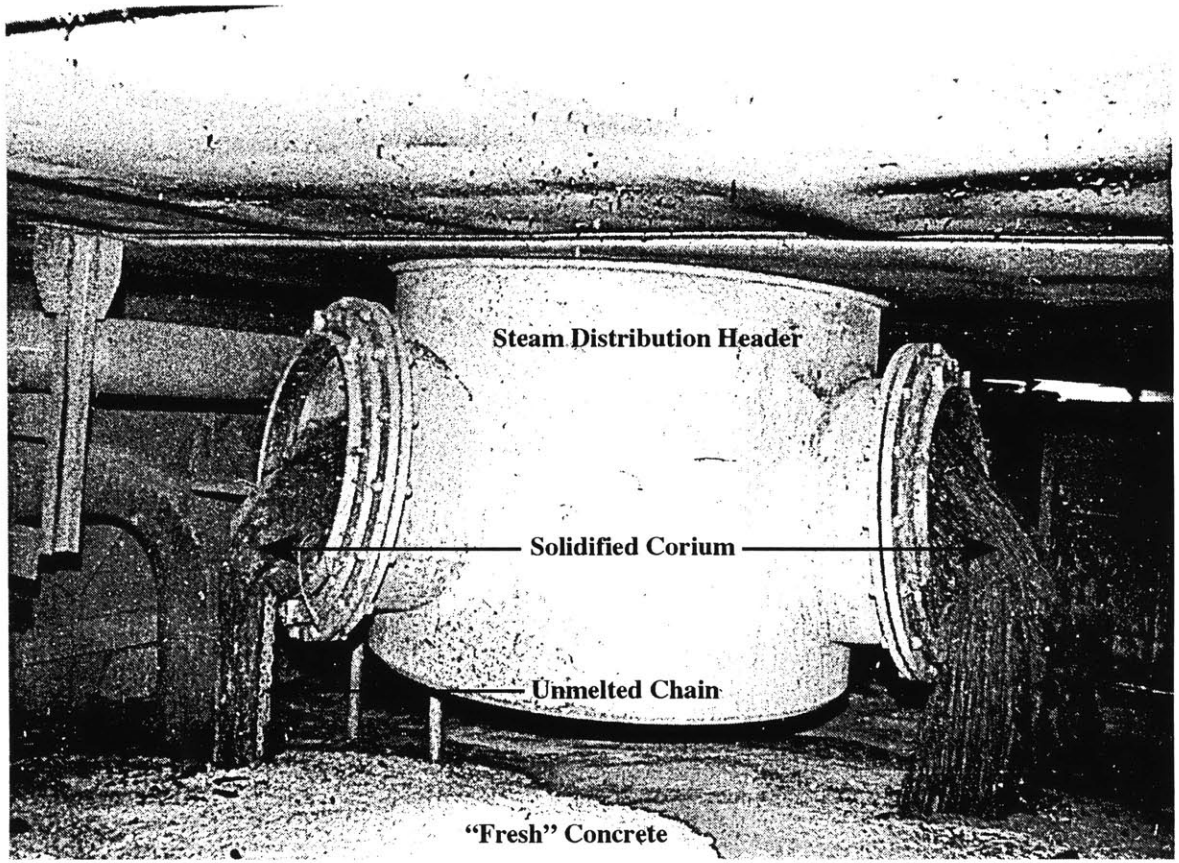
Photograph of a typical Steam Distribution Header in a 2nd-generation RBMK-1000 (Chornobyl Unit-3) attached to the ceiling of the Steam Distribution Corridor with the three opening ports nominally covered with pressure membranes. Seen jutting up out of the floor approximately 40–45 centimeters are several openings to the telescoping Steam Distribution Pipes that lead downward into the two floors of the Pressure Suppression Pool. Note the two researchers partially visible on either side of the photograph.



[21] Photograph courtesy of Viktor Danilovich Popov of the Inter-Branch Scientific & Technical Association "Shelter."

Figure IV.19[22]

Photograph of a Steam Distribution Header (SDH) showing nuclear fuel "frozen" in mid-flow. Note that this header seems not to have suffered any external damage, and that an unmelted chain hangs from the lip of the left port of the SDH.



22 Photograph courtesy of Alexandr Alexandrovich Borovoi of the Inter-Branch Scientific & Technical Center "Shelter" of the Ukrainian Academy of Sciences, Kyjiv and the Kurchatov Institute, Moscow.

Figure IV.20[23]

Photograph of a Steam Distribution Header (SDH) showing nuclear fuel "frozen" in mid-flow. Note that this header seems not to have suffered any external damage, and that an unmelted (but crushed) service ladder from the inside the SDH has been displaced and remains in the mouth of one of the SDH ports.

[23] Photograph courtesy of Konstantine Pavlovich Checherov of the Inter-Branch Scientific & Technical Center "Shelter" of the Ukrainian Academy of Sciences, Kyjiv and the Kurchatov Institute, Moscow.

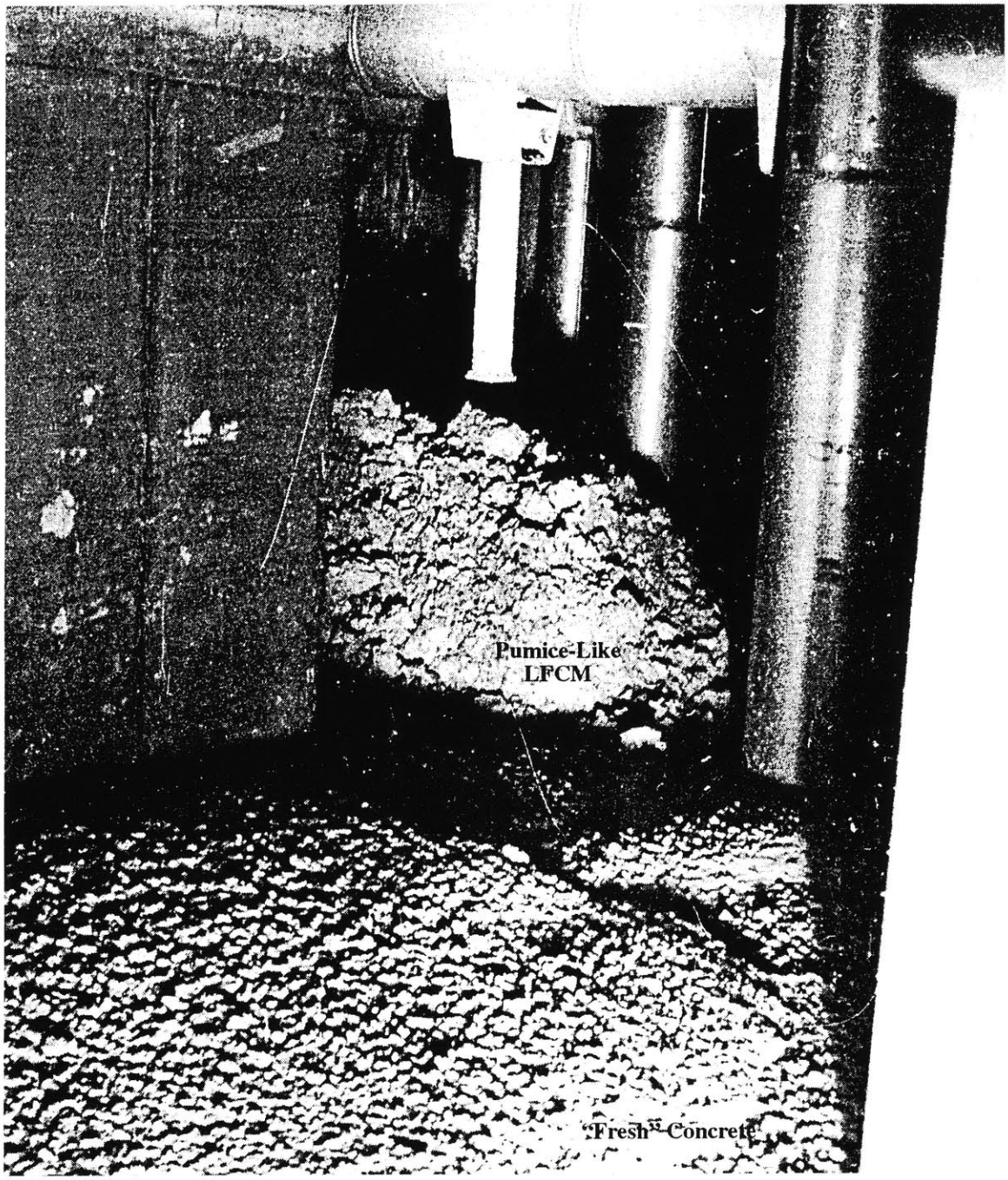
through three emergency steam distribution headers into the Steam Distribution Corridor (Figures V.17 – V.20). In Room 210/7 of the Steam Distribution Corridor a now reddish-brown form of the LFCMs flowed out of the southern header to form a pool about ten meters in length. Where the thickness of the lava of this flow reached 0.4 m, it was able to rise above (and probably melt) the "lips" of the steam distribution tubes (extending vertically above the floor at about 0.40 – 0.45 m) and flow down into the second and first floors of the Pressure Suppression Pool. On the first floor of the Pressure Suppression Pool it interacted with what little water remained† to form highly radioactive pumice-like LFCMs (Figure V.21). During the autumn of 1986 when *Shelter-I* was being constructed, concrete flowed through three other steam distribution headers in Room 210/7 (through which lava had not flowed) and covered most of the lava in the Steam Distribution Corridor. The concrete continued to flow downward unobstructed steam distribution pipes into the Pressure Suppression Pool eventually forming thick layers covering most of the lava.

In Room 210/6 lava flows analogous to those in Room 210/7 are observed. Through the two southern steam distribution headers located there, a now gray-black form of the LFCM flowed out of the Sub-Reactor Region forming two lava "streams" 0.1 meter and 0.3 meter thickness. Investigation of the steam distribution pipes in Room 012/7 of the Pressure Suppression Pool (directly below the lava flows in Room 210/6) has shown that these pipes are at least partially filled with LFCMs that solidified before they had a chance to drop into Room 012/7. It is assumed, then, that the lava flow must have reached a height of at least 0.3 – 0.4 meter in Room 210/6 to overcome the pipe protruding up from the floor. Concrete which flowed into Room 012/7 and covered the solidified lava located there is to this day warm – indicating, of course, the presence of LFCMs beneath. Particular to Rooms 210/7 & 210/6 is a layer of previously molten metal (underneath the LFCMs located there) varying in thickness from 0.05 to 0.15 meter. Room 210/5 does not

† The 1st floor of the Pressure Suppression Pool could not immediately be completely drained because the drain ports are located at several locations on walls about 10–20 cm above the floor.

Figure V.21[24]

Photograph taken on the 2nd floor of the Pressure Suppression Pool showing a pumice-like formation of nuclear fuel. Concrete poured into the reactor building during construction of the Sarcophagus is visible in the foreground.



[24] Photograph courtesy of Konstantine Pavlovich Checherov of the Inter-Branch Scientific & Technical Center "Shelter" of the Ukrainian Academy of Sciences, Kyjiv and the Kurchatov Institute, Moscow.

contain any silicate-like LFCMs, but a highly radioactive 0.02 meter thick solidified "pool" of reddish-brown metal approximately six meters in diameter is found under the steam distribution header between Axes K and L. Near Axis L the molten metal was able to somehow flow downward into Room 012/13 of the Pressure Suppression Pool – melting a steel steam distribution pipe along the way. Measurements taken of this melted pipe indicate an exposure rate of approximately 1200 R/hr – similar to surface exposure rates of LFCMs in the Steam Distribution Corridor and the south-eastern section of the Sub-Reactor Region (Room 305/2).

Investigation and inspection of the Central Hall – where the average exposure rate was approximately 300 R/hr – took place during 1989–90. By the end of May 1986, more than sixteen thousand tonnes of various materials (over five thousand tonnes during the Active Phase to smother the burning graphite) were dropped into the Central Hall by helicopter forming a large "pile" ranging from one to fifteen meters in thickness. (Other, more or less discernible piles of about two meters in height are located around the larger pile and in what is left of Room 804/3, which contain the southern steam-drum separators.) The pile is located beginning from the area of Room 804/3 about the Axes 44 & 45 and extending northeast partially covering the northern and southern spent fuel pools. (See Chapter IV). The northern area in general contains a great deal of graphite blocks, destroyed structural members of the central hall, fuel assemblies, etc. Apart from the high radiation fields encountered there, the rubble is very difficult to traverse even for humans, let alone robots. The walls of Rooms 804/4 & 804/3 facing the Central Hall were partially destroyed by the explosive shock wave at the moment of the accident. The UCCs are torn from the steam drums and hang in a tangled web of piping from both sides of *Component E*. The 450 tonne refueling machine, upset from its standard position by *Component E* when it was blown off the core, now lies partially covering *Component E* over the south-western sector of the reactor. The southern spent fuel pool's opening (at the 35.5 m Level of the Central Hall floor) is, as noted above, partially covered with debris. Inspection of

the lower regions of the pool indicates that the spent fuel there is practically undisturbed, but that there is no water present in the pool. Exposure rates in the lower regions approach 5000 R/hr.

V.3. The State of Nuclear Fuel Located Within *Shelter*

V.3.1. Overview and Material Balance**

V.3.1.1. Summary

By current estimates, between 1270 and 1350 tonnes of Fuel-Containing Materials (≈10.5% of which is fuel), 64,000 m^3 of other radioactive material (concrete, building metal, etc.), approximately 10,000 tonnes of construction metal, and 800–1000 tonnes of contaminated water are located within Shelter.[25,26] Research conducted during 1987-92 shows that the Fuel-Containing Materials (FCMs, or material containing partially "burned" nuclear fuel) within *Shelter* may be classified as follows:

(1) *Fragments or chunks of destroyed core.* These include parts of destroyed technological channels, fuel rods, control rods, graphite, etc. damaged and thrown out of the core area as a result of the explosions. The greater portion of these are currently located in the upper floors of the reactor building – in particular in the Central Hall into which approximately fifteen

---

** In an almost comical manner, the Soviet leaders wanted so much to believe that most of the contamination and core was contained within the sarcophagus that the stage was naturally set for the creation of a myth that would remain unquestioned for several years. For example, Academician Spartak Timofeëvich Belayev (of the Kurchatov Institute and Chairman of the Inter-Branch Coordinating Council Regarding Chornobyl Scientific Problems in the Presidium of the USSR Academy of Sciences), as late as 1990 in a *Pravda* article states quite categorically that greater than 185 tonnes (>97%) of nuclear fuel are contained within the sarcophagus [as reprinted in В. С. Губарев, И. Камиока, И. К. Лаговский, и др., Сост. Г. Малкин, Что делают люди в «Саркофаге,» *Ядерный След*, Энергоатомиздат, (1990): 49.]. Yet in September 1991 he "corrects" himself by stating that in the haste to construct the sarcophagus in an extreme radiation environment, there was no way to estimate how much fuel there was and where it was located. (Bill Thomson, "International Effort Needed on Sarcophagus," *Nuclear Engineering International*, (September 1991): 17.

[25] *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие,»* Чернобыль, Украина; Минск, Беларусь: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, Институт радиоэкологических проблем при АН Беларусь, (1992): 50–59.

[26] Панитков, Ю. С., И. А. Банель, А. М. Бер-надская, В. П. Бескоровайный, Н. В. Горбачева, Н. М. Груша, В. В. Котович, Л. Н. Козловская, В. Г. Молодых, Н. К. Мышкина, Н. В. Нитей, В. В. Ничипор, Т. А. Павлина, В. В. Скурат, Л. А. Станкевич, Э. М. Тащилова, *Отчёт о научно-исследовательской работе: Восстановление динамики разрушения 4-го блока ЧАЭС на основе физического и математического моделирования: Разработка физической модели чернобыльской катастрофы*, Минск, Беларусь: Академия Наук Беларуси, (1991): 108–114.

tonnes were thrown from the roof of the adjacent Auxiliary Building "V" where they were scattered by the explosions. Some pieces of the core (fuel and graphite) were found up to 150 meters from the reactor building and are now either covered with a thick layer of concrete or were collected and deposited into the reactor building's debris. On the scale of millimeters to centimeters they remain more or less intact.

(2) *Finely dispersed fuel particles (dust) or "hot" particles.* To a greater or lesser extent these particles were distributed over the entire Unit-4 area and beyond the bounds of the station as a result of the explosions and fires that carried them into the atmosphere. They are observed in virtually every area or room of the reactor building – found on open surfaces, imbedded in concrete and other materials, or as dust particles in the air. Dimensions of these particles vary in the range of 0.1 to 100 microns, and their total mass is estimated to be on the order of 10 tonnes.

(3) *Solidified Lava-like Fuel-Containing Materials (LFCM) or Metallic Fuel-Containing Materials (MFCM).* These formed during the Active Phase of the accident (April 26 through May 6) as a result of a portion of the core melting (from the great amounts of heat liberated by chemical reactions and fuel decay heat) and flowing downward through various pipes and ducts into the lower regions of the reactor building, and the interaction of this "lava" with surrounding metal and concrete structures. The LFCMs are characterized as glass-like or pumice-like siliceous substances containing varying amounts of fuel and other materials of the reactor including metallic alloys. The MFCMs are in the form of a one-to-several centimeter layer of solidified and highly-radioactive metallic (composed of fission product metals and structural steel) layer underneath the LFCMs located (mainly) in the Steam Distribution Corridor.

(4) *Contaminated Water.* In 1990 it was observed that water located in a number of rooms on several floors under the former reactor (in particular in the Pressure Suppression Pool) contained various quantities of dissolved uranium. Water enters *Shelter* through the above mentioned openings and flows into the lower regions where most of the fuel is located. There, both as a result of a slow weakening and break-up of surface layers of LFCMs from high radiation exposure and the subsequent washing away of this

newly formed dust by water, the water becomes enriched in uranium. The concentration of uranium is low, varying in the range of several milligrams/liter, yielding an estimated quantity of fuel in water of less than two kilograms.

V.3.1.2. Dust and Hot Particles

These particles, besides small, are characterized by their high densities and high beta activities. The average fuel material (UO_2) content of these particles is in the range of a few percent; and for the most part, they determine the atmospheric activity within *Shelter*. A scanning electron microscope was used to ascertain the sizes of particles, particle sedimentation techniques in high-density liquids were used to determine their densities, a 4π-scintillation detector determined isotopic activities.

As a result of research carried out at the Kurchatov Institute of Atomic Energy in Moscow, the particles contained within *Shelter* were classified into two broad categories. The first category defines larger particles (tens of microns in diameter) containing whole kernels of UO_2 fuel originating at or near the surface of fuel pellets destroyed at the moment of the accident. Externally they are of a very dark grey or black color and have a broken or pitted surface texture. Within the fuel matrix are encountered smaller fragments with a yellow-green or brown coloration – however, their overall quantity in these particles is small. A metallic sheen or brown tinge, as a rule, is found on those particles whose activity at the moment of measurement is predominated either by Ru-106 or Ru-106 plus Nb-95. The average density (bulk material) of these particles is 10.0 ± 0.8 gm/cm^3, which corresponds well with the theoretical density of 10.96 gm/cm^3, for UO_2. Stochiometric analysis of the particles yields an almost equal proportion of UO_2 and $UO_{2.3-2.4}$.[27] An interesting phenomenon is observed with the passage of time for these larger particles: they are slowly crumbling – becoming smaller and more easily transportable in air, and as

[27] Ibid., 31.

such posing a serious inhalation health threat to those who enter the sarcophagus.[28] Table V.1 below presents the results of activity measurements conducted on 500 particles in November and December 1988 (thirty-one months after the accident) and a comparison with calculated values, i.e. what one would expect in fuel if there had been no release.

Table V.1[29]
Fuel Particle Activities

Isotope	Average Measured Activity at t = 31 months [Bq/gm U]	Calculated Activity at t = 31 months [Bq/gm U]	Ratio of Measured to Calculated
Niobium–95	4.8e+06	2.16e+06	2.22
Ruthenium–106	1.0e+09	7.78e+08	1.29
Cesium–134	2.3e+08	3.73e+08	0.62
Cesium–137	9.2e+08	1.36e+09	0.68
Cerium–144	2.5e+09	2.00e+09	1.25
Strontium–90	8.8e+08	1.13e+09	0.78
Plutonium–(239+240)	1.5e+07	1.29e+07	1.16
Plutonium–238	6.9e+06	7.57e+06	0.91
Americium–241	5.0e+06	4.47e+06	1.12
Curium–244	1.5e+06	2.00e+06	0.75

The second category of hot particles consists of smaller grains (dust or aerosols a few microns in diameter) that were formed during the Active Phase of the accident when the fuel was oxidizing and interacting with surrounding materials, or are currently being formed with the breakup of the first (larger) category of particles described above. It was shown that the properties of the aerosols were identical to those that settled on free surfaces in the upper portions of the reactor building and *Shelter*. Research conducted in

---

[28] It is not only these particles that pose an inhalation health threat. The bulk Lava-Like Fuel-Containing Materials (LFCMs) are also slowly disintegrating at the surface. These particles are then available for transport either by air currents or migration by water wash-out. See also Богатов, С. А., et al., "Оценка скорости эрозии...."

[29] *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие,»* (1992): 32.

October–November 1988 showed that size variation and activity are satisfactorily described by log normal law with a median of five microns and 30 Bq/μm^3. The isotopic content of the aerosols agrees satisfactorily with that anticipated for "average" fuel corrected for decay. The average burnup of the fuel in these particles is 11.5 MWd/kg U. However, fuel of low burnup is also found in these particles corresponding to fresh fuel assemblies inserted shortly before the accident.[30]

V.3.1.3. Contaminated Water

The extent to which fission-products are being washed-out of the LFCMs by water entering through openings in *Shelter* (the total area open to the environment is estimated to be approximately 1200 m^2) may be estimated by studying water accumulations in various locations within Shelter-I. Unfortunately, research has only just recently begun (1991); and for now only approximate and incomplete results can be discussed. Investigations of rooms and areas on the first level of the Pressure Suppression Pool (012/6, 012/7, 012/8, 012/13, 012/14, 012/15, 012/16, 014/2, 017/2) indicates the total volume of water in these rooms to be approximately 600 m^3. The total activity of these waters exceed 200 Ci of which Cs-137 accounts for more than 90%, Sr-90 for approximately 10%, and Plutonium for less than one milliCurie. It also contains about 700 grams of uranium as various dissolved compounds – although there are no criticality concerns.[31]

---

[30] Ibid., 33. Aerosol releases from the sarcophagus and the environment within it are constantly being monitored. The following sources contain more detailed information on these aerosols and on possible accident scenarios that could emit significant quantities to the immediate area of the station: *Подготовка и совершенствование ТОРБ объекта «Укрытие» на основе оцененных баз данных по объекту и его влиянию на окружающую среду*, Чернобыль, Украина: Академия Наук Украины – Межотраслевой научно-технический центр «Укрытие», (23.XII.1993).

[31] For a more extensive treatment see, Ibid., 61–71.

V.3.1.4. Quantities and Locations of LFCMs*

During the period from the middle of 1987 through the beginning of 1990, the method used most often to determine the location and quantity of FCMs within the sarcophagus was remote thermographic analysis (thermography). This technique permitted a thermal survey of areas with extremely high levels of radiation (> 2000 R/hr – that were also heavily damaged or covered with concrete making access dangerous and nearly impossible for researchers) such as Room 305/2 directly under *Component OR* and the Sub-Reactor Region; and it led to the discovery in these areas of substantial quantities of the LFCMs. Secondly, after determining the location of LFCM accumulations, researchers were able to estimate the quantity of material by assuming the source's heat flux (coming through debris and concrete) was directly related to the mass of material found underneath or behind the rubble. This was confirmed by measuring the speed of convective currents of air induced by heat fluxes in areas where the geometry of the surroundings could be well established. Therefore, on the basis of peripheral measurements of heat flux in relatively low areas of radiation and relatively accessible areas of the reactor building, researchers succeeded in estimating quantities of highly radioactive materials buried within the sarcophagus.

In 1989 with the help of heat flux gauges mounted on long wands, a survey form the ceiling of the second floor of the Pressure Suppression Pool (to determine the heat flux from sources above) was conducted. Over one hundred measurements were taken that permitted not only the examination of this area, but also of a number of areas with moderately high but accessible radiation fields between the Steam Distribution Corridor and the Sub-Reactor Region. Calculations showed that in January 1990 the total LFCM heat being generated in the Steam Distribution Corridor was approximately 17 kWt. Knowing fairly well the amount of decay heat generated per tonne UO_2 corrected to that time, it

* Because of the lack of proper equipment for the extreme working conditions encountered within the sarcophagus, and the lack of substantial financial support for researchers at Chornobyl, what investigations have been carried out are more surveys than rigorous analyses. The summary here should then be viewed with a certain amount of caution – there is still a great deal of uncertainty in the figures presented below.

was estimated that this area contains 23 ± 8 tonnes of UO_2. Similarly, in July 1989 the heat being generated in Room 305/2, the Sub-Reactor Region, was approximately 60 kWt (by far the strongest source found) yielding 75 ± 25 tonnes of UO_2. In this area, even though it is virtually inaccessible, a convection geometry could be quite well established because heated air currents were constrained to exit through the reactor shaft upward into the Central Hall – thus aiding in the estimation of fuel mass. The balance of the fuel on the fourth floor is located in two corridors (301/5 and 301/6) and one room (304/3); while the total amount of fuel on this level is 95.7 ± 26 tonnes.

Since the Pressure Suppression Pool was more accessible than other areas, dimensional estimates from photographs, dose rate measurements, and analysis of samples of LFCMs found there in open "piles" (to determine their radiochemical compositions and densities) aided researches in estimating volumes, fuel content, and thus heat generation more precisely than in other areas. LFCMs were also known to be located in the pipes designed to direct steam downward to lower levels of the Pressure Suppression Pool. Although the geometry of these pipes is well know, it was not certain how and to what extent LFCMs were distributed within them. A remote-controlled collimated gamma detector was used to identify which pipes contained LFCMs along with their approximate distributions. The gamma detector also helped to define the gamma fields throughout the Pressure Suppression Pool so that dose measurements could be attributed to specific piles of LFCMs. As a result of these efforts, five pipes were identified to be the "flow paths" into LFCM piles and into Rooms 012/6 and 012/14. It was also found they were completely filled with LFCM with a total volume of $5.7m^3$. Assuming the pipes contain UO_2 in amounts similar to their associated piles, a good estimation could be made. Finally, thermography had to be used to locate and estimate the amount of fuel covered by concrete. The amount of fuel in the LFCMs of the Pressure Suppression Pool is estimated to be 12.5 ± 3 tonnes distributed as shown in Table V.2.

Table V.2[32,33]

Chornobyl Unit-4 Fuel Distribution and Mass Balance

Location and Description	Fuel Mass (te) Subtotal	Fuel Mass (te) Total
Upper Levels of the Reactor Building (Level ≥ 35.5 m)		**37.7 ± 5 + ?**
Central Hall (Estimate of Core Fragments)	15	
Central Hall (Hot particles and dust)	5 ± 2	
Central Hall (Under Pile of Materials Thrown from Helicopters)	?	
Core Fragments Attached to Upper Biological Shield	5 ± 3	
Steam Separator Drum Areas	2 ± 1	
Other Areas Above Reactor	5	
Fragments Within the Cascade Wall of the Sarcophagus	1.9	
Turbo-Generator Hall (Estimate of Core Fragments)	1.9	
Fuel Fragments Beyond Reactor Building but Under Concrete	1.9	
4th Floor – Sub-Reactor Region (Level 9.0 m)		**95.7 ± 26**
Core Fragments Scattered Upon the Lower Biological Shield	0.5 ± 0.2	
Sub-Reactor Region (Room 305/2)	75 ± 25	
Room 304/3	14 ± 5	
Room 303/3	0.2 ± 0.1	
Corridor 301/5	3 ± 1	
Corridor 301/6	3 ± 1	
3rd Floor – Steam Distribution Corridor (Level 6.0 m)		**27 ± 8**
Steam Distribution Headers (3 units)	1.8 ± 0.6	
Steam Distribution Corridor (Rooms 210/5, 210/6, 210/7)	23 ± 8	
Corridor 217/2 (Stalactites)	0.2 ± 0.1	
Corridor 217/2 ("Elephant's Foot")	2 ± 0.8	
1st & 2nd Floors – Pressure Suppression (Levels 0.0 & 3.0 m)		**12.5 ± 3**
Pressure Suppression Pool – **(2nd Floor)**	**(11 ± 3)**	
Open "Piles"	6 ± 1	
"Piles" Covered by Concrete or in Piping	5 ± 3	
Pressure Suppression Pool – **(1st Floor)**	**(1.5 ± 0.5)**	
Open "Piles"	0.9 ± 0.2	
"Piles" Covered by Concrete or in Piping	0.6 ± 0.5	
Total Fuel Contained Within Reactor Building		**172.9 ± 28 (?)**
Fuel Released Beyond the Chornobyl Station (3.5 ± 0.5%)		**6.7 ± 1**
Total Core Load at Time of Accident		**190.3**
Fuel Unaccounted For		**> 10.7 (?)**

---

[32] Шароваров, Г. А., et al, Характеристика объекта «Укрытие», его физическая и математическая модель, Отчёт о научно-исследовательской работе: *Обоснование ядерной безопасности объекта «Укрытие» на основе исследования динамики аварийных процессов*, Инв. 1448, Минск, Белорусь: Институт ядерной энергетики, 28.II.1990): 37-42.

[33] *Техническое Обоснование Ядерной Безопасности Объекта "Укрытие,"* Под редакцей группы в составе: С. Т. Беляев, А. А. Боровой, Ж. Г. Волков, А. Ю. Гагаринский, Н. Е. Кухаров, Г. А. Шароваров, В. Ф. Шикалов, Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, (1990): 22-25.

A number of smaller but no less significant quantities of LFCMs were located in various other areas. Three steam-distribution headers (Figures V.11, V.19, and V.20) in the Steam Distribution Corridor were found to contain a total of 1.8 ± 0.6 tonnes of fuel. Together with the fuel content of stalactite- and stalagmite-like LFCM formations (such as the well-known "Elephant's Foot" – Figure V.15 – that contains 2.0 ± 0.8 tonnes UO_2), the total amount of UO_2 located in these third floor areas is 20 ± 5 tonnes distributed as shown in Table V.2.

The amount of fuel distributed throughout the upper levels of the reactor building is much more difficult to establish, although attempts have been made. For example, the amount of fuel contained in hot particles impregnated in walls and other materials or that eventually settled out throughout the building was estimated roughly by taking swipe-samples in various locations of the reactor building (to determine the amount of fuel deposition per unit area) and multiplying by an estimate of the total amount of area available for deposition. Core fragments (graphite blocks and fuel assemblies) were counted from photographs taken before the cleanup efforts began. It is clear that because researchers were not able to enter the extremely hazardous environment of the destroyed reactor building to locate more precisely fragments of the core, these estimates introduce large errors into the mass balance.

The core mass balance presented in Table V.2 also presents another problem. If we assume that the Soviet value of 3.5 ± 0.5% of the core's 190.3 fuel load at the time of the accident (or 6.7 ± 1 tonnes) was released beyond the bounds of the station, this leaves approximately 11 tonnes of the core UO_2 fuel mass unaccounted for. However, because of the rather imprecise mass estimates in Table V.2, the "missing" fuel falls well within total estimate's error margin. Another possibility is that the fuel could be located under the pile of debris thrown from the helicopters during the first six days of the accident.† To date,

† The materials thrown from the helicopters was aimed at a "red, glowing mass" obscured by smoke and debris (i.e., it was never positively identified what could have been "burning" at that location – although it was assumed that part of the core graphite was responsible for the glow. Given the fact that the roof of Unit-4 was covered with a large amount of tar, an argument has been put forth that it wasn't gra-

researchers have not been able to verify what may be under the material pile in the Central Hall because the extreme radiation environment and building structural debris make this area very inaccessible for drilling equipment.[34] A final possibility is that part of the fuel may have been jammed upwards through the Upper Coolant Channels into the Upper Biological Shield by the initial explosions. Using a finely-collimated gamma spectrometer to survey of the Central Hall in 1990, researchers noted a large source in the center of the UBS – leading them to speculate that FCMs may be located within. However, if significant plate out occurred onto the surface of the USB during the Active Phase, this could also give rise to the observed source.

Several lower-bound estimates of the amount of fuel located in the lower regions of the reactor building have been made. (Recall that Table V.2 shows that 135.2 ± 27.4 tonnes of fuel are located below the nominal core position, i.e., in the lower regions of the reactor building.) A rather rough estimate of 90 tonnes is obtained by considering that 35% of the initial core inventory of Cs-137 (see Chapter VI for a core inventory estimate just prior to the accident) remains within the fuel in the lower regions of the sarcophagus.[35] Another rough estimate of 60 tonnes considers the amount of magnesium initially contained within the Lower Biological Shield (as part of the mineral Serpentine) that was taken up by the corium lava as it melted through the LBS.[36] Finally, a group of researchers attempted to estimated the amount of fuel in the lower regions of the reactor build-

---

phite that was seen burning (producing the "red glow") but rather a large quantity of tar (bitumen) that collapsed into the Central Hall together with the roof. However, considering the fact that the building's roof and highbay walls were swept outward with the explosion's pressure wave, this hypothesis appears less plausible.

[34] "From the existing balance we know that the full quantity of fuel which remains within Shelter accounts for 96.5% [~183.6 te ?] of the original load [of 190.3 te], in other words 180 t of heavy metal. Our appraisals of visible accumulations of FCM gives 150 t. The remaining 30 t could be found in the Central Hall (~ 15 t), under the northern Cascade Wall, in also in a number of as of yet uninvestigated areas of the upper parts of Unit-4." [*Техническое Обоснование Ядерной Безопасности...*, 25.]

[35] Андерсон, Е. Б., С. А. Богатов, А. А. Боровой, Б. Е. Бураков, А. С. Евстратенко, А. П. Криницын, Э. А. Пазухин, А. И. Сурин, *Лавообразные топливо-содержащие массы объекта «Укрытие»*, Киев, Украина: Межотраслевой научно-технический центр «Укрытие» и Институт кибернетики имени В. М. Глушкова при АН Украины, Препринт 93-17 (1993): 24–25.

[36] Ibid., 27. It was later found that the authors had underestimated the amount of Serpentine in the LBS because they had not considered its peripheral thermal expansion zone which contained substantial amounts of the mineral. This produced a new lower-bound estimate of approximately 100 tonnes. [Private communication with A. A. Borovoi.]

ing by using density measurements and visually estimating the volume of lava. However, their estimate of 22.8 – 32.7 tonnes[37] has been convincingly disputed by other researchers at Chornobyl who point to the wide range of LFCM densities (from 0.14 g/cm^3 for the pumice-like form of the corium to 2.8 g/cm^3 for ceramic glass-like forms) and the fact that "chunks" of graphite blocks and fuel assemblies are found in some accumulations of the lava; and to the imprecise volume estimates of lava accumulations located under "fresh" concrete.[38]

V.3.2. Classification and Analyses of the Lava-Like Fuel-Containing Materials

Part of the fuel, having melted from a combination of decay heat and chemical interactions with surrounding materials, formed peculiar lava-like flows that entered various areas of the reactor building beneath the core. Figure V.22 presents a flow schematic for the LFCMs located in the lower regions of the reactor building that includes the locations and mass transfer mechanisms thought to be responsible for the current configuration. These LFCMs were studied for their chemical, isotopic, and mineral content along with fraction of fuel contained and burnup. As solid, heterogeneous solutions in a silicate glass-like matrix, they may be classified into four distinct types:[39,40,41,42]

LFCM1 A chocolate-brown or anthracite-black ceramic (glass-like) having a density of 2.2 – 2.3 gm/cm^3 and represented by stalactite/stalagmite–like formations in corridor 217/2 (including the "Elephant's Foot") or by accumulations in the Steam Distribution Corridor and in the Sub-Reactor Region (Room 305/2).

---

[37] Киселёв, А. Н., А. Ю. Ненаглядов, А. И. Сурин, К. П. Чечеров, *Экспериментальные исследования лавообразных топливосодержащих масс (ТСМ) на 4-м блоке ЧАЭС (по результатам исследований 1986 – 1991 годах*, Припринт ИАЭ-5533/3, Москва, Россия: Институт атомной энергии им. И. В. Курчатова, (1992): 96.

[38] Андерсон, Е. Б., *Лавообразные топливо-содержащие массы...*, 24–26. See also Подготовка и совершенствование ТОРБ объекта «Укрытие» ..., 17–20.

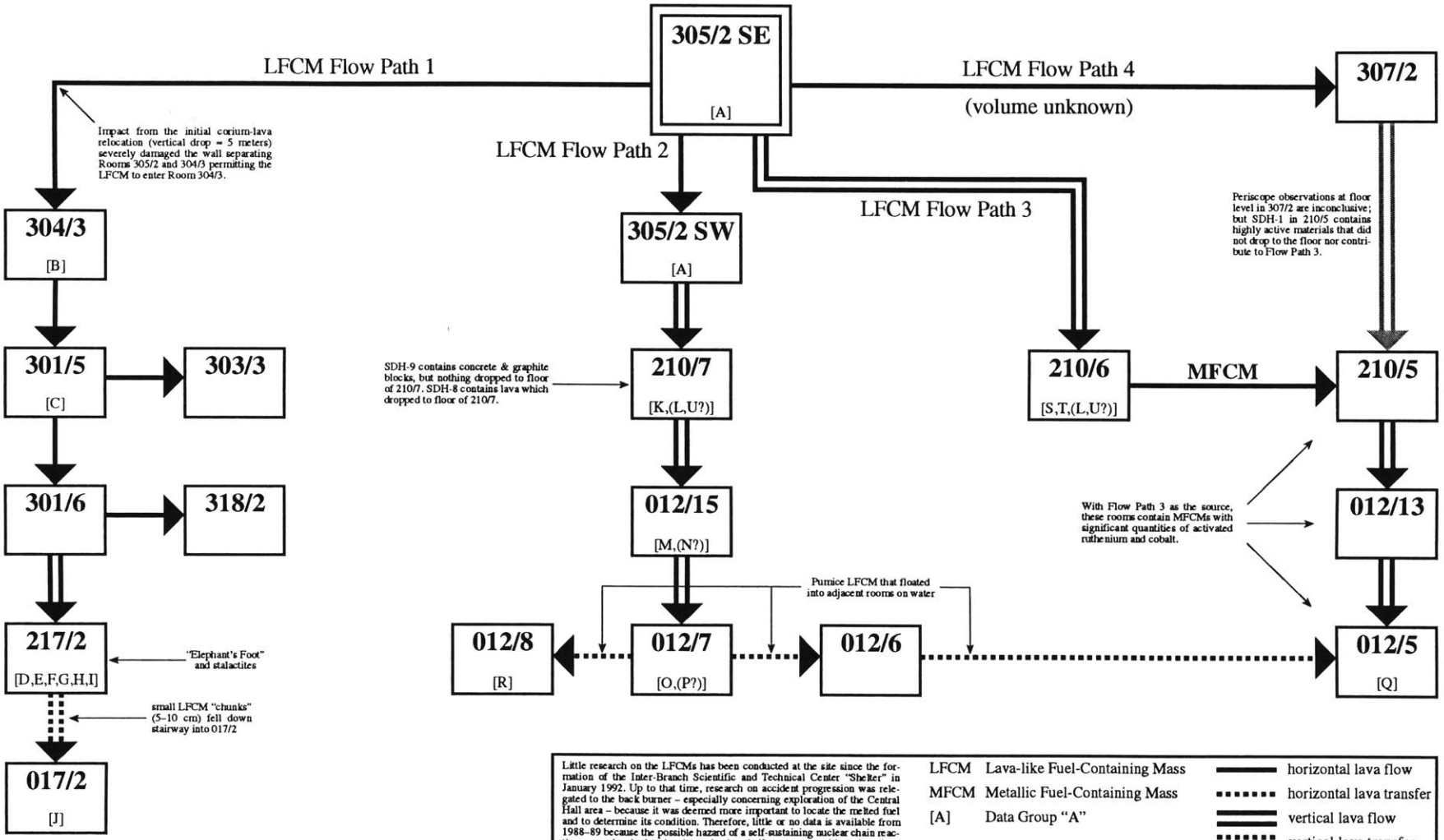
[39] *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие,»* (1992): 33.

[40] Borovoi, Alexandr Alexandrovich, "Post-Accident Management..., 51.

[41] МНТЦ «Укрытие». *Подготовка и экспертная оценка исходных материалов для новой редакции ТОРБ Объекта «Укрытие»*, 18.

[42] Богатов, С. А., А. А. Боровой, А. С. Евстратенко, А. П. Криницын, Э. А. Пазухин, А. И. Сурин. *Лавообразные топливо-содержащие массы объекта «Укрытие»*, 4–19.

Figure V.22
Lava-Like Fuel-Containing Material Flow Schematic



The optical refractive index is in the range of 1.45 to 1.6, and the melting temperature is approximately 1200° Celsius.

The *chocolate-brown ceramic* is brittle and at least at the surface contains many voids of varying diameter. It also contains large quantities of miniature metallic spheres which give it is characteristic color. The surface is mainly lustrous although some samples have a more matted shade of brown. It is found in all cases as an upper layer over a thin layer of previously-melted and highly-active metal – somewhat resembling a thick layer of impurities in high-temperature metallurgical smelting processes.

The *anthracite-black ceramic* in most cases has a matted hue with a great quantity of rather large voids averaging 1500 cm^3 in volume – making its bulk density low. This form of LFCM1 is most often observed near the southeast quadrant of the Sub-Reactor Region (Room 305/2) and in Room 304/3 and resembles coke from a steel smelting process. In a lesser number of cases that are located significantly far from Room 305/2 (in the form of stalactites and the "Elephant's Foot" in Corridor 217/2), the surface of this ceramic has a lustrous hue.

LFCM2 A gray-brown, crumbly, pumice-like material discovered in the Pressure Suppression Pools area of the of the reactor building almost directly below the nominal position of the core. It is assumed that this material was formed when the high-temperature lava contacted the remaining water in the Pressure Suppression Pool. Interestingly, adhering to the walls and pipes of the 1st floor of the PSP about 30–40 centimeters above the floor are several "bathtub ring" formations of this type of the LFCM. It is presumed that because of its low density (varying tightly around 0.14 gm/cm^3) it was at one time floating upon the surface of the water and was thus transported away from the main pile in Room 012/7.*

* The reason why water remained on the 1st level of the PSP (even though the PSP was emptied before the end of the Active Phase) was that the openings to the drain pipes are located on the walls about thirty centimeters above the floor. The pool, therefore, could not be completely drained.

LFCM3 A red-brown or flat-black slag-like material (an intermediate formation between a ceramic and a pumice) some of which is found in the Sub-Reactor Region but mainly in the Pressure Suppression Pool where its has formed "piles" of corium characteristic of that area of the reactor building.

LFCM4 Melted metals discovered in two forms: (1) as a lower-layer beneath the chocolate-brown LFCM1 in the Sub-Reactor Region, and (2) in the form of small (from one micron to several millimeter) droplets distributed in all other LFCM forms. Strictly speaking, the first form is not considered a LFCM because it does not seem to contain a significant amounts of fuel, but does contain enough fission products to make it highly radioactive.

According to Table V.2, the total amount of fuel contained within the LFCMs currently located below Component OR is approximately 135 ± 30 tonnes. The corresponding mass of the LFCMs is 1370 ± 300 tonnes.[43] On the macroscopic or bulk level, the LFCMs are quite varied in their morphologies and densities – the density of a given LFCM being a strong function of the void content within the solid solution. The density of the solid solution also varies greatly depending on the type of LFCM and its location with the reactor building. For example, the matte-black LFCM1 found in Room 304/3 (reaching a thickness of one meter) varies even throughout the bulk of the material – forming three layers based on density and void content (Table V.3).

[43] Additionally, 137 ± 30 tonnes are attributed to core structural materials (stainless steel and zirconium), 266 ± 60 tonnes are serpentine from *Component OR* including the Thermal Compensator Region, and 350± 50 tonnes is concrete from the floor of Room 305/2 which interacted with the lava just before it cooled. The balance (442 ± 130 tonnes) is attributed to materials dumped during accident mitigation efforts (including the construction of the sarcophagus). This does not make sense, however, given that little if any of the materials thrown onto the core during the Active Phase made it into the core; and that during the construction of Shelter, it is difficult to imagine any interaction of the solidified corium with concrete and construction materials. These figures must be viewed with caution. [Панитков, Ю. С., et al, *Восстановление динамики разрушения*...108.]

Table V.3[44]
Density-Variation of LFCMs in Several Locations

LFCM Type	Location	Room	Density (gm/cm^3)
black ceramic – upper layer	4th Floor	304/3	0.7 – 0.9
black ceramic – middle layer	4th Floor	304/3	0.9 – 1.8
black ceramic – lower layer	4th Floor	304/3	1.8 – 2.4
brown ceramic	SDC	210/7	up to 3.15
black ceramic	SDC	210/7	1.6 – 2.8
black ceramic	SDC	210/6	up to 2.9
black ceramic	SDC	210/6	2.0 ± 0.2
black ceramic	PSP-2	012/15	2.1 ± 0.2
pumice	PSP-1	012/7	0.14 – 0.18

The chemical compositions of the LFCMs also varied substantially depending on their type and locations. There were also variations within the matrix as well as in the dissolved constituents. For example, visual examination through a light-microscope has shown that the matrix of the chocolate-brown or anthracite-black ceramic LFCM1s and the slag-like LFCM3s are a silicate-like glass with complex morphological features filled with inclusions of varied size. A scanning electron microscope reveals that the solid-phase inclusions are on the average 0.5 microns in diameter; while ultrasonic microanalysis provided chemical makeup of the silicates and inclusions. The color of the lavas are defined by the varying amounts of inclusion dispersed throughout (primarily by thinly dispersed yellow-brown inclusions) as well as by the amount of iron contained in the matrix. Table V.4 shows the silicate matrix chemical composition (average) of several forms of LFCM1, while Table V.5 shows the bulk chemical composition (average) of LFCM1–3 along with various ratios for comparison.

[44] Андерсон, Е. Б., *Лавообразные топливо-содержащие массы...*, 6.

The fuel content in these materials varies from a few up to approximately eighteen weight percent with an average of around seven weight percent (Table V.6a). Fuel burnup in the LFCMs varies from 7.5 to 14.7 MW·d/kg U with an average of 11.7 MW·d/kg U. The burnup values are distributed evenly over all forms and locations of the LFCMs – which appears to indicate that *there was intense and thorough mixing of core materials* sometime before the lava flowed into the lower regions of the reactor building to cool and solidify. Tables V.6a and V.6b (following the flow distribution scheme presented in Figure V.22 and detailed in Appendix V) show the results of radiochemical analyses of 118 samples of the LFCMs from various locations; while Table V.7 presents a summary comparison of another approximately 110 samples showing the ratios of Cs-137 and Ru-106 to Ce-144.

Table V.4[45]

Chemical Compound Composition of the LFCM1 Silicate Matrix†
(weight percent of total)

LFCM Type	K_2O	CaO	MgO	Al_2O_3	ZrO_2	Fe_2O_3	U	Sum	[SiO_2 + O]
LFCM from 210/7 Chocolate-Brown Ceramic	1.5	6.8	5.8	5.2	3.2	—	2.4	**24.9**	[75.1]
LFCM from 210/6 Coal-Black Ceramic	1.7	7.2	4.9	5.3	2.8	8.6	2.1	**32.6**	[67.4]
LFCM from 217/2 "Elephant's Foot" Ceramic	1.7	7.2	1.9	5.1	4.5	—	4.0	**24.4**	[75.6]
Average	**1.6**	**7.1**	**4.2**	**5.2**	**3.5**	**(8.6)**	**2.8**	**(27.3)**	[(72.7)]

[45] Ibid., 14.

† Uranium content is given for all its oxide forms minus the oxygen. Note the lack of boron, carbon, or lead. In addition, although not reflected in the tables, the silicate matrix also contains small (d , 0.1 mm) granuals of graphite, Ibid., pg. 12.

Table V.5[1]

Elemental Composition of Bulk Lava-Like Fuel-Containing Materials
(weight percent of 75 samples, 15 – 20% error)

	LFCM Type	B (5)	Na (11)	Mg (12)	Al (13)	Si (14)	Ca (20)	Ti (22)	Cr (24)	Mn (25)	Fe (26)	Ni (28)	Cu (29)	Zr (40)	Ba (56)	Pb (82)	Sum[†]
1	LFCM1 Coal-Black Ceramic	0.041	4.2	2.4	4.8	29.8	5.5	0.11	0.18	0.32	1.40	0.14	0.0045	3.2	0.12	0.0065	**52.22**
2	LFCM1 Chocolate-Brown Ceramic	0.072	4.0	4.0	3.5	30.9	4.7	0.11	0.20	0.52	0.84	0.18	0.0018	4.8	0.18	0.0012	**54.01**
3	LFCM2 Suppression Pool Pumice	0.073	1.4	4.6	2.8	35.6	4.8	0.19	0.18	0.50	1.20	0.30	0.0018	3.3	0.15	0.012	**55.11**
4	LFCM3 Suppression Pool Slag	0.052	1.5	6.2	3.4	32.3	4.0	0.14	0.18	0.38	0.82	0.26	0.0015	4.5	0.15	0.11	**54.00**
5	LFCM3 Chocolate-Brown Ceramic (intermed.)	0.068	—	5.0	3.3	32.7	4.5	0.15	0.22	0.46	0.83	0.27	—	4.3	0.16	—	**51.96**
	Overall Average	**0.061**	**2.8**	**4.4**	**3.6**	**32.3**	**4.7**	**0.14**	**0.19**	**0.44**	**1.02**	**0.23**	**0.0024**	**4.0**	**0.15**	**0.032**	**54.07**
	1 / 2	**0.57**	**1.1**	**0.60**	**1.4**	**0.96**	**1.2**	**1.00**	**0.90**	**0.62**	**1.7**	**0.78**	**2.5**	**0.67**	**0.67**	**5.4**	**0.97**
	1 / 3	**0.56**	**3.0**	**0.52**	**1.7**	**0.84**	**1.1**	**0.58**	**1.0**	**0.64**	**1.2**	**0.47**	**2.5**	**0.97**	**0.80**	**0.54**	**0.95**
	1 / 4	**0.79**	**2.8**	**0.39**	**1.4**	**0.92**	**1.4**	**0.79**	**1.0**	**0.84**	**1.7**	**0.54**	**3.0**	**0.71**	**0.80**	**0.059**	**0.97**
	1 / 5	**0.60**	**—**	**0.48**	**1.5**	**0.91**	**1.2**	**0.73**	**0.82**	**0.70**	**1.7**	**0.52**	**—**	**0.74**	**0.75**	**—**	**1.01**

[1] Андерсон, Е. Б., С. А. Богатов, А. А. Боровой, Б. Е. Бураков, А. С. Евстратенко, А. П. Криницын, Э. А. Пазухин, А. И. Сурин, *Лавообразные топливосодержащие массы объекта «Укрытие»*, Киев, Украина: Межотраслевой научно-технический центр «Укрытие» и Институт кибернетики имени В. М. Глушкова при АН Украины, Препринт 93-17 (1993): 8–11.

[†] The content of these elements is given without the oxygen of their associated oxide forms, i.e., oxygen accounts for the ≈45% (weight) balance.

Table V.6a
Statistical Summary of Fuel-Containing Material Radiochemical Data
(Total of 118 Samples, Corrected to End of Active Phase – 06 May 1986)

Data Group	# samples	Location	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
A.1	3	Sub-Reactor Region (305/2)	11.89 ± 0.48	5.15 ± 0.97	5.26 ± 0.88	0.28 ± 0.13	0.087 ± 0.053	0.57 ± 0.02
B.1	23	Room 304/3	11.37 ± 0.39	4.01 ± 0.64	4.44 ± 0.50	0.34 ± 0.10	0.033 ± 0.022	0.55 ± 0.02
C.1	11	Corridor 301/5	11.55 ± 0.38	3.49 ± 0.59	4.20 ± 0.99	0.36 ± 0.06	0.038 ± 0.017	0.56 ± 0.02
D.1	1	Corridor 217/2 (undefined)	12.02 ± 3.47	4.26 ± 2.06	4.30 ± 2.07	0.33 ± 0.58	0.050 ± 0.224	0.58 ± 0.76
E.1	2	Corridor 217/2 (Elephant's 1)	10.57 ± 0.38	5.00 ± 0.31	5.33 ± 0.03	0.42 ± 0.04	0.040 ± 0.010	0.52 ± 0.02
F.1	9	Corridor 217/2 (Stalactite 1)	11.70 ± 0.32	4.67 ± 0.36	4.66 ± 0.31	0.35 ± 0.06	0.040 ± 0.023	0.56 ± 0.01
G.1	5	Corridor 217/2 (Stalactite 2)	11.62 ± 0.45	4.74 ± 0.39	4.78 ± 0.39	0.43 ± 0.05	0.038 ± 0.029	0.56 ± 0.02
H.1	2	Corridor 217/2 (Elephant's 2)	11.99 ± 0.61	4.48 ± 0.69	4.61 ± 0.22	0.35 ± 0.06	0.035 ± 0.015	0.58 ± 0.03
I.1	2	Corridor 217/2 (undefined)	11.32 ± 0.05	3.99 ± 0.03	4.38 ± 0.19	0.41 ± 0.01	0.020 ± 0.000	0.55 ± 0.00
J.1	3	Corridor 017/2	11.77 ± 0.44	4.96 ± 0.18	5.00 ± 0.18	0.34 ± 0.05	0.020 ± 0.008	0.57 ± 0.02
K.1	20	Steam Dist. Corr. (210/7)	11.82 ± 0.67	10.2 ± 1.10	9.86 ± 1.05	0.32 ± 0.11	0.042 ± 0.028	0.57 ± 0.03
L.1	1	Steam Dist. Corr. (undefined)	11.77 ± 3.43	5.12 ± 2.26	7.49 ± 2.74	0.68 ± 0.83	0.360 ± 0.600	0.57 ± 0.76
M.1	8	Press. Supp. Pool - 2 (012/15)	11.68 ± 0.35	9.59 ± 1.38	9.93 ± 1.15	0.35 ± 0.09	0.045 ± 0.026	0.56 ± 0.02
N.1	2	Press. Supp. Pool - 2 (undef.)	12.84 ± 0.38	11.5 ± 1.78	11.25 ± 0.25	0.34 ± 0.01	0.040 ± 0.000	0.62 ± 0.02
O.1	8	Press. Supp. Pool - 1 (012/7)	11.85 ± 0.34	9.75 ± 0.83	9.93 ± 0.76	0.32 ± 0.03	0.040 ± 0.019	0.57 ± 0.02
P.1	2	Press. Supp. Pool - 1 (undef.)	11.38 ± 0.41	10.20 ± 0.30	14.20 ± 4.20	0.31 ± 0.00	0.040 ± 0.010	0.55 ± 0.02
Q.1	1	Press. Supp. Pool - 1 (012/5)	11.53 ± 3.40	10.44 ± 3.23	8.90 ± 2.98	0.18 ± 0.42	0.030 ± 0.173	0.56 ± 0.75
R.1	1	Press. Supp. Pool - 1 (012/8)	11.59 ± 3.40	10.14 ± 3.18	8.16 ± 2.86	0.23 ± 0.48	0.030 ± 0.173	0.56 ± 0.75
S.1	10	Steam Dist. Corr. (210/6)	12.16 ± 0.49	6.26 ± 1.54	6.39 ± 1.30	0.48 ± 0.11	0.107 ± 0.041	0.58 ± 0.02
T.1	1	Press. Supp. Pool - 1 (012/6)	10.98 ± 3.31	9.05 ± 3.01	8.61 ± 2.93	0.16 ± 0.40	0.030 ± 0.173	0.53 ± 0.73
U.1	3	Steam Dist. Corr. (undefined)	11.08 ± 0.73	6.90 ± 1.38	5.81 ± 0.48	0.26 ± 0.06	0.053 ± 0.037	0.54 ± 0.03
$\langle x \rangle \pm \sigma$			11.66 ± 0.65	6.59 ± 2.88	6.78 ± 2.81	0.35 ± 0.11	0.049 ± 0.046	0.56 ± 0.024

Table V.6b
Statistical Summary of Fuel-Containing Material Radiochemical Data
(Total of 118 Samples, Corrected to End of Active Phase – 06 May 1986)

	α					γ						β
Data Group	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	Ce-144 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
A.2	3.84 ± 0.58	7.29 ± 0.65	1.25 ± 0.17	1.72 ± 0.27	0.98 ± 0.17	1.34 ± 0.25	2.52 ± 0.14	1.44 ± 0.81	2.69 ± 0.66	3.72 ± 2.48	0.16 ± 0.40	
B.2	3.82 ± 0.77	7.92 ± 1.93	2.56 ± 1.71	1.77 ± 0.76	1.17 ± 0.32	1.06 ± 0.15	2.26 ± 0.68	1.24 ± 0.37	3.40 ± 1.39	1.11 ± 0.87	1.46 ± 1.44	7.59 ± 0.84
C.2	4.14 ± 0.77	7.82 ± 1.46	2.98 ± 2.02	3.48 ± 1.76	1.73 ± 1.66	0.90 ± 0.15	2.06 ± 0.55	1.15 ± 0.30	1.64 ± 0.01	0.95 ± 0.50		5.64 ± 1.96
D.2	4.72 ± 0.01	7.84 ± 0.01	1.11 ± 0.01	2.58 ± 0.01	0.77 ± 0.01	1.11 ± 0.01	2.30 ± 0.01	1.33 ± 0.01		1.67 ± 0.01		
E.2	5.30 ± 0.01	9.70 ± 0.01	1.44 ± 0.01	1.90 ± 0.01	1.20 ± 0.01	1.27 ± 0.09	3.27 ± 0.07	1.68 ± 0.02	1.91 ± 0.01	1.43 ± 0.47		
F.2	3.93 ± 0.71	9.38 ± 2.12	1.34 ± 0.16	0.99 ± 0.40	1.22 ± 0.24	1.21 ± 0.09	2.64 ± 0.44	1.48 ± 0.23	1.96 ± 0.30	1.38 ± 0.67	3.80 ± 1.01	
G.2	4.26 ± 0.70	9.34 ± 1.99	1.35 ± 0.21	1.19 ± 0.67	1.06 ± 0.17	1.23 ± 0.11	3.32 ± 0.64	1.87 ± 0.43	2.41 ± 0.52	1.40 ± 1.19	4.00 ± 0.25	
H.2	4.38 ± 0.31	7.23 ± 0.63	0.60 ± 0.27	1.75 ± 0.13	0.81 ± 0.05	1.17 ± 0.19	2.45 ± 0.01	1.41 ± 0.07		1.18 ± 0.71		5.93 ± 0.52
I.2	4.76 ± 0.75	7.18 ± 0.52	0.67 ± 0.04	1.99 ± 0.04	0.74 ± 0.09	1.03 ± 0.01	2.59 ± 0.01	1.42 ± 0.00		0.56 ± 0.06		
J.2	4.31 ± 0.89	13.28 ± 3.02	1.43 ± 0.09	1.20 ± 0.36	1.47 ± 0.11	1.29 ± 0.05	2.72 ± 0.41	1.55 ± 0.27	2.68 ± 0.28	0.75 ± 0.26	4.52 ± 1.21	
K.2	9.02 ± 1.30	20.80 ± 4.56	2.98 ± 1.01	3.11 ± 0.92	1.87 ± 0.97	2.65 ± 0.31	5.20 ± 1.83	2.98 ± 1.11	5.67 ± 2.57	2.98 ± 1.06	5.49 ± 3.19	8.15 ± 0.91
L.2	6.28 ± 0.01	11.29 ± 0.01	1.35 ± 0.01	3.51 ± 0.01	1.49 ± 0.01	1.33 ± 0.01	5.60 ± 0.01	3.17 ± 0.01		14.26 ± 0.01		
M.2	8.95 ± 0.88	19.46 ± 5.61	4.79 ± 3.03	4.43 ± 2.40	2.18 ± 0.83	2.49 ± 0.36	5.26 ± 1.01	2.96 ± 0.57	4.21 ± 0.50	3.05 ± 1.26	7.55 ± 2.18	15.20 ± 1.66
N.2		13.30 ± 0.01			4.42 ± 0.01	3.02 ± 0.46	6.32 ± 0.83	3.85 ± 0.41		3.19 ± 0.51		
O.2	9.02 ± 1.33	19.61 ± 4.06	4.30 ± 2.96	4.04 ± 1.81	2.40 ± 0.50	2.54 ± 0.22	5.06 ± 0.62	2.89 ± 0.37	4.30 ± 0.31	3.02 ± 1.27	6.53 ± 0.87	15.30 ± 1.14
P.2	9.08 ± 0.01	17.52 ± 0.01		2.92 ± 0.01	2.11 ± 0.01	2.64 ± 0.01	5.06 ± 0.18	2.79 ± 0.19		3.16 ± 0.54		
Q.2	8.28 ± 0.01	15.38 ± 0.01	3.24 ± 0.01	3.62 ± 0.01	1.64 ± 0.01	2.71 ± 0.01	3.07 ± 0.01	1.71 ± 0.01	16.63 ± 0.01	2.11 ± 0.01	0.54 ± 0.01	
R.2	8.34 ± 0.01	15.62 ± 0.01	4.35 ± 0.01	3.75 ± 0.01	2.04 ± 0.01	2.63 ± 0.01	3.78 ± 0.01	2.11 ± 0.01	15.09 ± 0.01	2.45 ± 0.01	0.58 ± 0.01	
S.2	6.73 ± 1.51	11.55 ± 2.45	2.95 ± 1.04	3.05 ± 1.22	1.06 ± 0.67	1.64 ± 0.40	4.80 ± 1.27	2.81 ± 0.75	5.70 ± 2.00	4.87 ± 1.84	0.77 ± 0.11	8.09 ± 1.21
T.2	7.49 ± 0.01	14.06 ± 0.01	3.38 ± 0.01	3.40 ± 0.01	1.73 ± 0.01	2.32 ± 0.01	2.31 ± 0.01	1.23 ± 0.01	12.77 ± 0.01	1.88 ± 0.01	0.44 ± 0.01	
U.2	5.61 ± 1.16	10.04 ± 1.94	1.87 ± 0.75	1.82 ± 0.31	1.10 ± 0.18	1.77 ± 0.36	2.72 ± 0.44	1.47 ± 0.33	6.86 ± 3.06	2.78 ± 2.24	0.23 ± 0.04	
x ± σ	6.02 ± 2.47	12.69 ± 6.16	2.68 ± 1.93	2.55 ± 1.59	1.49 ± 0.89	1.72 ± 0.75	3.64 ± 1.70	2.06 ± 1.01	4.56 ± 3.14	2.42 ± 2.19	3.71 ± 2.93	8.23 ± 3.19

Table V.7[46]

Comparison of Calculated-to-Measured Relative Quantities of
Cs-137, Ru-106, and Ce-144

Lava Type	Measured $\frac{\text{Cs-137}}{\text{Ce-144}}$	Calculated $\frac{\text{Cs-137}}{\text{Ce-144}}$	Cs-137 $\frac{\text{measured}}{\text{calculated}}$	Measured $\frac{\text{Ru-106}}{\text{Ce-144}}$	Calculated $\frac{\text{Ru-106}}{\text{Ce-144}}$	Ru-106 $\frac{\text{measured}}{\text{calculated}}$
LFCM1 (≈ 50 samples) Brown Ceramic Vertical Flow	0.0216	0.0631	0.34	0.00978	0.295	0.033
LFCM1 (≈ 60 samples) Black Ceramic Horizontal Flow	0.0239	0.0631	0.38	0.0144	0.295	0.049
Average	0.0228	0.0631	0.36	0.012	0.295	0.041

V.4. Discussion

The consequences of the accident were intimately related to the specific design features of the 2nd-generation RBMK-1000 represented by Chornobyl Unit-4 and to surrounding conditions in the vicinity of the core during the Active Phase. Because the reactor had no containment, the release of fission products included an important component from the direct ejection of fuel by the explosion(s), while the chemical aspects of the later releases were determined by a chemically-oxidizing environment dominated by the graphite fire.

Unfortunately, although nearly eight years have passed since the accident, relatively little quantifiable data is available on the state of the melted fuel remaining within the Chornobyl Unit-4 sarcophagus.† Some radiochemical data is available (part of which is

---

[46] Андерсон, Е. Б., *Лавообразные топливо-содержащие массы...*, 8.

† Until the dissolution of the USSR, the Soviet government was not particularly interested in a thorough scientific investigation of the Active Phase of the accident. Rather, their main concerns were to locate all the fuel within the sarcophagus, to ensure that criticality could not be re-established under any plausible circumstances, to ensure that the other three operating units and their personnel were not affected significantly by Unit-4, and to monitor air, water, and soil samples in the region to ensure that the fuel (at least that contained within the sarcophagus) was not migrating into the environment. This is evidenced mainly by the relatively little information available on the state of the fuel and of the sarcophagus, and surprisingly to the fact that before myself there were no western nuclear engineers or scientists permitted to

presented here), but much more needs to be gathered to gain a clearer understanding of the processes occurring during the Active Phase; and more importantly, to properly quantify the source term. Despite these challenges, however, some conclusions may be drawn from what is available.

A strong indication of the fact that little if any of the bags of materials (thrown into the reactor building to smother the graphite fire – see Chapter IV) made it into the core region is the almost complete lack of lead and boron* in the radiochemical data. In the approximately 71% of the core's initial fuel load (135 tonnes) that flowed into the lower regions of the reactor building, approximately 0.01 weight percent lead (averaged over the entire LFCMs volume) was found in the corium. This is very roughly one tonne (out of 2,400 tonnes dumped from the helicopters) or about 0.1 m^3 of lead that may have entered the reactor shaft and reached the corium. Additionally, the fact that only trace amounts of carbon-graphite and no carbon compounds are found in the LFCMs seems to indicate not only that complete oxidation of the pulverized graphite moderator and reflector took place (at least that graphite which made up the remains of the core that settled to the bottom of the reactor shaft), but also that little if any carburization took place.[47]

---

investigate the accident or have access to what little data there was available. The Ukrainian government is struggling with a severe economic crisis that precludes substantial funding for basic scientific research at the site (most of the money goes toward maintenance, clean-up, and monitoring). In fact, Ukraine has yet to establish a concrete policy regarding the 30-km zone – its main concern is to attract international aid to construct a second more-reliable sarcophagus and to help clean up the surroundings. To better grasp the conditions in which the handful of researchers at Chornobyl conduct their work, during my year and one-half stint at Chornobyl, when it was necessary I was forced to drive 120 kilometers to Kyjiv to photocopy material relevant to my research – due as much to a lack of paper as to the lack of a working photocopier.

* In the highly oxidizing conditions at Chornobyl, the boron carbide of the control rods (or what little may have been thrown in from the helicopters) would have turned into the highly volatile B_2O_3 (melting point 450°C, boiling point ≈ 1800°C) by either of the following reactions,

$$B_4C + 4O_2 \longrightarrow CO_2 + 2B_2O_3$$
$$B_4C + 8H_2O \longrightarrow CO_2 + 2B_2O_3 + 8H_2$$

The oxide melt of the fuel / serpentine mixture, however, would tend to partially retain this product.

[47] D. A. Powers has argued for carburization as a possible mechanism for activity releases during the Active Phase. Not only are there no carbon compounds observed in the LFCMs nor uranium carbide, but this analysis is based upon the dubious Soviet accounts of the core being covered with materials thrown from helicopters to smother the graphite fire. [D. A. Powers, "Carburization As a Mechanism for the Release of Radionuclides During the Chernobyl Accident," In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 113–125, Moscow, Russia: Nauka, 113–125.

Finally, it appears clear upon comparing Table V.4 and V.5 with the chemical compositions of concretes and specialty stainless steels presented at the end of Appendix III.B, that the major componental contributor to the LFCMs is the Lower Biological Shield.

The current configuration of the LFCMs located in a thick layer above the lower-layer of solidified metal on the floor of the Steam Distribution Corridor seems to indicate that prior to melting through the Lower Biological Shield (whose center appears to be approximately about the coordinates [K, 46+3m]), the molten debris had separated into distinct layers – a lower molten metal-containing layer consisting of structural metal and metallic fission products, and a upper ceramic layer consisting of molten $(U,Zr)O_2$ and oxidation resistant metals. (Fission product release from the ceramic "pool" during the Active Phase before the melt-through would be determined by bubble dynamics and the oxygen potential.) During the initial period of contact between the molten debris and the serpentine contained within the LBS, it is expected that the gas release from the serpentine was very vigorous,* and in most cases, the oxides and the metals in the debris became well mixed. Later in time, depending on the initial melt temperature, the oxide phase would have detrained from the metal phase forming layers – in general, a metal phase will be more dense and will be the lower layer in such a situation.

Of vital interest to a source term analysis is the almost complete lack of ruthenium in the LFCMs and the high activity of Ru-103 and Ru-106 in the MFCMs.† On the one hand, one would expect ruthenium metal (generally thought to be in the low volatility

---

* For serpentine, a hydrous magnesium silicate, $3MgO{\cdot}2SiO_2{\cdot}2H_2O$ or $Mg_6[Si_4O_{10}]{\cdot}[OH]_8$, the water of crystallization present in the mineral is retained up to high temperatures of the order of 450 to 500 °C – as opposed to ordinary concrete, where roughly half of the water content is lost due to vaporization at a temperature of 100 °C. A major feature of serpentinite concrete is that its water content is relatively higher than that of ordinary concrete – implying that a direct interaction with corium would release more gases for sparging effects.

† The behavior of ruthenium during the Chornobyl Accident is important for two reasons: (1) the toxicity of the volatile ruthenium oxides (RuO_2 and RuO_4) and the radiation hazards of Ru-103 and Rr-104 should be considered in a reevaluation of the Chornobyl source term and its effect on the local population; and (2) ruthenium characteristics in oxidizing environments are distinctive enough to make an understanding of the kinetic behavior of ruthenium releases very useful for post-accident source term analyses. [F. C. Inglesias, C. E. L. Hunt, F. Garisto, and D. S Cox," Ruthenium Release Kinetics From Uranium Oxides," presented at the International Seminar *Fission Product Transport Processes In Reactor Accidents*, Dubrovnik, Yugoslavia, (May 22–26, 1989): 1.

group) to remain in the molten debris and be drawn into the lower metal layer now observed at Chornobyl.[48] On the other hand, the high loss of ruthenium from the ceramic layer seems consistent if it was exposed to a highly-oxidizing atmosphere at high temperatures during the Active Phase. The very high volatility of RuO_2 and RuO_4, would then appear to indicate a high release of ruthenium to the environment. In fact, although the Soviets stated that only 2.9% of the core inventory ruthenium was released during the accident, there is some inconsistency in the activity release data as presented in Vienna that seems to indicate that ruthenium may have been released in greater quantities. This conjecture, in fact, may be at least partially supported by findings in Sweden where some hot particles deposited on their territory as a result of the accident were found to be nearly pure ruthenium.[49] Indeed, one expects a more complex elemental composition of hot particles assuming the release mechanism from the fuel were mechanical in nature. Moreover, Demin and Khodakovsky have noted that hot particles analyzed in the immediate vicinity of Unit-4 (on the grounds of the power station) are greatly enriched in the non-volatiles barium and cerium; and that ruthenium was "fractionating" as tellurium and iodine.[50]

---

[48] Richard Hobbins expects that because of its very high oxygen potential, ruthenium should exist in its elemental form under severe accident conditions and very small releases are expected based on the low volatility of the metal. He also points out that large releases from the fuel (but negligible releases from the core) were observed for ruthenium in the TMI-2 accident; and that ruthenium is retained in molten metallic materials in agreement with that observed at Chornobyl (albeit more qualitatively than quantitatively) and western out-of-pile meltdown studies. [R. R. Hobbins, D. A. Petti, D. L. Hagrman, "Fission Product Release from Fuel Under Severe Accident Conditions," *Nuclear Technology*, Vol. 101, No. 3, (March 1993): 274.] In general, medium- to low-volatility fission products can be retained in large fractions by the chemistry of ceramic melts with metallic inclusions.

[49] L. Devell, H. Tovedal, U. Bergström, A. Appelgren, J. Chyssler, and I. Andersson, "Initial Observations of Fallout from the Reactor Accident at Chernobyl," *Nature*, (321, May 15, 1986): 192–193, as reported in D. A. Power, et al, 14.

[50] V. F. Demin and I. L. Khodakovsky, "Released Radioactive Material During the Chernobyl Accident," as Appendix 10 in *USNRC Workshop on the Chemical Reactions and Processes in Severe Reactor Accidents*, (November 1987): 141 & 140. Demin's findings that more ruthenium may have been released is disputed by Aleksandr Borovoi of the Chornobyl research group. He points out that the very volatile oxides RuO_2 (which decomposes at low temperatures) and RuO_4 (with a melting point of 25.5°C and which decomposes at 108°C) were released from the surfaces of the LFCMs after the Active Phase in the elevated temperatures of the particularly hot summer of 1986 in addition to the decay heat generated in the remains of the fuel – thus artificially enriching hot particles releases. Borovoi bases his argument on the analyses of ejected fuel fragments (as yet unavailable) which indicate that ruthenium as well as other middle and non-volatiles left as "fuel chunk aerosols." He could not, however, explain the apparently higher re-

Finally, the results of the analyses show that within the 135 tonnes of fuel (≈ 71% of initial core load) now located in the lower regions of the reactor building in the form of LFCMs, approximately 35% of the calculated inventory of Cs-137 remains – implying that 65% x 71% or 46% of the initial 7.01 MCi inventory* (3.23 MCi) was released to the environment. If one also considers the remaining 29% of the core (in the form of larger core fragments ejected beyond the bounds of the reactor building or that now located under the pile of materials on the floor of the Central Hall) and what contribution to the overall release it may have had, it is clear the releases of volatile radioisotopes were substantially greater than that reported by the Soviets in Vienna. This also corroborates Warman's release estimates of 30–50% radiocesium and 40–60% radioiodine into the environment,[51] and thus may help to explain why a very significant increase in childrens' thyroid cancers are now appearing in Belarus and Ukraine. (Note that the Soviets reported a 13% release of Cs-137 and 20% release of I-131 in Vienna.) Unfortunately, there appears to be I-129 data available to further strengthen this conjecture.†

Regarding a credible source term estimate, two things remain unknown in the findings. The first is whether or not there was significant plateout along the release path and into the environment. By all indications the reactor shaft was partially blocked by the Upper Biological Shield, some of its highly damaged moderator coolant channels along the periphery, part of the upper coolant channels, and several larger fragments of the Central Hall wall from above the 35.5 m (floor) level. Although certainly the release was

---

lease of cerium and Ba-140. (Private communication, August 12, 1993.) It is unfortunate that Demin and Khodakovsky did not present much new information besides that reported by the Soviets at Vienna in August 1986.

* See results of a more precise core inventory estimate in Chapter VI.2.2.

[51] Edward A. Warman, "Soviet and Far-Field Radiation Measurements and an Inferred Source Term From Chernobyl," presented at the *New York Chapter Health Physics Society Symposium on the Effects of the Nuclear Reactor Accident at Chernobyl,* April 3, 1987, Brookhaven National Laboratory. Because iodine is one of the most hazardous fission products, its chemical forms and behavior after releases are particularly important.

† Fission product source terms should not necessarily assume highly volatile forms of iodine. Because iodine and cesium tend to form condensable species that form aerosols during transport away from a hot or molten core (at least in the steam environment of a western LWR), aerosol behavior must be considered for volatile fission product analysis. [Richard R. Hobbins, David A. Petti, Daniel J. Osetek, and Donald L. Hagrman, "Review of Experimental Results on Light Water Reactor Core Melt Progression," *Nuclear Technology*, Vol. 95, (September 1991): 302.]

open to the atmosphere, it was what is usually termed a "torturous" path making plateout quite likely. However during the Active Phase the UBS and other fragments were probably being heated by the molten corium (convective heating by hot updrafts, radiative heating, and self-heating from deposited fission products). In this case, revaporization (the release to the environment of volatile fission products previously deposited on surfaces along the release path) would be a very likely release mechanism for volatiles such as cesium and iodine.

The second and more enigmatic finding is that, although clearly more radiocesium and radioiodine were released from Unit-4 than previously thought, a considerable amount of Cs-137 (35%) remains within the solidified remanents of the core. In fact, the amount of Cs-137 retained in the LFCMs (on the average) is *significantly higher* than that retained at TMI-2 in the molten ceramic lower plenum debris (average of 3% retained) or in the upper plenum debris (average of 19% retained).[52] This is particularly unexpected given the long (nine day) duration of the Active Phase, the oxidizing environment to which the core was exposed, the thorough mixing of the core, and the apparent high volatility of cesium. It seems to suggest that some of the cesium may be in an involatile chemical form stable at high temperatures,[53,54] or if a significant crust did form above the corium, it may have presented a very formidable effective barrier to volatile fission product releases.

---

[52] David A. Petti, James P. Adams, James L. Anderson, Richard R. Hobbins, "Analyses of Fission Product Release Behavior from the Three Mile Island Unit-2 Core," *Nuclear Technology*, Vol. 87, No. 1, (August1989): 247. According to Hobbins, et al, "Fission Product Release...," 276, 12% of the Cs-137 inventory is retained in the lower plenum, while 20% is retained in the upper debris.

[53] Hobbins, et al, "Fission Product Release...," 276. Interestingly, it is thought that "Chemical and/or physical phenomena cause *retention of 5 to 15%* iodine and *cesium* for extended periods in molten corium." (emphasis added) [Richard R. Hobbins, et al, "Review of Experimental Results...," 302.]

[54] Even quite recent experiments that simulate fission product releases for severe accidents conditions conclude that cesium retention is low: "The results [of the investigations] for the volatile species show clearly that the release rates for the rare gases, the halides, and the alkali metals all are very high and are similar for LWR fuel in the temperature range 1700 to 2700 K." [Morris F. Osborne and Richard A. Lorenz, "ORNL Studies of Fission Product Release Under LWR Severe Accident Conditions," *Nuclear Safety*, Vol. 33, No. 3, (July – September 1992): 362.

Obviously, much remains to be investigated at Chornobyl because the findings are as yet far too sketchy to provide an accurate account of the Active Phase. Radiochemical analyses and a quantification of large core chunks ejected beyond building are needed, as well as more detailed analyses of LFCMs and MFCMs. Moreover, a more precise material balance of the FCMs located within the sarcophagus is required to account for all the fuel (it is imperative, for example, to identify what is lying under the pile of materials (dumped by the helicopters) located on the floor of the Central Hall.) Finally, western experts, who have considerable degraded-core experimental and accident experience (e.g., Oak Ridge National Laboratory with the transport of volatile fission products, and Idaho National Laboratory with TMI-2), should explore opportunities with the Ukrainians for joint research at Chornobyl.

CHAPTER VI

THE CHORNOBYL SOURCE TERM REVISITED

VI.1. Basic Principles of Source Term Analysis

VI.1.1. Introduction to the Case of Chornobyl

An examination of the Chornobyl releases in terms of physical and chemical processes taking place within the reactor fuel would be useful if a relationship can be established between these processes and the observed releases of radioactivity. In turn, it may be possible to determine if observations during the Chornobyl accident have any relevance or applicability to source term predictions for severe accidents at other types of reactor installations in the West.[1] Moreover, if a reliable model can be established, it may be possible to account for discrepencies in far-field measurements of fallout from the accident with those presented by the Soviets at Vienna. This would prove invaluable for radiological experts to determine the extent of contamination shortly after the accident, and by extension, for comparisons with the currently observed rise in oncological sicknesses in Ukraine and Belarus (see Chapter II.4.) Ultimately, this information will also provide a scientific basis for the construction of a second, more permanent cover, *Shelter-II*, for the destroyed reactor.

Indeed, one of the frustrating consequences of the accident is the gap between the conclusions of scientific research and the realities of the effects of the accident among the population at large and upon the surrounding environment. While scientists and engineers have concluded that in certain cases radiation fallout was too low to have significant effects, in many villages there has already been a discernible and even alarming rise in oncological

---

[1] D. A. Powers, T. S. Kress, and M. W. Jankowski, "The Chernobyl Source Term," *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 9.

(tumor) sicknesses – even though the latent period for these cancers is somewhat greater than the time since the accident (see Chapter II). Additionally, although the Soviets were to be commended for displaying a great deal of candor at the Vienna meeting in August 1986, because of recent revelations of cover-ups concerning the causes and extent of the accident (Chapter I), fission product release information presented in Vienna must be reviewed to determine which data may be reliably used to estimate release rates during the Active Phase of the accident. Moreover, because of circumstance and the general unpreparedness of the Soviets for an accident of this magnitude brought on, in part, by their relatively lax attitude toward nuclear safety,[2] much of the information, including information on the source term, is presented in a summary or representative fashion. There are many gaps in the information that render some of it (excepting general descriptive accounts of what may have occurred a few days after the accident) virtually unusable.

Clearly, the new AMA findings presented in Chapter IV will have the most consequential and far-reaching impact on source term estimates for Chornobyl. Of these, perhaps most relevant to Chornobyl is the fact that little if any of the 5020 tonnes of sand, clay, dolomite, and lead dropped on top of the reactor in the few days following the accident (to smother the burning core) ever hit the intended target, and that no nitrogen purging of the core occurred. (Recall that in Vienna the Soviet delegation claimed these two actions succeeded in cooling, smothering, and sealing the core almost completely from the environment; and all scenarios and analyses of the accident in the West to date have been based on this information.) The strong implication is that during the Active Phase the core "burned" virtually uncovered for approximately nine days – releasing radioisotopes into the upper levels of the destroyed reactor building and directly to the environment. This not only calls into question previous western analyses of the accident, but also has important ramifications for the planning of western accident management actions.

---

[2] See, for example, Chapter 5 "Safety in the Soviet Nuclear Power Industry" in David R. Marples, *Chornobyl & Nuclear Power in the USSR*, St. Martin's Press, New York, 1986; Maurice Strong, "40 Chernobyls Waiting to Happen," *The New York Times*, Vol. CXLI, No. 48913 (Sunday, March 22, 1992): 15; and "Chornobyls-in-Waiting," *The Economist*, Vol. 324, No. 7772 (August 15, 1992): 18.

It is important, therefore, to provide a reliable estimate of the core inventory of fission products and transuranics as the first "node" in the overall release path to the environment. Given a description of the reactor, surrounding materials and structures, operating conditions at the time of the accident, physical processes of the accident itself, and actions taken to control and seal-off the core from the environment immediately following the accident, it is then possible to devise a model (the second "node" in the overall release path) that will predict the most probable paths for the release of radioactive materials into the environment.

After discussing the elements of source term theory and analysis, this chapter reviews several of the widely-varying source term estimates published since the accident – focusing mainly upon Soviet estimates as they have changed over time, followed by the results of a refined core fission product and transuranic inventory calculation. It then presents newly-acquired release data; and, by drawing upon information presented in preceding chapters, appraises the validity of this source term data while providing a simple release dynamics analysis, a possible scenario for the nine days of the Active Phase of the accident, and a new source term estimate.

VI.1.2. Elements of Source Term Theory[3]

The extent, nature, and rate of radioactive materials release during a severe accident is known as the "source term" because it is the starting point in any calculation to determine the dispersion of radionuclides in the environment. The source term is, therefore, an important link in the chain of events to be analyzed in considering the consequences of accidents – not only as part of the safety evaluation of existing and planned reactors and as a guide to design, but also (in this case) to confirm the extent of environmental contamination resulting from the Chornobyl accident.

---

[3] An excellent discussion on the subject is G.W. Parker and C.J. Barton, "Chapter 18: Fission-Product Release," *The Technology of Nuclear Reactor Safety – Volume 2: Reactor Materials and Engineering*, Editors T.J. Thompson and J.G. Beckerley, Cambridge, MA: MIT Press, (1973): 525–618.

In order to accurately define a "source term," information is needed on the quantity and chemical nature of fission-products released, and also on the characteristics of the release. The release characteristics include the timing of the release, release duration, release height*, and release energy. Moreover, the identification of potential pathways for the release of fission-products to the environmnet is closely tied to the evaluation of fission-product barrier failure modes and mechanisms.† Any meaningful confirmation of the consequences of the Chornobyl accident must, of necessity, start at the source of the fission products and trace the behavior of individual fission products as the barriers to their release are successively breached. In broadest terms, the potential pathways for the release of fission-products to the environment are related to the type of barriers under consideration and the likelihood and mechanism of their postulated failure modes under various core-melt accident scenarios. A postulated containment building failure, for example, with its associated breach size, location and energetics, will dictate not only a particular pathway for the release of fission-products to the environment, but also have impact on the fission-product sources. For instance, an explosive event energetic enough to cause a gross rupture of the containment would provide both a direct path to the environment and cause oxidation of fission-products as they escape – quite similar to what happened at Chornobyl. On the other hand, a less energetic event may result in containment failure later – allowing time for various fission-product removal mechanisms to operate†† and leading to release paths which have more effective fission-product retention capabilities.

---

* For purposes of this dissertation and as outlined in Section I.2., atmospheric release, dispersion, subsequent contamination of the environment, ground and water transport, and effects on flora and fauna, although important, are not considered in great detail.

† Generally speaking, nuclear power reactors have four major barriers preventing the release of fission products to the environment: 1) fuel matrix, 2) fuel cladding, 3) boundary of the primary coolant loop system (e.g., pressure vessel and piping for some LWR designs), and 4) containment building. Each of the four barriers must be breached in order for the fission products to escape to the outside environment and pose a potential risk to the general public. Chornobyl's Unit-4 (as with all RBMK's built in the former Soviet Union) had no containment building to speak of and the core was not contained in a pressure vessel.

†† Engineered safeguards and safety systems are designed into a nuclear power plant in an effort to prevent failures of barriers (such a the containment building) and to limit the amount of fission products which ultimately cross each barrier in the event of their failure.

As postulated later, at Chornobyl the core graphite and other debris, while at the same time burning away, were covering and slightly insulating the molten core as it melted through the Lower Biological Shield. This layer of burning graphite effectively acted as a filter that partially retained a significant portion of the volatile fission-products being released during the Active Phase – although it itself, along with retained fission products, was eventually burned away and released into the environment. On the other hand, when the graphite burned away, the non-volatile radioactive species lost a significant transport mechanism – namely, the transport of non-volatile radionuclides that may have condensed onto particulate graphite "carriers."

A description of the transport processes occurring from the point of release from the fuel to leakage from the outermost barrier involves a large number of variables – including the identification and analyses of possible transport mechanisms operating during the release period. The development of a model, which may be simplified or sophisticated depending on the needs and the information available, is therefore the first step in such analyses. Moreover, the behavior of accident-released fission products is complex and quite dependent on the exact nature of the accident, and the release is by no means instantaneous. Mechanisms such as diffusion through the lattice of the ceramic fuel, mass transfer through a boundary-layer-type concentration gradient near a phase boundary in a molten fuel, and gas-phase diffusion external to the fuel have definite time-dependent transport rates (which are strongly functions of ambient conditions) that lend themselves to calculations – provided a reasonably descriptive model can be formulated. For example, fission products, which may include fine particulate matter, are transported by liquids, gases, or two-phase mixtures encountered along the release path. The relative transport by such fluids and possible depostion on interior surfaces is quite dependent on the physical and chemical forms of the release product and surface in question. Most fission products have varying chemical characteristics that affect both adsorption and desorption rates on surfaces, and analytical description of transport and deposition becomes quite complicated.

From the early development of nuclear reactors, the radioactive fission products as well as the actinides (both generated in the fuel during operation) have been recognized as the major biological hazard. For purposes of analyses, these fission products are usually divided into volatility groups. For example, although gases under ambient conditions and therefore of extremely high volatility, the noble-gas fission products krypton and xenon are not considered strong biological hazards because of their relatively low fission yield, high escape probability, and their chemical inertness. On the other hand, iodine, cesium, and, to some extent, tellurium are considered to be the most important fission products in the *early* stages of a severe accident as they exhibit similar high volatilities and diffusion properties. Although I-131 has a relatively short half-life (8.01 days), it is a particularly hazardous fission product, and therefore its chemical forms and behavior after releases are important. Cesium, which has a fission yield approximately ten times that of iodine and has a longer half-life (Cs-137 – 30.0 years), is another major contributor to personnel and equipment-property hazard. The less-volatile species may be divided broadly into three groups – the semi-volatiles (tellurium and antimony), the low-volatiles (strontium, barium, and europium, and the refractories (molybdenum, ruthenium, zirconium, cerium, neptunium, etc.)

Although the quantities of fission products existing in a given reactor core at a given time can be accurately estimated from the history (reactor power level versus time) of that core, the fraction of fission products that will be released under a given set of circumstances and conditions cannot be accurately estimated by any simple means. It was for this reason, in early evaluations of the safety of nuclear reactors, that it was assumed that 100% or, at least, a very large percentage of the fission products would be released from the fuel to the containment.[4,5]

---

[4] Staff of Brookhaven National Laboratory, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants," *USAEC Report WASH-740*, (March 1957).

[5] Norman Rasmussen, Chairman of the Reactor Safety Study Group, United States Nuclear Regulatory Commission, *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants WASH-1400*, (October 1975).

There are nearly thirty-five elements and over two-hundred different isotopes formed in the fission process. Many of these isotopes have sufficiently short half-lives and therefore do not figure predominantly in the amount of radioactivity present approximately one day after shutdown. What complicates time-dependent source term estimates (especially for the case of Chornobyl's nine-day long Active Phase) is that the longer-lived fission products continue to decay, obviously, until a stable product is formed. The physical and chemical states of the intermediate species in a given decay chain are important since some may be volatile, others may be nonvolatile, while the rest are of intermediate volatility. There can be little question that the chemical form of the fission products has a profound effect on their release from fuel during reactor accidents and on their subsequent behavior.

The two physical properties most relevant to source term estimates are the vapor pressure of the compounds that can form under accident conditions, and the free energies of formation of these compounds. The latter indicate the stability of the compounds at elevated temperatures, and are of considerable importance in the prediction of the form of released fission products – not only because UO_2 fuels are being used in most nuclear power reactors, but also because oxygen is likely to be present in the environment of accident-ruptured fuel materials. Furthermore, these properties are strong functions of temperature, but also are significantly affected by the atmosphere and time. (Burnup, irradiation temperature, and grain size of the fuel are also known to affect releases, but to lesser extents.) For example, the most volatile fission-products – krypton, iodine, and cesium – are released almost totally at the highest temperatures, with little effect of atmosphere; but the releases of fission products such as strontium, molybdenum, ruthenium, tellurium, antimony, barium, and europium are quite sensitive to atmosphere.

Oxidation of the fuel may be a fission product release mechanism in severe accidents if the pressure vessel or containment are breached. This mechanism becomes significant, for example, if fission products escape from finely divided fuel droplets that are formed as the result of a steam explosion. The release is due to extensive oxidation of the droplets upon

their dispersal into an air atmosphere. Additionally, burning of either a metallic fuel or of a lower oxide greatly enhances fission-product release by increase of the exposed surface area by many orders of magnitude, as well as by local overheating and gas expulsion. Any solid material, when heated to a temperature sufficient to induce surface oxidation, will disperse a small quantity of fine particles to the atmosphere. At temperatures approaching the melting, ignition, or boiling point of the material, the process is accelerated.

It should be recognized that thermodynamic data apply, strictly speaking, only to equilibrium conditions, which seldom, if ever, exist in reactor accidents. Consequently, it is necessary to be cautious in the use of such data to predict the behavior of fission products under accident conditions. However, it appears probable that, at elevated temperatures resulting from loss-of-coolant accidents in reactors fueled with high-melting materials, equilibrium will be at least approached, so that conclusions based on thermodynamic considerations are of some value.

It is not within the scope of this dissertation to rigorously model the release mechanisms summarized above. Rather, this chapter of the dissertation will attempt to shed some light on Chornobyl radioisotope release dynamics by clearing up inconsistencies in previously published (Soviet) release data and source term estimates. A new, more precise core inventory is presented as well as a review of previous source term estimates. New release data is then presented and together with previously published data are appraised for their reliability. Finally, the new data is analyzed to produce release curves over the period of the Active Phase, and a new source term estimate is presented.

Although the core inventory calculation is presented in the next section, for reference Tables VI.1 & VI.2 below present volatility characteristics of the more significant isotopes and compounds that may have formed during the period of the Active Phase, as well as their respective initial core inventory estimates. Note that these isotopes were chosen not only on the basis of their release data availability, but also based on their quantities, biological toxicities, and significance to the volatility grouping.

Table VI.1

Partial Core Inventory at t = 0, and Radionuclide Grouping by Elemental Volatility

Volatility Class		Group / Radionuclide	Core Inventory at t = 0 (Bq e+18)[a]	Half-life[b]	Melting Point (°C)[c]	Boiling Point (°C)[c]
I. Inert		**A. Noble Gases**				
	G	Krypton-88	3.102	2.84 h	-157.37	-153.23
	G	Xenon-133	6.501	5.245 d	-111.76	-108.00
	G	Xenon-135	6.673	9.104 h		
	G	Xenon-138	6.536	14.08 m		
II. Volatile		**B. Halogens**				
	S3	Iodine-129		1.574 e+07 y	113.5	184.3
	S3	Iodine-131	3.079	8.04 d		
	S3	Iodine-132	4.478	2.284 h		
	S3	Iodine-133	6.696	20.8 h		
	S3	Iodine-134	7.692	52.6 m		
		C. Alkali Metals				
	S2	Rubidium-86	1.660	18.66 d	39.48	688
	S2	Rubidium-88	3.102	17.8 m		
	S2	Cesium-134	0.170	2.062 y	28.39	671
	S2	Cesium-136	6.253	13.16 d		
	S2	Cesium-137	0.259	30.0 y		
	S2	Cesium-138	6.549	32.2 m		
	S2	Cesium-139	6.179	9.27 m		
		D. Tellurium Group				
	S3	Tellurium-129m	1.039	33.6 d	449.57	988
	S3	Tellurium-132	4.487	78.03 h		
	S3	Tellurium-134	7.692	41.8 m		
III. Nonvolatile		**E. Alkaline Earths**				
(mod-volatile)	(S1)	Strontium-89	3.949	50.55 d	769	1382
(mod-volatile)	(S1)	Strontium-90	0.228	28.5 y		
(mod-volatile)	(S1)	Strontium-92	5.265	2.71 h		
(mod-volatile)	(S1)	Strontium-93	5.769	7.4 m		
(mod-volatile)	(S1)	Barium-139	6.169	84.6 m	729	1805
(mod-volatile)	(S1)	Barium-140	6.055	12.746 d		
		F. Noble Metals (Volatile Oxides – Ru-group)				
(Refr. Metal)	S2	Molybdenum-99	6.089	65.76 h	2623	4639
(Refr. Metal)	S2	Molybdenum-101	5.963	14.6 m		
(Refr. Metal)	S2	Technetium-99m	5.402	6.01 h	2204	4265
(Refr. Metal)	S2	Technetium-101	5.963	14.2 m		
(Refr. Metal)	S2	Ruthenium-103	3.774	39.25 d	2334	4150
(Refr. Metal)	S2	Ruthenium-106	0.860	372.56 d		
	S2	Rhodium-103m	3.774	56.12 m	1963	3697
	S2	Rhodium-105	1.980	35.26 h		
	S2	Rhodium-106	0.710	29.8 s		

a As calculated by in sections VI.2.2. ahead.

b Edgardo Browne and Richard B. Firestone, *Table of Radioactive Isotopes*, Edited by Virginia S. Shirley, New York: John Wiley & Sons, 1986.

c *CRC Handbook of Chemistry and Physics, 1991–1992*, **4**-122 – **4**-123.

Volatility Class		Group / Radionuclide	Core Inventory at t = 0 (Bq e+18)	Half-life	Melting Point (°C)	Boiling Point (°C)
III. Nonvolatile		**G. Rare Earths (La-group)**				
	S1	Yttrium-90	0.227	63.93 h	1522	3338
	S1	Yttrium-91	4.933	58.51 d		
	S1	Yttrium-92	5.265	3.54 h		
	S1	Yttrium-93	5.769	10.25 h		
	S1	Lanthanum-140	6.055	40.16 h	918	3464
	S1	Lanthanum-141	5.643	3.93 h		
	S1	Lanthanum-142	5.631	92.52 m		
(Refr. Oxide)	S1	Cerium-141	5.540	32.5 d	798	3443
(Refr. Oxide)	S1	Cerium-143	5.551	32.91 h		
(Refr. Oxide)	S1	Cerium-144	3.903	284.9 d		
	S1	Praseodymium-143	5.540	13.58 d	931	3520
	S1	Praseodymium-144	3.846	17.28 m		
	S1	Neodymium-147	2.163	10.98 d	1021	3074
	S1	Promethium-148m	1.614	41.29 d	1042	3000
	S1	Europium-154	0.014	8.8 y	822	1527
	S1	Europium-155	0.011	4.96 y		
		H. Refractory Oxides				
	S1	Zirconium-95	5.837	64.02 d	1855	4409
(Volatile Oxide)	S2	Niobium-95	5.677	34.97 d	2469	4744
(Volatile Oxide)	S2	Niobium-96	5.952	23.35 h		
(Volatile Oxide)	S2	Niobium-97	5.757	72.12 m		
		I. Transuranics				
(Refr. Oxide)		Neptunium-237	2.620 e-07	2.14 e+06 y	639	3902
(Refr. Oxide)		Neptunium-239	58.00	2.355 d		
(Refr. Oxide)	S2	Plutonium-236	1.140 e-07	2.851 d	640	3230
(Refr. Oxide)	S2	Plutonium-238	1.300 e-03	87.74 y		
(Refr. Oxide)	S2	Plutonium-239	9.480 e-04	24,110 y		
(Refr. Oxide)	S2	Plutonium-240	1.480 e-03	6,563 y		
(Refr. Oxide)	S2	Plutonium-241	0.183	14.4 y		
(Refr. Oxide)	S2	Plutonium-242	2.880 e-06	376,300 y		
	S2	Americium-241	1.650 e-04	432.7 y	1176	2607
	S2	Americium-243	9.690 e-06	7,380 y		
	S2	Curium-242	0.043	162.94 d	1345	–
	S2	Curium-244	4.270 e-04	18.11 y		

KEY

- **Shaded radionuclides** have release data available – see section VI.3. ahead.
- **G** = Gaseous includes all noble gases – considered extremely volatile
- **S 1** = Solid – Zr, Y, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Np
  form more stable oxides than UO_2; their oxides are soluable in fuel matrix; group sometimes includes Ba & Sr that form insoluable zirconates $BaZr0_3$ & $SrZrO_3$
- **S 2** = Solid – Ge, As, Nb, Mo, Tc, Ru, Rh, Cs, Rb, Pd, Ag, Cd, In, Sn, Sb
  either form less stable oxides than UO_2 (volatile at fuel operating temperture) or readily react to form ionic compounds; major portion reduce to elemental state and percipitate out of fuel matrix to form metallic inclusions; Cs & Rb are chemically reactive but their oxides are unstable and dissociate above 650°C into elemental forms
- **S 3** = Solid – Br (liquid), I, Te, Se – considered volatile metals
- **NOTE** I (S3) and Cs, Mo, Ru (S2) migrate against the temperature gradient
  Refractory Metals have very high elemental boiling points; oxidize rapidly because their oxides are not refractory (i.e., their oxides have a relatively low melting points)
  Refractory Oxides in elemenatal form are not themselves refractory (i.e., have lower melting temperatures), but their oxides are stable and have a high melting temperatures.

Table VI.2[3]

Basic Chemical Compound Volatility Data for
Radioisotopes with Release Data for the Chornobyl Accident

Isotope	Core Inventory at t = 0 (Bq e 18)	Half-life	Half-life (sec)	GMM	Elemental M.P. (°C)	Elemental B.P. (°C)	Oxide Compound	Oxide M.P. (°C)	Oxide B.P. (°C)
I-131	3.079	8.01 days	6.93 e 5	130.9061	113.5	184.3	IO_2, IO_4, (CsI)	d 75–130 (626)	—, (1280)
I-132	4.478	2.284 hours	8.22 e 3	131.9080	113.5	184.3	IO_2, IO_4, (CsI)	d 75–130 (626)	—, (1280)
Te-132	1.039	78.03 hours	2.81 e 5	131.9085	449.57	988	TeO, TeO_2	d 370, 733	d, 1245
Cs-134	0.170	2.062 years	6.51 e 7	133.9068	28.39	671	Cs_2O, Cs_2O_2	>400, 400	—, 650 -O_2
Cs-136	6.253	13.16 days	1.13 e 6	135.9073	28.39	671	Cs_2O, Cs_2O_2	>400, 400	—, 650 -O_2
Cs-137	0.259	30.0 years	9.47 e 8	136.9068	28.39	671	Cs_2O, Cs_2O_2	>400, 400	—, 650 -O_2
Ru-103	3.774	39.25 days	3.38 e 6	102.9063	2334	4150	RuO_2, RuO_4	d, 25.5	—, d 108
Ru-106	0.860	372.56 days	3.21 e 7	105.9073	2334	4150	RuO_2, RuO_4	d, 25.5	—, d 108
Mo-99	6.089	65.76 hours	2.37 e 5	98.9077	2623	4639	MoO_2, Mo_2O_5	6.47, —	—, —
Zr-95	5.837	64.02 days	5.52 e 6	94.9080	1855	4409	ZrO_2	*ca* 2700	*ca* 5000
Nb-95	5.677	34.97 days	3.01 e 6	94.9068	2469	4744	NbO_2, Nb_2O_5	—, 1520	—, —
Ba-140	6.055	12.746 days	1.10 e 6	139.9106	729	1805	BaO, BaO_2	1918, 450	*ca* 2000, 800 -O
La-140	6.055	40.16 hours	1.45 e 5	139.9094	918	3464	La_2O_3	2307	4200
Ce-141	5.540	32.5 days	2.80 e 6	140.9082	798	3443	Ce_2O_3, CeO_2	1692, 2600	—, —
Ce-144	3.903	284.9 days	2.45 e 7	143.9136	798	3443	Ce_2O_3, CeO_2	1692, 2600	—, —
Nd-147	2.163	10.98 days	8.46 e 5	146.9161	1021	3074	Nd_2O_3	≈ 1900	—
Np-239	58.000	2.355 days	2.03 e 5	239.0529	639	3902	NpO_2, Np_3O_3	—, d 500	—, —

[3] *CRC Handbook of Chemistry and Physics, 1991–1992*, "The Elements and Inorganic Compounds."

VI.2. Chornobyl Unit-4 Core Inventory Estimates

VI.2.1. Review of Previous Core Inventory Estimates

Ever since the Chornobyl accident, a number of studies have attempted to calculate the fission product and transuranic inventory of Chornobyl Unit-4 just prior to the explosion(s) that destroyed the reactor. Although in general these estimates agree with each other, a number of significant differences arise with respect to several biologically important transuranic isotopes. A brief explanation of the calculational basis for each estimate is followed by Table VI.4, which presents core inventories for forty-one isotopes estimated in earlier studies compared to the estimate for this dissertation; and following this, Figures VI.1 & V1.2 present the calculated total core fission product and transuranic inventory as a function of time.

At the IAEA Meeting of Experts in Vienna in August 1986, the Soviet delegation did not directly provide a core inventory but instead supplied isotope release amounts as a fraction of total core inventory relative to May 6 (i.e., ten days after the initial explosions and the end of the Active Phase) as well as core average burnup of 10.3 GW·d/t U.[7] From this information it is possible to directly calculate the core inventory just prior to the accident by considering radioactive decay only. Warman calculates this[8] and the results are presented in the column labeled "IAEA 1986" in Table VI.4.

In 1990, the Nuclear Society of the (former) USSR republished the inventory data presented at Vienna corrected to April 26.[9] Although generally the results for "NS USSR 1986" agree quite well with Warman's results, it is puzzling that there is any difference at all considering the same source is used. Assuming this data is calculated by simple decay schemes back to the beginning of the accident, there should be no difference. The only

---

[7] U.S.S.R. State Committee on the Utilization of Atomic Energy (comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Parts I & II: General Material and Appendices*, report presented at the International Atomic Energy Agency Expert's Meeting, August 25–29, 1986, Vienna.

[8] Edward A. Warman, "Soviet and Far-Field Radiation Measurements and an Inferred Source Term From Chornobyl," Presented at the *New York Chapter Health Physics Society Symposium on the Effects of the Nuclear Reactor Accident at Chornobyl*, April 3, 1987, Brookhaven National Laboratory, New York.

[9] As presented in И. И. Крышев, Радиоэкологические последствия чернобыльской аварии, Серия "Радиоэкологические аспекты ядерной энергетики," Москва: Ядерное Общество СССР, 1991: 9.

added information given in the Nuclear Society's information is that the greater part of the fuel assemblies had a burnup of 12–14 GW·d/t U at the time of the accident, with a core-averaged burnup of 10.9 GW·d/t U. (This was obtained from the "Borovoi 1990" calculations explained below.)

An interesting approach to estimate the core inventory was taken by Kirchner and Noack.[10] Because at the time of their article detailed burnup information and irradiation history of the reactor core prior to the accident were not available, they based their calculations on a comparison of activity ratios for five isotopes (Cs-134/Cs-137; Cs-136/Cs-137; Te-129/Te-132) detected in hot particle fallout near Munich, Germany. These ratios yielded a core averaged burnup of 12.85 ± 0.15 GW·d/t U at the time of the accident. Besides the fact that the use of an average core burnup introduces some error in calculated concentrations of nuclides that do not build up linearly with fuel depletion (among other problems), by not considering hot particle samples other than from those collected near Munich, the authors' estimates yielded a value of 722 equivalent-full-power days (the correct value is 715 days) indicating core shutdown between April 20 and April 22. (As stated in the article, Devell et al.[11] estimate a correct shutdown date on late April 25 based on I-133/I-131 ratios observed in Sweden.) The authors, however, maintain that this results in an uncertainty in the calculated fuel inventory of less than 20%. The one-dimensional cell-based code system SAS 2(UHB)/ORIGEN-S(UHB) was used for fuel inventory calculations. Results of their estimates are given in column "Kirchner... 1988."

Column "Borovoi... 1989," although providing initial core inventories for only seven isotopes, is nevertheless significant because it is the first openly published core inventory estimate by the Soviets (albeit in "preprint" form) following the Vienna meeting.[12] (In the

---

[10] Gerald Kirchner and Cornelius C. Noack, "Core History and Nuclide Inventory of the Chernobyl Core at the Time of Accident," *Nuclear Safety*, Vol. 29, No. 1 (January–March 1988): 4.

[11] L. Devell, H. Tovedal, U. Bergström, A. Appelgren, J. Chyssler, and L. Andersson, "Initial Observations of Fallout fom the Reactor Accident at Chornobyl," *Nature*, 321(May 15, 1986):192-193.

[12] Alexandr Alexandrovich Borovoi, "Fission Product and Transuranic Element Release During Chernobyl Accident" (preprint), Presented at *The International Conference "The Fission of Nuclei – 50 Years," Leningrad, USSR, October 16–20, 1989*, Chornobyl, Ukraine: The Chornobyl Complex Expedition of the I. V. Kurchatov Institute of Atomic Energy, 1990: 3.

summer of 1989 the USSR Ministry of Atomic Energy and Industry declared all Chornobyl data open for publication.) For this calculation the author assumes a core averaged burnup in the range of 11–17 GW·d/t U at the time of the accident and states the reactor operated for 715 equivalent-full-power days.

The next column, "Borovoi... 1990," presents the results of more refined core inventory calculation.[13] Most of the fuel assemblies (approximately 75%) had a burnup in the range of 12–14 GW·d/t U, and burnup values for all assemblies ranged widely from 4.4 to 14.8 GW·d/t U. The core average burnup (implicitly taking into account the core's 1.48 radial peak-to-average power ratio) is 10.9 GW·d/t U as first calculated in Begichev et al.[14] and obtained from the following "group" or "zone" burnup averages in the core:

Table VI.3

Chornobyl Unit-4 Fuel Assembly Group-Averaged Burnups

Fuel Assembly Group	Number of Fuel Assemblies	Group-Average Burnup (GW·d/t U)
1	721	13.7
2	392	12.3
3	154	10.5
4	101	8.8
5	35	7.0
6	43	5.4
7	41	3.5
8	172	1.2
Total / Average	1659	10.9

[13] С. Н. Бегичев, А. А. Боровой, Е. В. Бурлаков, С. Л. Гаврилов, А. А. Довбенко, Л. А. Левина, В. М. Мар-кушев, А. Е. Марченко, А. А. Строганов, А. Л. Татуров, "Топливо Реактора 4-го Блока ЧАЭС," (Припринт ИАЭ-5268/3), Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990. See also A. A. Boro-voj, *Post-Accident Management of Destroyed Fuel From Chernobyl: Technologies Used and Lessons Learned*, Chornobyl, Ukraine and Moscow, Russia: International Atomic Energy Agency, 1990: 6.

[14] S. N. Begichev, A. A. Borovoi, E. V. Burlakov, A. Ju. Gagrinsky, V. F. Demin, I. L. Khodakovsky, and A. A. Khrulev, "Radioactive Releases Due to the Chornobyl Accident," *Presented at the International Seminar on Fission Product Transport Processes in Reactor Accidents*, May 22 – 26, 1989, Dubrovnik, Yugoslavia.

Interestingly, although this more accurate core-average burnup data is provided, it is not used in the core inventory calculation. Instead, codes WIMS and CACH2 were used to supply radioisotope burnup production rates to calculate amounts of fission products individually in each of the 1659 fuel assemblies in the core at the time of the accident. (Burnup data for each individual channel became available at that time – see next section.) The calculations for most of the fission products assumed an average burnup for each fuel assembly. However, in the case of such short-lived isotopes as Ce-144, core operating history prior to the accident was considered.

Finally, column "Current 1993" in Table VI.4 (see also Figures VI.1 & VI.2) presents estimates from more refined calculations for this dissertation (see Section VI.2.2.2. "Computational Basis..." ahead). In this case the significant non-linear accumulation of transuranics (actinides) as a function of burnup was considered in more detail by taking into account the core's 1.40 axial peak-to-average power ratio. In addition, rather than simply assuming a time averaged burnup over the operating period of the reactor core, consideration was given to the burnup history for all fission products and transuranics prior to the accident to more precisely calculate radioisotope production as a function of burnup history. (Kirchner and Noack above, estimated this time-dependent burnup by taking into account the ratio of the short-live fission products Te-129/Te-132 which is affected both by short-term power changes and by the power level in the few months before the accident.) Most notable about these results is that the inventory of transuranics is significantly higher than the previous estimate – in the case of Cm-244 by a factor of approximately 2.4.

In general, the published estimates of core inventories reviewed here agree quite well. Some notable exceptions, however, are Sr-89 (up to one and one-half orders of magnitude difference), Ru-103 and Ru-106 (up to a factor of two), and the transuranics Np-239, Am-243, Cm-242, Cm-244 as discussed above.

Table VI.4
Core Inventory Estimates (Ci) for Chornobyl Unit-4 at the Time of the Accident

Isotope	IAEA 1986(87)	NS USSR 1986(91)	Kirchner... 1988	Borovoi 1989	Begichev... 1990	Current 1993
H-3			3.9 e+04		3.8 e+04	
C-14			2.7 e+03		2.7 e+03	
Kr-85	8.9 e+05	9.0 e+05				7.55 e+05
Sr-89	6.2 e+06	6.3 e+07	9.3 e+07			1.07 e+08
Sr-90	5.4 e+06	6.0 e+06	6.2 e+06	6.0 e+06	6.158 e+06	6.16 e+06
Zr-95	1.4 e+08	1.3 e+08	1.5 e+08			1.58 e+08
Nb-95						1.53 e+08
Mo-99	2.0 e+09	1.6 e+08				1.65 e+08
Ru-103	1.3 e+08	1.3 e+08	1.3 e+08			1.02 e+08
Ru-106	5.4 e+07	6.0 e+07	3.4 e+07		2.32 e+07	2.32 e+07
Ag-110m		5.0 e+05				3.59 e+04
Sb-125		7.0 e+05			5.19 e+05	3.99 e+05
Te-132	9.0 e+07	7.3 e+07	5.7 e+07			1.21 e+08
I-129			2.2 e+00		2.2 e+00	
I-131	8.5 e+07	8.6 e+07	6.7 e+07			8.32 e+07
I-132						1.21 e+08
Xe-133	2.0 e+08	1.7 e+08				1.76 e+08
Cs-134	5.0 e+06	4.0 e+06	4.2 e+06	4.0 e+06	4.138 e+06	4.60 e+06
Cs-136			2.2 e+06			1.69 e+08
Cs-137	7.8 e+06	7.7 e+06	8.2 e+06	7.0 e+06	7.020 e+06	7.01 e+06
Cs-138						1.77 e+08
Ba-140	1.4 e+08	1.4 e+08	1.3 e+08			1.64 e+08
La-140			1.5 e+08			1.64 e+08
Ce-141	1.5 e+08	1.5 e+08				1.50 e+08
Ce-144	8.6 e+07	9.0 e+07	1.1 e+08		1.06 e+08	1.06 e+08
Nd-147						5.85 e+07
Eu-154			2.4 e+05			3.71 e+05
U-235			2.6 e+00			
U-236			2.3 e+01			
U-238			6.2 e+01			
Np-237			6.2 e+00		7.083 e+00	7.08 e+00
Np-239	9.8 e+07	7.2 e+08	5.7 e+08		1.567 e+09	1.57 e+09
Pu-236					3.093 e+00	3.08 e+00
Pu-238	2.7 e+04	2.7 e+04	2.2 e+04		2.534 e+04	3.51 e+04
Pu-239	2.3 e+04	2.3 e+04	2.4 e+04	2.6 e+04	2.562 e+04	2.56 e+04
Pu-240	3.2 e+05	3.3 e+04	5.0 e+04	4.0 e+04	4.005 e+04	4.00 e+04
Pu-241	4.6 e+06	4.7 e+06	5.7 e+06	5.0 e+06	4.958 e+06	4.95 e+06
Pu-242		6.7 e+01	6.7 e+01	5.5 e+01	5.57 e+01	7.78 e+01
Am-241			4.3 e+03		3.712 e+03	4.46 e+03
Am-243			1.7 e+02		1.455 e+02	2.62 e+02
Cm-242	7.0 e+05	7.0 e+05	9.8 e+05		8.32 e+05	1.17 e+06
Cm-244			4.9 e+03		4.807 e+03	1.15 e+04

Figure VI.1
Total Calculated Core Fission Product and Transuranic Inventory
and Specific Heat Generation Rate

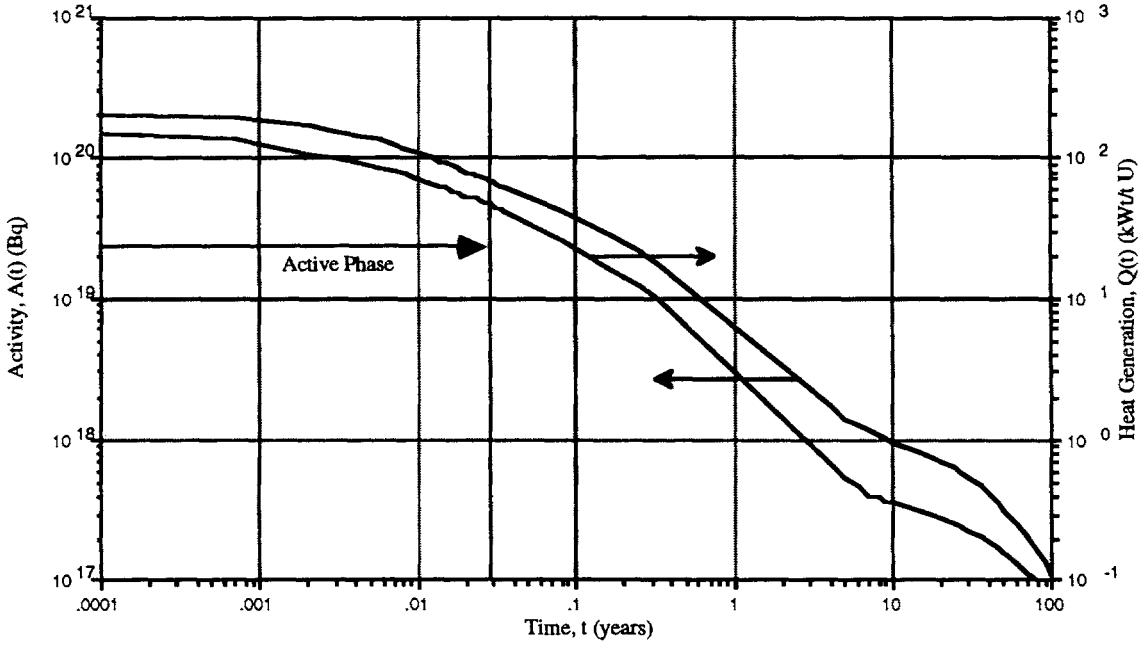
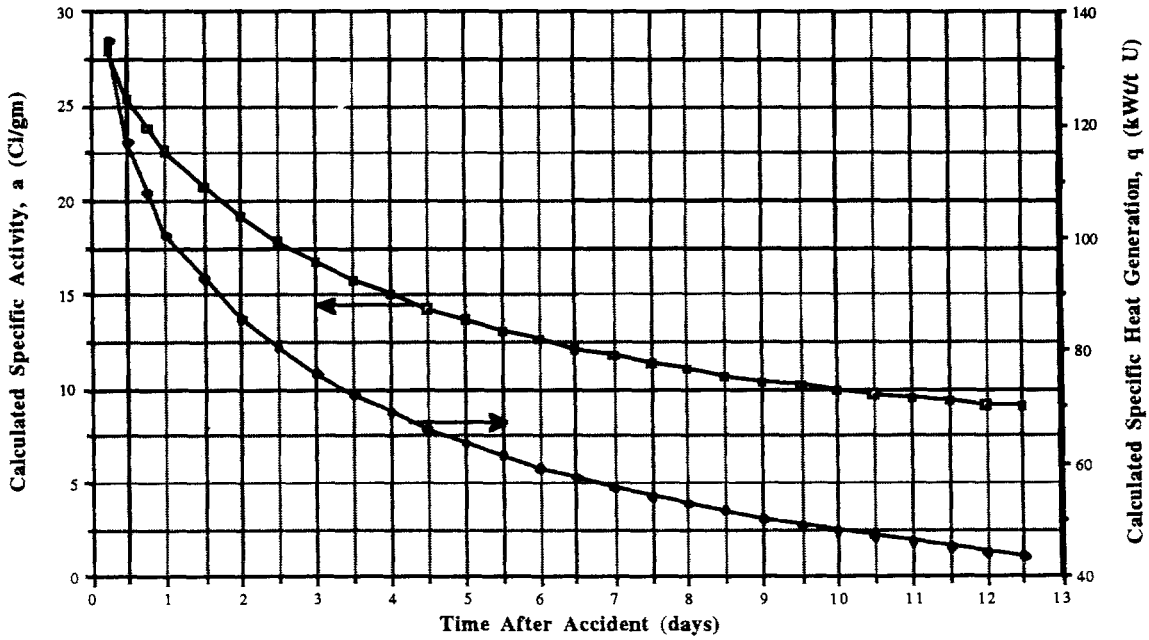


Figure VI.2
Calculated Specific Activity and Heat Generation
Over the Period of the Active Phase



VI.2.2. Chornobyl Unit-4 Core Inventory Calculation

VI.2.2.1. State of the Unit-4 Core Just Prior to the Accident.

Unit-4 of the Chornobyl Nuclear Power Station achieved criticality on 13 December 1983. Just prior to the accident it operated for 865 calendar days and 715 effective full-power days (82.7% load factor over the reactor's first cycle.) At the time of the accident, 1659 of the core's 1661 "technological channels" (core pressure tubes or "channels") contained fuel assemblies (two 3.5m "fuel cassettes" stacked one on top of the other); one technological channel did not contain fuel but only circulating water coolant; and one contained a auxiliary absorber assembly. The initial mass of UO_2 in each fuel channel was 114.7 kg for a total core fuel load of 190.3 tonnes UO_2. A large fraction of the fuel (more than 75%) had a burnup between 12 and 15 GW·d/kg U (burnup values for all assemblies ranged widely from 4.4 to 14.8 GW·d/kg U; and the core average burnup was approximately 10,900 MW·d/t U.† Appendix VI.A provides average burnup values for each of the 1659 fuel channels just prior to the accident. Results of calculations for 65 radioisotopes are provided in Appendix VI.B, while Table VI.4 above provides an abbreviated listing.

VI.2.2.2. Computational Basis for Estimating the Core Inventory.

An equivalent cylinderical cell geometry for the RBMK-1000 core lattice representing a "technological fuel channel" (graphite moderator, light water coolant, pressure tube, and fuel assembly) consisting of nine zones was employed in calculations to determine the core inventory just prior to the accident. Inasmuch as the RBMK is a boiling water reactor, the density of the coolant varies substantially with distance along the flow path in the core. For this reason, the equivalent cell has been divided into three vertical sections of equal length, and each section assigned an average coolant density along that length. Table VI.5 below presents dimensions, densities, and material content of the equivalent cell used in the calculations; while Figure VI.3 presents a schematic of the equivalent cell.

† Nominal discharge burnup for 2.0% enriched RBMK-1000 fuel is approximately 20 GW·d/t U.

Codes WIMS and CACH2 were used to supply radioisotope burnup production rates to calculate amounts of fission products individually in each of the 1659 fuel assemblies in the core at the time of the accident.[15] The significant non-linear accumulation of transuranics (actinides) as a function of burnup was considered in detail by taking into account the core's 1.40 axial peak-to-average power ratio. In addition, rather than simply assuming a time-averaged burnup over the operating period of the reactor core, consideration was given to the burnup history for all fission products and transuranics prior to the accident to more precisely calculate radioisotope production.

---

[15] Fuel channel (average) burnup data for each individual channel are presented in Appendix VI.A as taken from Панитков, et al, *Отчёт о научно-исследовательской работе: Восстановление динамики разрушения 4-го блока ЧАЭС на основе физического и математического моделирования: Разработка физической модели чернобыльской катастрофы,* Минск: Академия Наук Беларуси, (1991): 28.

The chapter entitled "Attributes of the Initial Conditions of the Accident" has quite a bit of information on the initial state of the reactor just prior to the accident. Among other information, it includes the initial core loading and mapping, radial neutron flux mapping, vertical positions of control assemblies, main coolant pump parameters, axial flux variation in several channels, flow rates through each reactor channel, steam-drum separator parameters. The goal of this internally published report was to model the forces that destroyed the reactor.

Table VI.5[16]
RBMK-1000 Equivalent Cell Dimensions and Material Concentrations

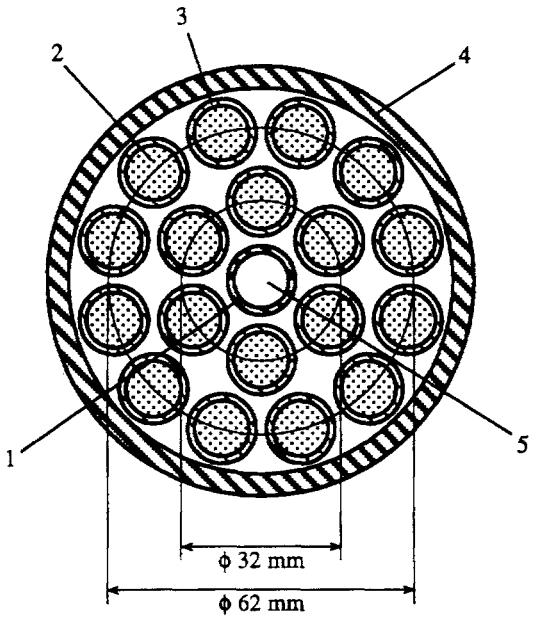
Zone	Outer Radius (cm)	Material	Material Concentration in Zone at Given Coolant Density (x 10e24 cm^{-3})		
			0.25 gm/cm^3	0.41 gm/cm^3	0.68 gm/cm^3
1	0.750	Zircaloy-2.5	4.16e-04	4.16e-04	4.16e-04
2	1.165	H O	1.67e-02 8.37e-03	2.74e-02 1.37e-02	4.55e-02 2.28e-02
3	2.035	U-235 U-238 Zircaloy-1 O	3.01e-04 1.48e-02 1.89e-02 3.01e-02		
4	2.651	H O	1.67e-02 8.37e-03	2.74e-02 1.37e-02	4.55e-02 2.28e-02
5	3.550	U-235 U-238 Zircaloy-1 O	3.01e-04 1.47e-02 1.90e-02 3.01e-02		
6	3.980	H O	1.67e-02 8.37e-03	2.74e-02 1.37e-02	4.55e-02 2.28e-02
7	4.400	Zircaloy-2.5	4.16e-02		
8	5.975	C	8.51e-02		
9	14.105	C	8.51e-02		

Notes: (1) The equivalent cell can only be used for calculating certain reactor physics parameters of the core (cross sections, resonance integrals, hardness of the neutron spectrum, etc.), which determine fuel burnup. The equivalent cell cannot be used for core criticality calculations.
(2) Zones 1 and 7 correspond to the Zircaloy-2.5 pressure tube.
(2) Zones 2, 4, and 6 correspond to the light water coolant.
(3) Zones 3 (inner) and 5 (peripheral) represent two rings of homogeneously distributed fuel rod materials (Zircaloy-1 and fuel) corresponding to the inner and peripheral fuel rods as seen in the assembly cross section of Figure VI.2.
(4) The two zones 8 and 9 are given for the graphite moderator to permit temperature changes across in the cell to be taken into account.

[16] А. С. Герасимов, Т. С. Зарицкая, А. П. Рудик, *Справочник по образованию нуклидов в ядерных реакторах*, (Москва: Энергоатомиздат, 1989), 145.

Figure VI.3

Schematic Representation of an RBMK-1000 Technological (Fueled) Channel



1 – Central support rod and instrumentation guide, composed of Zr-2.5% Nb.

2 – UO_2 fuel.

3 – Fuel rod, composed of Zr-1.0% Nb.

4 – Technological Channel Pressure Tube, composed of Zr-2.5% Nb.

5 – Instrumentation guide – empty space.

VI.3. Source Term Releases

As opposed to core inventory estimates, there is more controversy and disagreement surrounding widely ranging fission product release estimates.[17] This is partly due to the fact that the effectiveness of accident management actions during the Active Phase (as discussed in IV.3.) was not properly clarified from the beginning. Moreover, the widely ranging estimates are also due to the generally unrefined and sketchy data presented in Vienna by the Soviets.† Finally, the fact that some release data was suppressed until ap-

[17] See, for example, the 100% of core inventory radioiodine release estimate in an unpublished paper cited in D. A. Powers, "Carburization as a Mechanism for the Release of Radionuclides During the Chernobyl Accident," In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, Moscow, Russia: Nauka , 117.

† "There were many organizations which collected data about environmental contamination in [the] control zone, especially during the months after [the] accident. Some thousands [of] samples were collected, but differences in methodics of sample analyzing, uncoordination in methodics of sample preparation and description, absence of special data management systems and data filtration systems lead to low effective

proximately 1989–90 did not provide a complete picture of how much contamination was deposited on the territory of the former Soviet Union. It was suspected quite early (see Warman below, for example) that the Soviets, based on the way information was presented in Vienna, had not provided a full accounting of releases from the destroyed reactor. Only now, as new release data and analyses of fuel masses remaining within the sarcophagus are being made available, is it clear that earlier western suspicions were justified.

VI.3.1. Review of Previous Source Term Estimates

For ease in comparison, Soviet total release data for twenty-three radioisotopes presented in Vienna is reproduced below in Table VI.6 below. Note that, according to the Soviets, there is a 50% error associated with this data which they attribute to dosimeter measurement error, errors in isotopic composition analyses of air and ground samples, and error in averaging fallout over a large area. Note further that these integrated release fractions are inconsistent with expectations based on relative elemental vapor pressures of the various radioisotopes.† In addition, the Soviets in their Vienna report stated that,

> "According to an analysis of *Goskomgidromet's** aerial gamma-ray photography, beyond the limits of the special zone, the activity of the radionuclides settling on the ground was 10–30 MCi. It follows from an analysis of the data that the *total activity* of the radionuclides released from the disabled reactor to the environment does not exceed 50 MCi, i.e., it represents approximately 3–4% of the total activity of the fission products in the reactor of the fourth unit of the Chornobyl plant on 6 May 1986."[18] [emphasis added]

---

using of information. *There were no possibility to estimate reliability of [the] information.*" (emphasis added) [Borovoi, "Fission Product and Transuranic Element Release...," 8.]

† It will be shown later, based on the review of Accident Management Actions in Chapter 4, on an appraisal of Soviet data-gathering techniques, and on consistency checks of the Soviet data, that Soviet estimates are inaccurate.

* *Goskomgidromet* – State Committee for Hydro-Meteorology.

[18] USSR State Committee, Part II, Appendix 1.

Table VI.6[19]

Radioisotope Release Composition from Unit-4 According to the Soviet's Vienna Report

Isotope	Core Activity Release (%) up to May 6	Isotope	Core Activity Release (%) up to May 6
Xe-133	~ 100	Ce-141	2.3
Kr-85m	~ 100	Ce-144	2.8
Kr-85	~ 100	Sr-89	4.0
I-131	20	Sr-90	4.0
Te-132	15	Np-239	3.2
Cs-134	10	Pu-238	3.0
Cs-137	13	Pu-239	3.0
Mo-99	2.3	Pu-240	3.0
Zr-95	3.2	Pu-241	3.0
Ru-103	2.9	Pu-242	3.0
Ru-106	2.9	Cm-242	3.0
Ba-140	5.6		

In January 1987, the US Nuclear Regulatory Commission published their report on the accident, NUREG-1250, in which they presented far-field release estimates from various countries. This information is summarized for several of the more volatile radioisotopes in Table VI.7 below. Note the wide range in these estimates, especially for the cases of iodine and cesium.

Table VI.7[20]

Far-Field Estimates of Chornobyl Unit-4 Releases (% of Initial Core Inventory)

Element	British	French	Canadian	U.S. LLNL†	U.S. NRC
Noble Gases	large	–	–	50 – 100	100
Iodine	15 – 20	–	75	12 – 60 I-131	20
Cesium	15 – 20	20	16	14 – 86 Cs-137	20
Tellurium	small	7	–	–	3
Ruthenium	1	1 – 2	–	–	0.3 – 0.4
Strontium	small	–	16	0.01 – 1.1 Sr-90	–
Barium	small	–	–	–	0.4 – 0.7
Lanthanum	small	0.01 – 0.04	–	–	0.06 – 0.2
Neptunium	small	0.02 – 0.04	–	–	0.04 – 0.1

† The LLNL figures were originally given as release activity (MCi). For this table they have been converted to a per-centage of the newly-calculated core inventory presented in Table 1.

[19] USSR State Committee, Part II, Appendix 4, 21.

[20] U. S. Nuclear Regulatory Commission, comp, *Report on the Accident at the Chornobyl Nuclear Power Station* (NUREG-1250), Washington, DC: U.S. Government Printing Office (1987): 6-12.

In April 1987, Warman maintained that the source term estimates reported by the Soviets in Vienna taken alone were not sufficient to characterize volatile fission product releases and concluded that an adequate characterization can be obtained only if the data representing releases within and outside the former Soviet Union are summed.[21] The study bases its conclusions on Soviet measurements, satellite photos analyses of ground deposition in the near field, and Cs-137 isotopic ratios of hot particles analyzed in central and western Europe. Its preliminary estimate for releases from the accident are shown in Table VI.8. Note that the Soviets that same year published a revised figure for Cs-137 fallout onto the territory of the former Soviet Union of 0.8 MCi (11.4% of the initial Cs-137 inventory).[22]

Table VI.8[23]

Warman Composite Source-Term Estimates for the Chornobyl Accident
(% of Initial Core Inventory)

Group	European part of USSR	Central & Western Europe	Northern Hemisphere	Total
radiocesium	13	13	<10	30 – 50
radioiodine	20	20	20	40 – 60
radiotellurium	13	13	<10	30 – 50
non-volatiles	3.5 – 4.0	≤ 0.5	~ 0	≤ 4
noble gases	–	–	–	100

A 1988 UNSCEAR report bases its estimates on analyses of fallout in the northern hemisphere. It concludes that approximately 1.9 MCi (≈ 27% of the initial core inventory) of Cs-137 was released from the destroyed core. Of this amount, 42% (0.8 MCi) was deposited on the territory of the former Soviet Union, 37% (0.7 MCi) in western and central Europe, 6% (0.1 MCi) in the ocean, and 15% (0.3 MCi) in the balance of the northern

[21] Edward A. Warman, 1 (abstract).

[22] USSR State Committee of Hydrometeorology and Control of the Natural Environment, "Radioactive Contamination of the Environment in the Chornobyl Emergency Zone," Moscow, (1987).

[23] Edward A. Warman, 3.

hemisphere. The report further estimates that by May 6, 8.9 MCi (21.1 MCi corrected to April 26 or 25.3% of the initial core inventory) of I-131 was deposited in the northern hemisphere.[24] Also in 1988, a British researcher reported that 40% and 25% (33.3 MCi and 1.75 MCi) of the respective initial core inventories of I-131 and Cs-137 were released to the environment as a result of the Chornobyl accident.[25] Unfortunately, the author does not reference this data.

The first mention by the Soviets that more Cs-137 may have been released than reported at Vienna is by Borovoi in 1989. Almost as an aside, the total release of Cs-137 is estimated to be in the range of 1.5 – 2 MCi (21 – 29% of initial inventory), with 40% of this deposited on the territory of the former Soviet Union and 35% deposited in Europe.[26] The same author, in another publication two years later, increases the Cs-137 release estimate to 2.3 ± 0.7 MCi (33 ± 10%); and it is worth quoting the article at length here for purposes of the analysis,

> "... the release of Cesium-137 from rooms in the *lower* floors of the reactor [building] should be (3.3 ± 0.7) MCi or (47 ± 10)% of the total quantity accumulated in the reactor.
>
> A question arises – was this entire quantity of radioactive cesium released outside the [sarcophagus] and the power station site, or could some of this cesium have remained within and around the reactor building?
>
> Samples taken from the upper rooms in Unit-4 demonstrate a real cesium-137 enrichment. This enrichment varies significantly, but its mean concentration is 1.5 times greater than that of cerium. This number of 1.5 is confirmed by measurements made with a semiconductor gamma spectrometer when overflying the [sarcophagus] in [a] helicopter.
>
> If it is assumed that the radioactivity in the upper floors is equal to 1.5 times that in the cesium, this would mean that (2.3 ± 0.7) MCi or (33 ± 10)% of its original quantity would remain outside the [sarcophagus].
>
> There is no doubt that this estimate can be improved during future works on the [sarcophagus]."[27] [editorial corrections and emphasis added]

---

[24] UNSCEAR, "Sources, Effects, and Risks of Ionizing Radiation," Report to the General Assembly, United Nation, New York, 1988.

[25] P. N. Clough, "Source Terms and the Chernobyl Accident," *Nuclear Safety After Three Mile Island and Chernobyl*, Ed. G. M. Ballard, Elsevier Applied Science: London, (1988): 311.

[26] Borovoi, "Fission Product and Transuranic Element Release..., 7.

[27] Belyayev, Spartak T. and Alexandr A. Borovoi. "Radioactive Releases from the Chornobyl Nuclear Power Station Unit-4," in *Nuclear Accidents and The Future of Energy: Lessons Learned from Chernobyl: Proceedings of the International Conference in Paris, France, April 15–17, 1991*, by the European Nuclear Society (ENS). Paris, France: European Nuclear Society, (1991): 161.

In an article published in the British *Journal of Radiological Protection* in 1990, Ilyin provides a table of I-131 and Cs-137 contamination over the northern hemisphere. According to the article, the data in the table was derived "from Soviet and other data included in the UNSCEAR report."[28] However, it is unclear how this was done and to what date the data was referenced. Moreover, there appears to be an inconsistency in the I-131 figures as reported in this article – both compared to the UNSCEAR report and in expectations based on relative elemental vapor pressures, i.e., it is not immediately clear why a greater fraction of the more volatile I-131 remained within the bounds of the former Soviet Union as compared to the less volatile Cs-137. If the total release figures given are referenced to May 5th (the end of the Active Phase approximately 9.5 days after the accident), the release fractions of I-131 and Cs-137 are 48.4% and 27.1% respectively – more than twice that originally reported by the Soviets in Vienna. The article's data is summarized in Table VI.9.

Table VI.9[29]

Ilyin et al, I-131 and Cs-137 Chornobyl Unit-4 Release Estimates

Location	I-131 (%)	I-131 (MCi)	Cs-137 (%)	Cs-137 (MCi)
European part of USSR	65	11.1	42	0.80
Asian part of USSR	1	0.2	2	0.04
TOTAL USSR	*66*	*11.2*	*44*	*0.84*
Europe (excluding USSR)	28	4.8	38	0.72
Rest of the World	6	1.0	18	0.34
TOTAL (MCi)	(100%)	17.0	(100%)	1.9
TOTAL [26 Apr] (MCi)		38.6		1.9
Initial Core Inventory (MCi)		83.2		7.01
% Initial Core Inventory		46.3 %		27.1%

[28] L. A. Ilyin et al., "Radiocontamination Patterns and Possible Health Consequences of the Accident at the Chornobyl Nuclear Power Station," *Journal of Radiological Protection*, Vol. 10, No. 1 (1990): 3.

[29] Ibid., 4.

In a book by Izrael published in 1990, the author reports that only 4 – 6% of the total initial core inventory of Cs-137 (0.28 – 0.42 MCi) was released beyond the territory of the former Soviet Union[30] – strongly contradicting other estimates including Ilyin's data above. Moreover, later in Table 2.3 of the book (assuming the 1.2 MCi figure given is correct) this value actually represents a 17.1% Cs-137 release. Interestingly, Table 2.3 also provides a total Cs-137 release of 2.3 – 2.4 MCi, or 32.8 – 34.2 % of the initial core inventory – not the ≈ 15% as presented there.[31]

In the IAEA's *International Chornobyl Project* report, somewhat similar inconsistencies appear. Without reference to any publication the report states, "According to current estimates, the release of cesium in gaseous or aerosol form is equivalent to 2 MCi. The release of iodine is estimated to be 10 MCi, although several experts consider the release to be twice as large."[32] One immediate problem is that the radiocesium and radioiodine isotopes are not specified for these releases, leading one to assume they represent the total release for each element. However, if the 13% release of Cs-137 (presented in Vienna) is taken to be correct, and assuming that chemically all cesium isotopes behave in a similar fashion, if one considers Cs-136 ($t_{1/2}$ = 13.16 days) which had an initial core inventory of 169 MCi, one can estimate that the release of Cs-136 alone amounts to approximately 15 MCi – which contradicts the 2 MCi release as stated in the report. (More than likely, the cesium referred to in the report is Cs-137 – which would be consistent with other estimates of 25 – 28% of core inventory Cs-137 releases.)

Finally, the recently published *Chornobyl: Five Difficult Years*, while still holding to the initially reported 13% of core inventory Cs-137 release, a footnote adds that this figure

---

[30] Израэль, Ю. А., С. М. Вакуловский, В. А. Ветров, В. Н. Петров, Ф. Я. Ровинский, и Е. Д. Стукин, *Радиоактивное загрязнение природных сред*, под редакцией Ю. А. Израэля, Ленинград: Гидрометеоиздат, (1990): 26.

[31] Ibid., 47.

[32] Международного консультативного кометета МАГАТЭ, *Международный Чернобыльский Проект: Технический Доклад*, Оценка радиологических последствий и защитных мер, Вена: МАГАТЭ (1992): 90.

may actually be closer to 30%. It also states that a "significant" amount of core inventory iodine was released.[33]

VI.3.2. Appraisal of Soviet Release Data

In their Vienna report, the Soviets provided a table of relative releases for various radioisotopes as a function of time during the Active Phase of the accident – reproduced in Table VI.10. Unfortunately, there are a number of problems with this table that makes some of the data unusable, or at the very least its reliability questionable.[34] First, there are several missing data points which, especially in the case of the volatile and biologically important Cs-137, make it difficult to analyze release rates over the early part of the Active Phase and to properly estimate the source term. Second, there are two large gaps in the data between April 26th to April 29th (two days missing) and April 29th to May 2nd (two days missing) further complicating the analysis. Third, the release data for Te-132 and I-132 are combined making it impossible to determine the absolute (or even relative) activities of these isotopes; and hence they cannot be used in a release rate analysis over the Active Phase. Fourth, the method of collection is not fully known – which makes nearly impossible an assessment of the reliability of the data. For example, the data will obviously be sensitive to the precise times, number of, and positions (elevation and ground coordinates) of the sample collections, what filters were used if any, time of analysis of the samples, etc. Fifth, the data was not properly normalized to 100% on any of the days, but especially for April 29th and May 5th.[35] If the data were properly normalized, it would have been possible to determine values for some of the missing data points – one may not simply

---

[33] Ю. В. Сивинцева, В. А. Качалова общие редакторы, *Чернобыль: Пять трудных лет*, Сборник материалов о работах по ликвидации последствий аварии на Чернобыльской АЭС в 1986–1990 гг. Москва: ИЗДАТ, (1992): 105.

[34] Inconsistencies in the Soviet data are also discussed in D. A. Powers, T. S. Kress, and M. W. Jankowski, "The Chernobyl Source Term," *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 13–14.

[35] This is confirmed in D. A. Powers, et al, "The Chernobyl Source Term," 14; and in S. N. Begichev, et al, "Radioactive Releases Due to...," 16.

normalize the existing data for a given day if that day has missing data.[36] Sixth, efforts on the ground to contain the graphite fire and limit the consequences of the accident (dropping material on the destroyed reactor and tunnel excavation underneath the building) may have artificially increased the amount of contamination in the air above the reactor – the Soviets themselves mention this possibility.[37]

Table VI.10[38]
Soviet/IAEA Radioisotope Release Data

	Fractional Activity, ∂_i, of 17 Radioisotopes in Air Samples Taken 200m Over Unit-4					
Date	26/IV	29/IV	02/V	03/V	04/V	05/V
Days	0.5	3.5	6.5	7.5	8.5	9.5
Hours	12	84	156	180	204	228
Zr–95	0.044	0.063	0.093	0.006	0.070	0.200
Nb–95	0.006	0.008	0.090	0.013	0.082	0.180
Mo–99	0.037	0.026	0.020	0.044	0.028	0.037
Ru–103	0.021	0.030	0.041	0.072	0.069	0.140
Ru–106	0.008	0.012	0.011	0.031	0.013	0.096
I–131	0.056	0.064	0.057	0.250	0.082	0.190
Te–132 + I–132	0.400	0.310	0.170	0.450	0.150	0.086
Cs–134	0.004	0.006	0.006	0.016	0.006	
Cs–136	0.003	0.004	0.005	0.009		
Cs–137			0.014	0.037	0.013	0.022
Ba–140	0.032	0.041	0.080	0.033	0.130	0.120
La–140	0.110	0.047	0.150	0.023	0.190	0.170
Ce–141	0.014	0.019	0.076	0.009	0.064	0.150
Ce–144	0.016	0.024	0.061		0.051	0.110
Nd–147	0.014	0.017	0.025		0.021	0.054
Np–239	0.230	0.030	0.110	0.006	0.028	0.068
SUM	0.995	0.701	1.009	0.999	0.997	1.623
[ΣAi (Ci/l)]	3.60E-07	3.20E-07	5.00E-08	7.00E-08	1.00E-06	7.00E-09

Note: $\partial_i = \frac{A_i}{\sum_i A_i}$

[36] Despite this, Demin and Khodakovsky attempt to "correct" this by normalizing the column for April 29th of this data in another publication. [V. F. Demin and I. L. Khodakovsky, "Released Radioactive Material During the Chernobyl Accident," as Appendix 10 in *USNRC Workshop on the Chemical Reactions and Processes in Severe Reactor Accidents*, (November 1987): Table 12a, 151.] Not only is less information presented than in Table 4.10 of the Soviet/IAEA report at Vienna (they neglect to include data for May 4th and May 5th), but in their senseless attempt to normalize without including Cs-137 (one cannot normalize only part of a set of data), they obfuscate the information even more. The implication from the normalized data is that no Cs-137 was released on that day! The same normalization is applied to two of the unnormalized columns of the original Soviet data by D. A. Powers et al, (Table 3, 15), which is subsequently used in their analysis to produce fractional release rate curves.

[37] USSR State Committee, Part II, Appendix 4, 18.

[38] USSR State Committee, Part II, Appendix 4, 13.

A seventh reason for doubting the data's reliability concerns the data corresponding to April 26th (column one or the first day), and deserves a separate explanation. There is a question as to whether the data for this column are valid at all, first because it is difficult to imagine that air samples would have been taken above the reactor so soon after the accident.[39] This is especially true given the unpreparedness of the Soviets for the scale of the accident, the lack of basic dosimetric equipment at the station, and that the next column of data represents samples taken two and one-half days after the accident.[40] Moreover, the director of the Chornobyl Station at the time of the accident, Viktor Brjukhanov, in the early hours of the morning reported that the reactor was still intact – a myth that persisted for many hours and caused not only delays in the evacuation of the plant and the surrounding areas, but also down-played the need for specialists to arrive quickly to monitor the situation.[41] As a consequence, the Soviet government's Chornobyl Commission, did not "officially" nor accurately ascertain the extent of the accident until at least after 3:00 P.M. the day of the accident.[42] It is thus difficult to believe that, given the circumstances, properly collected air samples above the reactor were taken on the first day. In fact, a number of the scientists who analyzed data coming in during the first few months after the accident confirm this.[43] The data supposedly representing air samples taken twelve or so hours after the accident actually represent very roughly averaged and integrated soil samples collected later and "fit" to a standard model.

---

[39] Interestingly, in Piers Paul Read notes that air sampling within the 10-km inner exclusion zone (but not necessarily above the reactor) began on April 29th: "... sent in three groups of specially equipped helicopters, staggered at heights from fifty meters to two kilometers. Every two minutes each helicopter sucked in a sample of the air. By measuring the radioactivity... the active emission every twenty-four hours was about one hundred times higher than that estimated by the physicists on the ground." Read, Piers Paul, *Ablaze: The Story of the Heroes and Victims of Chernobyl,*" New York: Random House, Inc., (1993): 114–115.

[40] See for example Zhores Medvedev, *The Legacy of Chornobyl*, New York W.W. Norton Press, (1990): 43; but even more so Grigori Medvedev, *The Truth About Chernobyl*, New York: Basic Books, Inc., (1991): 115, where the author recounts how even the operators could not get at the dosimeters because they had been locked up in storage.

[41] Micheal Dobbs, "Chornobyl's Ex-Engineer Out of Jail – And Angry," *The Washington Post* Foreign Service, April 27. See also Read, Piers Paul, Part 2, Chapters IV–VI.

[42] Viktor Haynes and Marko Bojcun, *The Chernobyl Disaster*, London: Hogarth Press, (1988): 142.

[43] Inquiries with scientists from Kyjiv, Moscow, and St. Petersburg with Alexandr Borovoi and Edvard Pazukhin during 1992–93.

Recently, new data has been made available from the PROBA data bank system at the Kurchatov Institute of the Russian Scientific Center.[44] This new data is presented in Table VI.11 and represents samples collected by a Soviet military helicopter flying at an altitude of 200 meters directly over the center of the reactor shaft (building coordinates L-47) with a zig-zagging pattern. Unfortunately, from all that can be gathered, the sample collection method employed here and managed by a unit of the Soviet Army's special Chemical Warfare Division was not properly carried out.[45] A sample collection system dubbed "Gondola" employed three cigar-shaped plastic canisters about one meter long and 20–30 centimeters in diameter (with one opening) attached under the wings of a Soviet AN-26 airplane. It is not clear what types of filters were used, although it is almost certain that charcoal-activated ones were *not* used – making the filter effectively "invisible" to gaseous releases. (Proper filters were used only after the Active Phase.)* The quantification of the volatile species, especially cesium and iodine, is very dependent on gaseous and chemical behavior of these elements; and even if the data was corrected to account for the low efficiency of the filters for trapping gaseous species, a significant amount of error would have been introduced. Of the filters used, those from the Ministry of Defense were sent to Semipalatinsk (a military installation) for analysis, while those from the State Committee of Hydrometeorology (*Goskomgidromet*) were sent to Obninsk near Moscow. Some of the latter filters were analyzed at the Kurchatov Institute in Moscow, and the results of (ostensibly) all analyses were combined to form the data presented in Table VI.11. Although it is not clear when during the day these air samples were taken, it may be assumed for purposes of the analysis that the samples were taken at 12 o'clock in the afternoon.)

---

[44] See Borovoi, "Fission Product and Transuranic Element Release...," 8–9 for an explanation.

[45] The following account is from a description of the collection system given to Alexandr Borovoi and Edvard Pazukhin (of the Chornobyl research group) by F. F. Rimski-Korsakov of the Khlopin Institute in St. Petersburg in April 1993.

* Although certainly not rigorous as far as data gathering is concerned, a correction was later introduced to take into account the low efficiency of the filters. (Private conversations with researchers at Chornobyl and from St. Petersburg.)

Table VI.11
PROBA Fractional Activity, ∂_i, Release Data

#	1	2	3	4	5	6	7	8	9	10	11
Date	28/IV	29/IV	02/V	03/V	04/V	05/V	06/V	07/V	08/V	09/V	11/V
Days	2.5	3.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	15.5
Hours	60	84	156	180	204	228	252	276	300	324	372
Sr-89		0.0899			0.0263				0.0004		
Sr-90		0.0056			0.0032						
Zr-95	0.0581	0.2629	0.0927	0.0062	0.0677	0.1243	0.1273	0.0553	0.0276	0.0820	0.1518
Nb-95	0.0681	0.0000	0.0897	0.0129	0.0795	0.1095	0.1115	0.0457	0.0121	0.1048	0.1802
Mo-99	0.0422	0.0083	0.0200	0.0443	0.0270	0.0167	0.0104	0.0582	0.0497	0.0150	
Ru-103	0.0397	0.0765	0.0411	0.0772	0.0667	0.0895	0.0728	0.2236	0.2302	0.1159	0.0898
Ru-106	0.0115	0.0206	0.0110	0.0315	0.0133	0.0592	0.0428	0.0671	0.0633	0.0392	0.0796
Te-132	0.1436	0.0570	0.0709	0.1904	0.0561	0.0532	0.0331	0.0611	0.0709	0.0626	0.0194
I-131	0.1295	0.0714	0.0564	0.2494	0.0792	0.0706	0.0463	0.1345	0.1797	0.1755	0.0773
I-132	0.0649	0.0673	0.0940	0.2561	0.0922	0.0516	0.0228	0.1099	0.1050	0.0756	0.0322
Cs-134		0.0107	0.0060	0.0162	0.0053		0.0081	0.0096	0.0094	0.0079	
Cs-136	0.0034	0.0038	0.0056	0.0090				0.0053	0.0061		
Cs-137			0.0140	0.0370	0.0128	0.0136	0.0114	0.0216	0.0242	0.0195	
Ba-140	0.0573	0.0760	0.0797	0.0319	0.1229	0.0736	0.0587	0.0305	0.0432	0.0364	
La-140	0.1103	0.1756	0.1491	0.0232	0.1893	0.1021	0.1391	0.0507	0.0918	0.0719	0.1501
Ce-141	0.0454	0.0320	0.0760	0.0087	0.0621	0.0910	0.1200	0.0611	0.0331	0.0614	0.0762
Ce-144	0.0384	0.0358	0.0607		0.0491	0.0699	0.1260	0.0611	0.0357	0.0715	0.1433
Nd-147	0.0281	0.0065	0.0245		0.0200	0.0334	0.0228	0.0047	0.0102	0.0226	
Np-239	0.1593		0.1089	0.0058	0.0275	0.0418	0.0470		0.0072	0.0382	
SUM	0.9998	0.9999	1.0003	0.9998	1.0002	1.0000	1.0001	1.0000	0.9998	1.0000	0.9999
Σ Act (Bq/m^3)	369820	194729	48960	74570	1009200	10777	1524	51877	85144	32428	17589

#	12	13	14	15	16	17	18	19	20	21	22
Date	13/V	14/V	15/V	16/V	17/V	18/V	19/V	20/V	21/V	22/V	23/V
Days	17.5	18.5	19.5	20.5	21.5	22.5	23.5	24.5	25.5	26.5	27.5
Hours	420	444	468	492	516	540	564	588	612	636	660
Sr-89											
Sr-90											
Zr-95	0.0198	0.1261	0.0510	0.1943	0.2129	0.1385	0.0805		0.1649	0.0249	
Nb-95	0.3932	0.1416	0.0322	0.2105	0.2352	0.1611	0.1180		0.1806	0.0302	
Mo-99	0.0075		0.0245	0.0020		0.0119	0.0279			0.0252	
Ru-103	0.3161	0.0476	0.2112	0.0961	0.0735	0.1254	0.2825	0.4141	0.1538	0.4234	0.2487
Ru-106	0.1005	0.0331	0.1040	0.0344		0.0606	0.1165	0.3233	0.0561	0.1788	0.6490
Te-132	0.0083		0.0178	0.0017		0.0055			0.0104		
I-131	0.0651	0.0300	0.2921	0.0153		0.1033	0.2430	0.2626	0.0939	0.2847	0.1023
I-132	0.0097		0.0322			0.0135	0.0303		0.0169	0.0328	
Cs-134	0.0023										
Cs-136											
Cs-137	0.0051		0.0245	0.0071		0.0111					
Ba-140		0.1250		0.0554							
La-140	0.0121	0.1958	0.1389	0.1313	0.1277	0.1385			0.0945		
Ce-141	0.0227	0.1539	0.0716	0.1176	0.1656	0.0911	0.0540		0.1037		
Ce-144	0.0256	0.1470		0.1323	0.1851	0.1137	0.0473		0.1252		
Nd-147	0.0120			0.0021		0.0257					
Np-239											
SUM	1.0000	1.0001	1.0000	1.0001	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000	1.0000
Σ Act (Bq/m^3)	10249	18643	404	380936	7186	21292	6337	1234	46020	2142	792

The PROBA data set does, however, have several advantages over the data presented in Vienna. First, there is an additional day of data (April 28th) which Table VI.10 doesn't have. Second, data for Te-132 and I-132 are separated. Third, the data (given as absolute activity values) is well normalized and presents release data for more radionuclides over a longer period. (Data is given through May 23rd and, although is not usable for an Active Phase analysis, does provide releases for almost a month after the accident.) Interestingly, it lacks data for April 26th, which supports the conjecture that first-day data presented by the Soviets in Vienna was not derived from air samples but rather from integrated ground depositions. Moreover, it seems puzzling that both data sets look remarkably similar as concerns missing data points – leading one to speculate that the Vienna conference data is a combination of the PROBA data and integrated estimates for the first day.†

Unfortunately, the PROBA also data shares some of the same unknowns or problems associated with the data in Table VI.10, as well as presenting new difficulties. For example, the fact that fires generally do not burn uniformly and release smoke in puffs or small "bursts" (density variations), makes the data appear quite meager given that it was gathered only once per day at one location. (Hot particles undoubtedly had substantially different transport dynamics as compared with gases and elemental releases – made even more significant if the samples collected were not taken in the release plume.) Based on the weather conditions at the site during the accident and the high heat content of the plume, McInall estimates the transport elevation to correspond to the 850 mbar pressure level or approximately 1500 meters, while the maximum mixing level, where vertical dilution of the plume reaches ambient conditions, was at approximately 3000 meters.[46] (NUREG-1250 however reported that beginning on approximately April 28th, the elevation of the plume did not ex-

† One of my colleagues at Chornobyl is sure that this is the case. Data was *purposely* "denormalized" strongly on certain days while data for day 2.5 was eliminated altogether to hide the fact that the Ministry of Defense gathered the data. This is, of course, is speculation; but it fits the pattern of Soviets withholding or manipulating, and again raises the question of the reliability of the data and the trustworthiness of Soviet accounts of the accident.

[46] McInall, Steven Gardiner. *Atmospheric Transport of Radionuclides Due to the Accident at the Chernobyl Unit-4 Nuclear Power Station.* Master of Science Dissertation. Department of Nuclear Engineering: Massachusetts Institute of Technology, (January 1988): 40.

ceed 200 to 400 meters.[47]) Third, air sample filter efficiency plays an extremely important role in the "capture" of the various physical forms the releases may have taken. If indeed the "wrong" filters were used to collect samples during the Active Phase, they would have collected hot particles and aerosols depleted in volatile elements while at the same time they would have been quite transparent to gaseous species – in effect "missing" them. As reported by D. A. Powers, Devell indirectly supports the significance of filter efficiency for Chornobyl by reporting that "60% to 90% of iodine captured in their samples [in Sweden] was in a gaseous form or a form desorbable from particles rather than as particulate cesium iodide."[48] Fourth, the PROBA data is *assumed* to be uncorrected for radioactive decay, i.e., presented are the radioisotopes' absolute release activities – however even this is not positively confirmed. Finally fifth, the PROBA data does not agree with similar data presented in Table 4.7 of the Soviet report – in some cases release activities are off by an order of magnitude.[49] This appears to further discredit at least some of the data presented by the Soviets at Vienna.

The PROBA and Soviet/IAEA data sets may be combined by limiting ourselves to the Active Phase and assuming the PROBA data is the more reliable of the two, i.e., data from twelve hours is added to the PROBA set from the Soviet Vienna report since it doesn't record sample data for this period. Also, since PROBA contains only two data points for Sr-90 over the Active Phase, we will not consider them in the combined set. The most we can say is that the release rate of strontium *appears* to have increased from three and one-half days to eight and one-half days after the accident. Table VI.12 presents the combined normalized data sets.

---

[47] NUREG-1250, 6-9.

[48] L. Devell, H. Tovedal, U. Bergström, A. Appelgren, J. Chyssler, and L. Andersson, "Initial Observations of Fallout from the Reactor Accident at Chornobyl," *Nature*, 321 (May 15, 1986): 192-193; as referenced in D. A. Power et al, 14.

[49] USSR State Committee, Part II, Appendix 4, Table 4.7, (8).

Table VI.12

Combined Data for the Fission Product Fractional Activity, ∂_i

Date	26/IV	28/IV	29/IV	02/V	03/V	04/V	05/V	06/V
Days	0.5	2.5	3.5	6.5	7.5	8.5	9.5	10.5
Hours	12	60	84	156	180	204	228	252
Zr-95	0.044	0.058	0.291	0.093	0.006	0.070	0.124	0.127
Nb-95	0.006	0.068		0.090	0.013	0.082	0.109	0.111
Mo-99	0.037	0.042	0.009	0.020	0.044	0.028	0.017	0.010
Ru-103	0.021	0.040	0.085	0.041	0.077	0.069	0.090	0.073
Ru-106	0.008	0.012	0.023	0.011	0.032	0.014	0.059	0.043
Te-132	??	0.130	0.079	0.056	0.249	0.082	0.071	0.033
I-131	0.056	0.144	0.063	0.071	0.190	0.058	0.053	0.047
I-132	??	0.065	0.074	0.094	0.256	0.095	0.052	0.023
Cs-134	0.004		0.012	0.006	0.016	0.005		0.008
Cs-136	0.003	0.003	0.004	0.006	0.009			
Cs-137				0.014	0.037	0.013	0.014	0.011
Ba-140	0.032	0.057	0.084	0.080	0.032	0.127	0.074	0.059
La-140	0.11	0.110	0.194	0.149	0.023	0.195	0.102	0.139
Ce-141	0.014	0.045	0.035	0.076	0.009	0.064	0.091	0.120
Ce-144	0.016	0.038	0.040	0.061		0.051	0.070	0.126
Nd-147	0.014	0.028	0.007	0.025		0.021	0.033	0.023
Np-239	0.23	0.159		0.109	0.006	0.028	0.042	0.047
Total Act $A_{i,k}$ (Bq/m^3)	13320000	369820	176139	48960	74570	979460	10777	1526

This data may now be tested for consistency by comparing the measured (i.e., released) mass ratios of isotopes of the same element against their calculated (i.e., no release) mass ratios. Assuming isotopes of the same element were released at the same *mass* release rate, we expect the measured ratio to be fairly close to the calculated ratio. Table VI.13 presents these ratios for five elements over the Active Phase; and it also presents the ratio of measured-to-calculated ratios. For each ratio grouping, the top value corresponds to air sample (release or measured) data, the middle value corresponds to the calculated (non-release or fuel) value, while the bottom value is the ratio of these two. Bearing in mind that a significant amount of release data is missing for these elements (making a statistical analysis less conclusive), we may nevertheless conclude that the results for all except Cs-136 deviate on the order of 20–25% from the expected – which, given the sample collection methodology and considering the circumstances, is quite good. Interestingly, iodine over

the Active Phase appears to have a fairly good $(I\text{-}131/I\text{-}132)_{meas}$-to-$(I\text{-}131/I\text{-}132)_{calc}$ ratio – although it deviates the most over that period. Cerium exhibits the best behavior because its ratio is closest (of the elements shown) to one while deviating the least. However, even for this refractory oxide (as for iodine) the first day shows a poor ratio – further strengthening the argument that the first day's data is poor. Ruthenium's ratio compares fairly well to cerium except for the last two days.

Table VI.13

Soviet Data Consistency Check

Date	26/IV	28/IV	29/IV	02/V	03/V	04/V	05/V	06/V	<x> ± σ
Days	0.5	2.5	3.5	6.5	7.5	8.5	9.5	10.5	
Hours	12	60	84	156	180	204	228	252	
Ru-103/Ru-106 (M)	0.269	0.341	0.378	0.382	0.246	0.505	0.156	0.174	
Ru-103/Ru-106 (C)	0.446	0.432	0.425	0.405	0.399	0.393	0.386	0.380	
RATIO M/C	**0.603**	**0.790**	**0.891**	**0.942**	**0.618**	**1.286**	**0.404**	**0.457**	**0.75±0.29**
I-131/I-132 (M)		185.7	71.38	63.33	62.23	51.19	85.45	171.3	
I-131/I-132 (C)	59.55	76.70	87.06	127.5	144.8	164.3	186.6	211.9	
RATIO M/C		**2.422**	**0.820**	**0.497**	**0.430**	**0.312**	**0.458**	**0.809**	**0.82±0.73**
Cs-134/Cs-137 (M)				0.029	0.029	0.026		0.049	
Cs-134/Cs-137 (C)	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044	
RATIO M/C				**0.658**	**0.664**	**0.591**		**1.119**	**0.76±0.24**
Cs-136/Cs-137 (M)				0.001	>0.001				
Cs-136/Cs-137 (C)	0.028	0.025	0.024	0.020	0.019	0.018	0.017	0.016	
RATIO M/C				**0.025**	**0.015**				**0.02±0.01**
Cs-134/Cs-136 (M)				0.029	0.029	0.026		0.049	
Cs-134/Cs-136 (C)	1.578	1.752	1.847	2.161	2.277	2.400	2.529	2.666	
RATIO M/C				**0.013**	**0.013**	**0.011**		**0.018**	**0.01±3e-3**
Ce-141/Ce-144 (M)	0.098	0.132	0.098	0.139		0.140	0.145	0.106	
Ce-141/Ce-144 (C)	0.158	0.152	0.149	0.141	0.138	0.136	0.133	0.131	
RATIO M/C	**0.620**	**0.870**	**0.655**	**0.987**		**1.033**	**1.090**	**0.814**	**0.87±0.18**

VI.3.3. Active Phase Release Dynamics

Radioisotope release is generally considered a classic vaporization process: the driving force for vaporization is the disequilibrium between the fuel-debris mixture and the ambient gas. If this is the case, releases driven by the vapor pressures of the radioisotopes would be expected to display substantial release rate differences. If not the case, it suggests that some other factor other than vapor pressure is driving (or limiting, as the case may be) the rates of radioisotope release. By converting the activity release data in Table VI.12 to releases in terms of mass, a statistical analysis shows that the mass releases correlate quite well for all seventeen isotopes over the Active Phase (Appendix VI.C). This may be depicted graphically by plotting the ratio of the released (sampled) masses to the calculated masses in the fuel (i.e., normalizing assuming no release) – shown in Figure VI.5. Additionally for ease in comparison, Figure IV.5 – the "Bathtub" Curve – is reproduced below as Figure VI.4.

Figure VI.4
Release Rate Curve Presented by the Soviets in August 1986 at Vienna
The "Bathtub" Curve

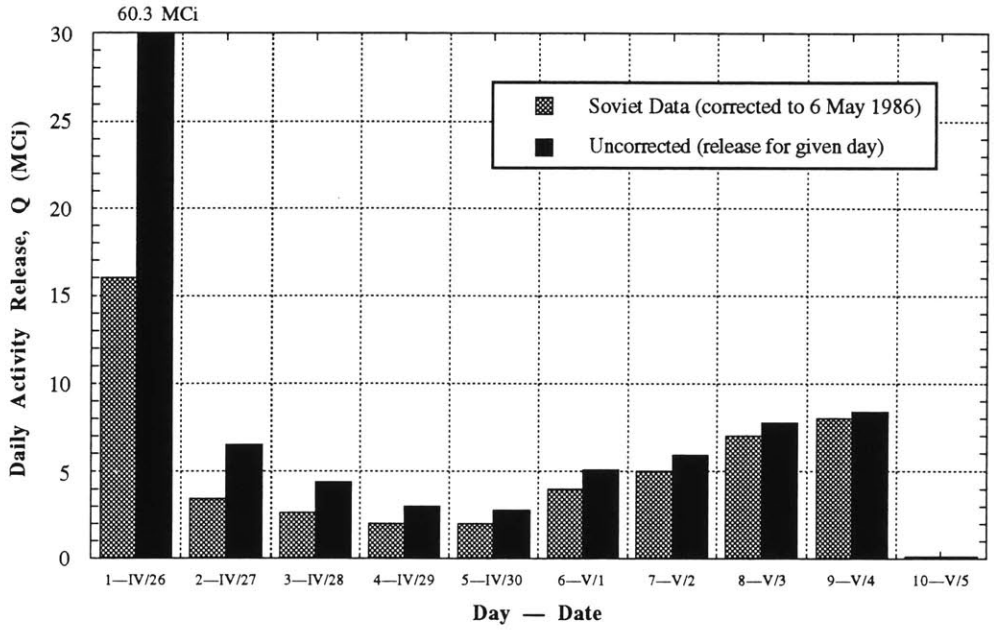
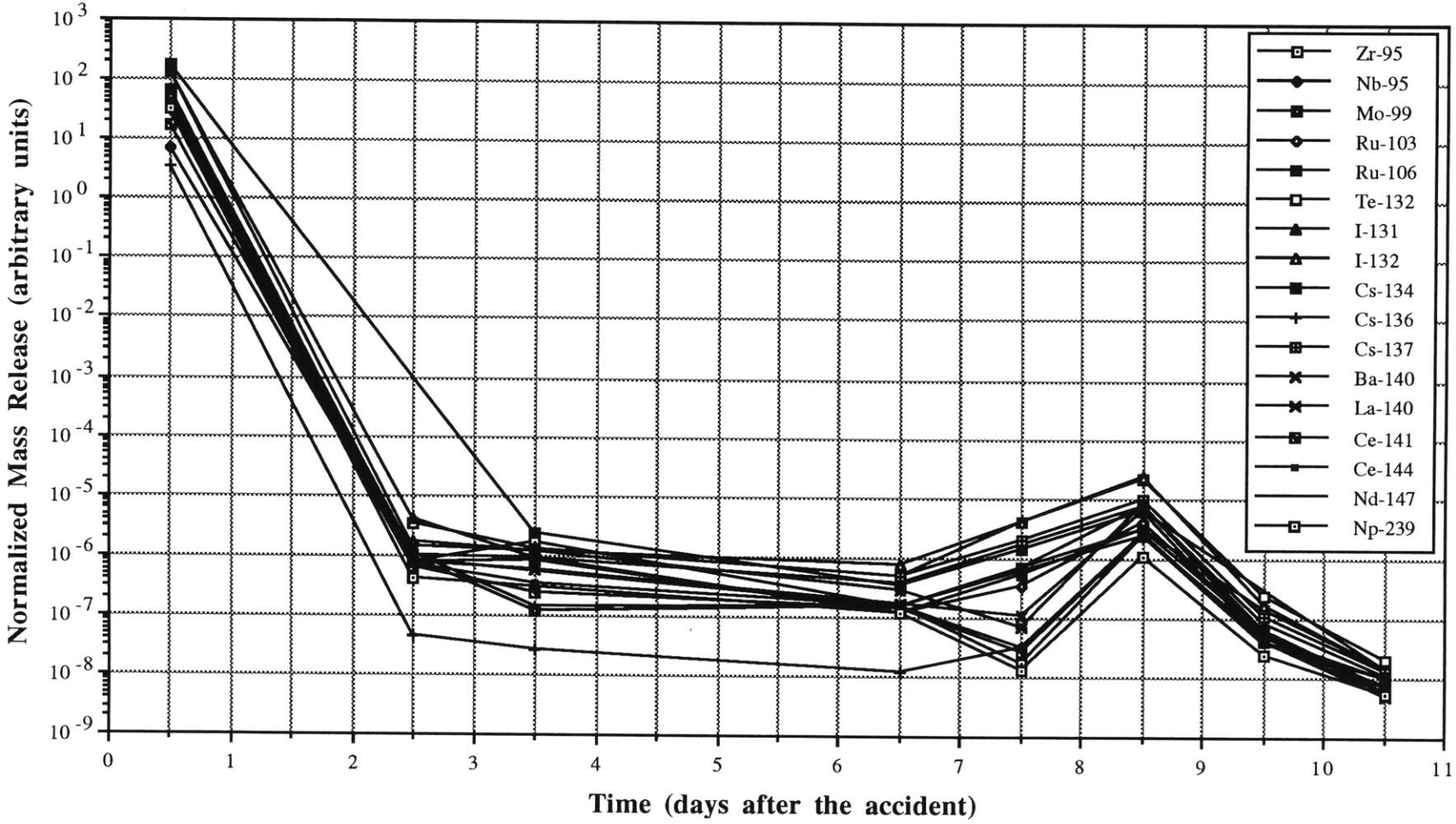


Figure VI.5

Normalized Mass Release Over the Period of the Active Phase



The first thing to note, both from the results of the correlation analysis and Figure VI.5, is how closely the release behaviors of all seventeen isotopes are with respect to each other, and (with the exception of the peak on day 8.5) how relatively flat and decreasing the releases are over time. This seems to suggest that the releases were occurring isothermally over the period of the Active Phase. Additionally, as the corium's decay heat decreased and heat energy continued to escape, one would have expected that for an *uncovered* core the releases would decrease over time. (Significant temperature variations would lead to very large differences in the release behaviors – at least between the volatiles and non-volatiles.) With the exception of day 7.5 and Cs-136, the releases are, unexpectedly, all within one and one-half orders of magnitude of each other – suggesting some mechanism must have been substantially limiting the release of the volatile radionuclides during this period. Also, the peak in releases near the end of the Active Phase occurs at 8.5 days after the accident. This seems to be in slight disagreement with the peak of releases as depicted in the "bathtub" curve – although from Figure VI.5 (because of the one-day frequency of data collection) it is clear that the peak in releases could have occurred anytime after day 7.5 and before day 9.5. (In fact, the general shape of curve corresponds to the "bathtub" curve with the (assumed) initial peak due to steam-explosion ejection, and another peak near the end.) Finally, data for the first day again appears unreliable based on the approximately eight orders of magnitude difference between it and the rest of the Active Phase.*

The most notable features of Figure VI.5 is the peak in releases around day 8.5, and the sudden and significant drop around day 9 – indicating the termination of releases and the end of the Active Phase. Generally, the volatiles are releasing approximately one-half an order of magnitude more than the non-volatiles. The release isotopes may be separated

---

* That the data for the first day is unreliable is clear. However, this is not to say that the low on the first day. Given the relative kinetics of the oxidation of zirconium and graphite, a very high first-day(s) release could be postulated to be associated, at least partially, with a very rapid zirconium burning, followed by the somewhat slower burning-off of the graphite. This hypothesis supports the general shape of the mass release curves, at least during the first few days when the graphite amy have served to retain some releases. It is also supported by the "red and blue fire" and "powerful updraft" coming from the mouth of the reactor crater as reported by witnesses. [Medvedev, *The Truth About Chernobyl*, 103.]

roughly into these two groups, volatiles and non-volatiles, based partially on the as yet unexplained difference in their behaviors approximately 7.5 days into the Active Phase (Figures VI.6 & VI.7). Interestingly ruthenium and molybdenum, usually considered non- and mid-volatiles respectively, behave much like the volatiles. In Figure VI.6 we see demonstrated quite clearly, first of all, the unreliability of data for Cs-136 because of its almost two order of magnitude release difference from that of Cs-134 and Cs-137. Second, Mo-99 has a substantial and mysterious drop in its releases on day 3.5 – which may be due to sample collection or measurement error. Third, all the release behaviors of all the isotopes converge rapidly after day 8.5. However, the most dramatic difference occurs at day 7.5: without exception all the volatile isotopes show an increase in releases, while the non-volatiles show a decrease. (Despite missing data on day 7.5 for Ce-144 and Nd-147, because both are refractory oxides and Ce-144's sister isotope, Ce-141, behaves as the other non-volatiles, we can be fairly certain that cerium and neodymium may be grouped into the non-volatiles for this analysis.) This is followed by similar behaviors for all the isotopes after the peak on day 8.5.

The most plausible explanation for this behavior (taking into account also the new information presented in Chapters IV and V) is that the graphite moderator and reflector must have burned off at approximately day 7. This would enhance the release of the volatiles because at the temperatures expected in the corium mass, the filtering effect of an (assumed) upper graphite layer would be gone. It would also decrease the releases of the non-volatiles because there would no longer be a particulate release mechanism available as a pathway to the environment. The peak at day 8.5 could be explained by the possibility that at that time the Lower Biological Shield may finally have been melted through – followed by a rapid relocation of approximately 135 tonnes of corium to the lower regions of the reactor building. The relocation (physical mechanism) and spread (larger surface area) of the corium would have provided greater opportunity for releases. The larger surface area would also, how

Figure VI.6

Normalized Mass Release Over the Period of the Active Phase for the Volatiles

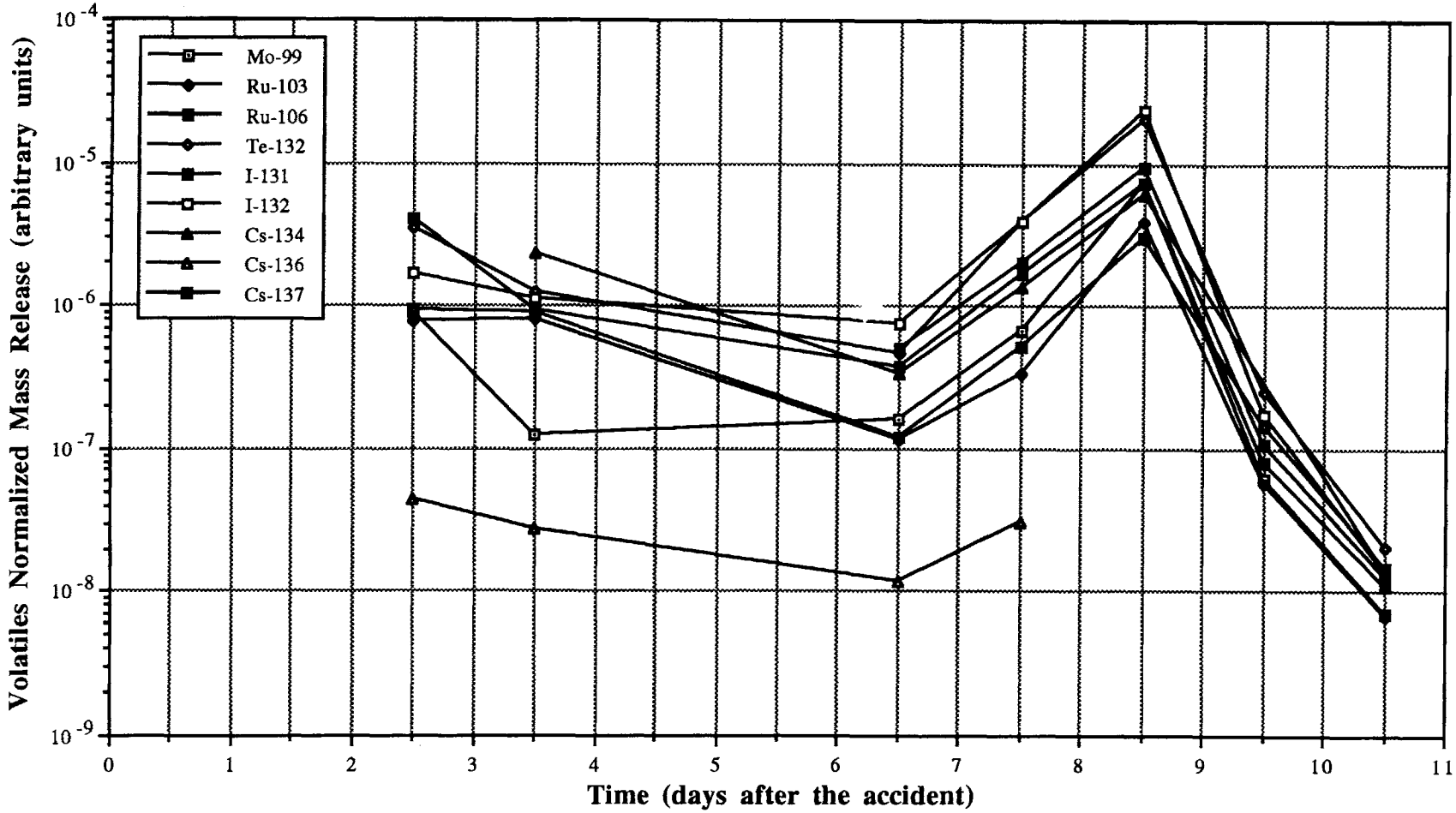
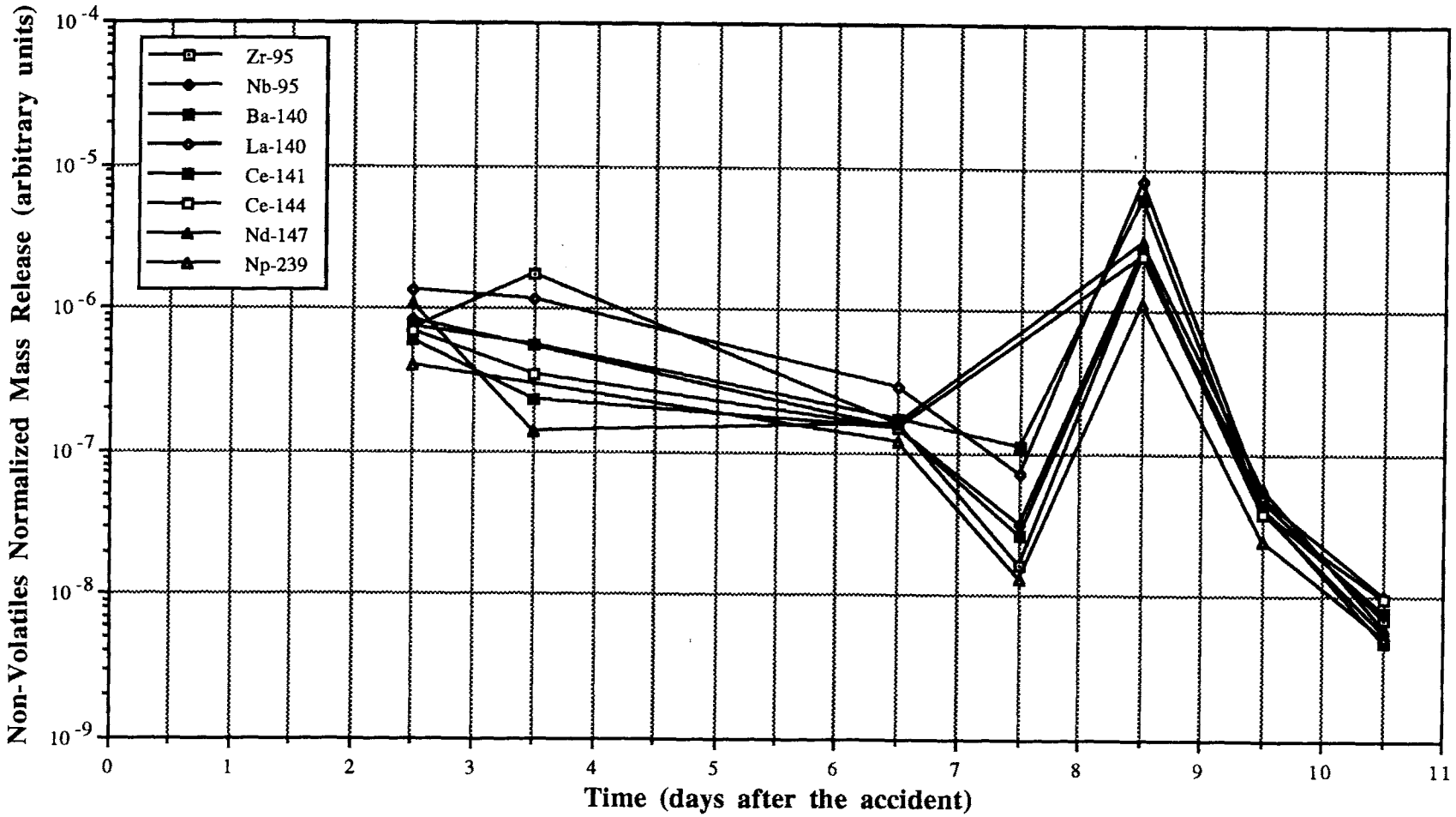


Figure VI.7

Normalized Mass Release Over the Period of the Active Phase for the Non-Volatiles



ever, provide for more rapid cooling. This, together with the fact that the chemistry of the corium would have been complicated by taking-up the approximately one-quarter section of the LBS (raising its solidus), and the fact that significantly less decay heat was available as input energy by day 8.5, would make the corium much less able to interact with surrounding materials and give it a propensity for rapid solidification.

Samples of hot particles analyzed both within the former Soviet Union and in the west show that, except for volatile radioisotopes, the non-volatiles were released more or less in fuel-form, i.e., the isotopic content and character of material released are heavily skewed toward the non-volatile radioisotopes and actinides implying these radioisotopes did not vaporize but were transported to the environment within the matrix of small fuel particles. On the other hand, to explain why some particles were enriched in cesium,[50] a certain fraction of the released particles may have served as "carriers" onto which the volatiles condensed. As mixtures of vapors (volatiles) and mechanically produced aerosols (containing non-volatiles in the matrix) cool, the surfaces of the aerosols are preferred sites for condensation of the volatiles because of the high surface area to volume ratio (approximately 3000 cm^{-1}).

The total amount of radioactive "dust" or hot particles contained within the sarcophagus is estimated to be 5 ± 2 tonnes (see Chapter V); and it is likely this formed as a result of hot, molten fuel (melted as a result of the power excursion) accelerated from the rupture of fuel rods into the cooling water in the pressure tubes, and because of hydrodynamic instabilities disintegrated into aerosol-sized droplets. Another possible mechanism for the comminution of fuel is its expulsion into an oxidizing environment. During the oxidation of UO_2 to U_3O_8 there is a change in the crystal structure that ruptures the fuel grains – assuming the fuel is not melted. The exposed surfaces, therefore, provide a direct path for the vaporization of volatile radioisotopes that is further enhanced by virtue of a particle's high surface area to volume ratio. Also, the pulverized fuel particle itself is available for transport out of the fuel mass, restricted by bulk gas flow rate over the surface of the fuel and

[50] D. A. Power et al, 14.

filtering material (if any) between the fuel and the environment. The conclusion, then, is that depending on ambient conditions, the surface of the fuel or hot particle can enhance either vaporization or condensation of volatile radioisotopes – implying that the composition of aerosols is not a reliable indicator of the mechanical aerosolization process. Therefore, Soviet release rate data as presented in Vienna[51] along with western analyses of hot particle fallout from Chornobyl should be viewed with caution inasmuch as they reflect two release mechanisms strongly influencing releases during the Active Phase of the accident: the vaporization of volatiles and aerosol transport of hot particles.

The Soviets have typically presented their release analyses in terms of a dimensionless "fractionation factor," $k_{i\text{-}j}$, defined in the following manner: in the event of a severe nuclear reactor accident in which there is melting or severe destruction of the core, and in which the containment or reactor building is breached, a certain fraction of the fission products will escape the fuel (vaporize) while another fraction will remain trapped within the fuel or within a fuel-and-structural material admixture. We may relate the activity of any fission product remaining in fuel-containing masses (FCMs) to the total calculated activity for that fission product as,

$$A(t)_i^{FCM} = \xi(t)_i \, A(t)_i^{TOT} \tag{1}$$

$$A(t)_i^{REL} = (1-\xi(t)_i) \, A(t)_i^{TOT} \tag{2}$$

where,

$A(t)_i^{TOT}$ = Total calculated core inventory of nuclide "i"
$A(t)_i^{FCM}$ = Nuclide "i" activity remaining in Fuel Containing Mass
$A(t)_i^{REL}$ = Nuclide "i" activity released from Fuel Containing Mass
$\xi(t)_i$ = Fuel binding coefficient, $0 \leq x_i \leq 1$ (i.e., for full release $\xi_i = 0$).

All of these, of course, are complex functions of time whose physical basis depends upon the nuclide's half-life, the element's chemical and thermodynamic properties, and its inter-

[51] See, for example, Table 4 in D. A. Powers, et al, 16.

actions with surrounding materials. Consequently, for any nuclides "i" and "j" we may define the fractionation factor, k_{i-j}, using (1) and (2),

$$\frac{A_i^{REL}}{A_j^{REL}} = \frac{(1-\xi_i)}{(1-\xi_j)} \frac{A_i^{TOT}}{A_j^{TOT}} \tag{4}$$

or,

$$\frac{(1-\xi_i)}{(1-\xi_j)} = \frac{(A_i/A_j)_{REL}}{(A_i/A_j)_{TOT}} = k_{i-j} \tag{5}$$

where, $0 \leq k_{i-j} \leq \frac{1}{1-\xi_j}$ assuming ξ_j is known.

This provides us with somewhat of a useful tool for a dimensionless analysis of radioisotope release rates. Assuming we can determine the initial core inventory just prior to the accident (i.e., A_i^{TOT} where "i" is any isotope), assuming further we can measure or "fix" the amount of a certain long-lived non-volatile "tracer" fission product in the melted fuel (i.e., A_j^{FCM}), and finally assuming we can measure the isotopic composition of releases relative to the total activity released (i.e., $A_i^{REL}/\sum A$), it is possible to measure the efficacy or volatility of release of a particular radioisotope over time with respect to the tracer isotope using the fractionation factor. (Note this tells us little about whether once released from the fuel, the fission products may become trapped by debris (plate out on a cooler surface) or chemically interact with structural or other reactor and building materials before escaping into the environment where it is detected.)

Several tables of fractionation factors over the period of the Active Phase have been published by the Soviets.[52] Unfortunately, either the data is scant and incomplete, or in some cases the values for the same tracer isotope have been inconsistent between studies – making the results of their analyses inconclusive.[53] For the current analysis, we assume the

---

[52] The first such method for presenting release data, using Zr-95 and Ce-141 as the tracer isotopes, was published in the proceedings of the IAEA/Soviet conference at Vienna in 1986: USSR State Committee, Part II, Appendix 4, Table 4-11, 14.

[53] Ibid. Refer also to the inconsistencies in fractionation values (Ce-144 tracer isotope) presented in (1) Rimski-Korsakov, F. F., "Use of Relative Fission Products Releases to Estimate the Fuel Temperature After Chernobyl Accident," *Report at the International Conference "50th Anniversary of Nuclear Fission,"*

results of the core inventory calculations introduced above are the most precise to date. The tracer isotope is chosen to be Zr-95 which has a relatively long half-life over the period of the Active Phase (64.02 days decaying to Nb-95) as well as all release activities (Table VI.12) from the PROBA data. Table VI.14 presents the fractionation factors for the PROBA data, while Figures VI.8 –VI.10 present these data graphically divided roughly into three groups: volatiles, refractory metals, and refractory oxides.

Table VI.14
Radioisotope Fractionation Factor, $k_{i\text{-}95}$, During the Active Phase

Date		26/IV	28/IV	29/IV	02/V	03/V	04/V	05/V	06/V
Days		0.5	2.5	3.5	6.5	7.5	8.5	9.5	10.5
Hours		12	60	84	156	180	204	228	252
Zr-95	RO	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Nb-95	RO	0.14	1.17		0.93	1.98	1.10	0.82	0.81
Mo-99	NM	0.91	1.27	0.07	1.00	41.89	2.97	1.28	1.00
Ru-103	RM	0.74	1.08	0.46	0.72	20.32	1.62	1.19	0.95
Ru-106	RM	1.23	1.32	0.52	0.76	32.29	1.23	2.97	2.07
Te-132	V:T		4.81	0.72	2.95	239.4	8.52	5.06	2.87
I-131	V:H	2.51	5.66	0.54	2.37	102.7	2.99	1.66	1.53
I-132	V:H		2.34	0.66	4.77	238.6	9.62	3.59	1.91
Cs-134	V:A	3.11		1.35	2.09	83.52	2.48		1.91
Cs-136	V:A	0.07	0.06	0.02	0.07	1.86			
Cs-137	V:A				3.16	124.1	3.88	2.23	1.76
Ba-140	AE	0.72	1.06	0.32	1.09	6.83	2.51	0.85	0.70
La-140	RE	2.40	1.87	0.68	1.80	4.36	3.39	1.04	1.44
Ce-141	RO	0.34	0.84	0.13	0.92	1.60	1.05	0.85	1.10
Ce-144	RO	0.54	0.97	0.29	0.93		1.01	0.78	1.36
Nd-147	RE	0.88	1.49	0.08	1.00		1.24	1.19	0.84
Np-239	RO	0.61	0.56		0.75	0.80	0.46	0.50	0.73

Key:
RO Refractory Oxide
RM Refractory Metal
AE Alkaline Earth
RE Rare Earth
NM Noble Metal
V:T Volatile: Tellurium Group
V:A Volatile: Alkaline
V:H Volatile: Halogen

Leningrad, USSR, Oct 16–20, 1989; and (2) Ponomarev-Stepnoi, N. N. and Khrulëv, A. A., "Effect of the Annealing Temperature on Escape of Metal Fission Products from Different Media," presented at the *International Seminar "Fission Product Transport Processes in Reactor Accidents,"* Dubrovnik, Yugoslavia, (May 22–26, 1989), Table 10. My own calculations using Ce-144 as the tracer isotope also disagree with these two studies.

Figure VI.8

Fractionation Factor, $k_{i\text{-}95}$, for the Volatiles Over the Period of the Active Phase

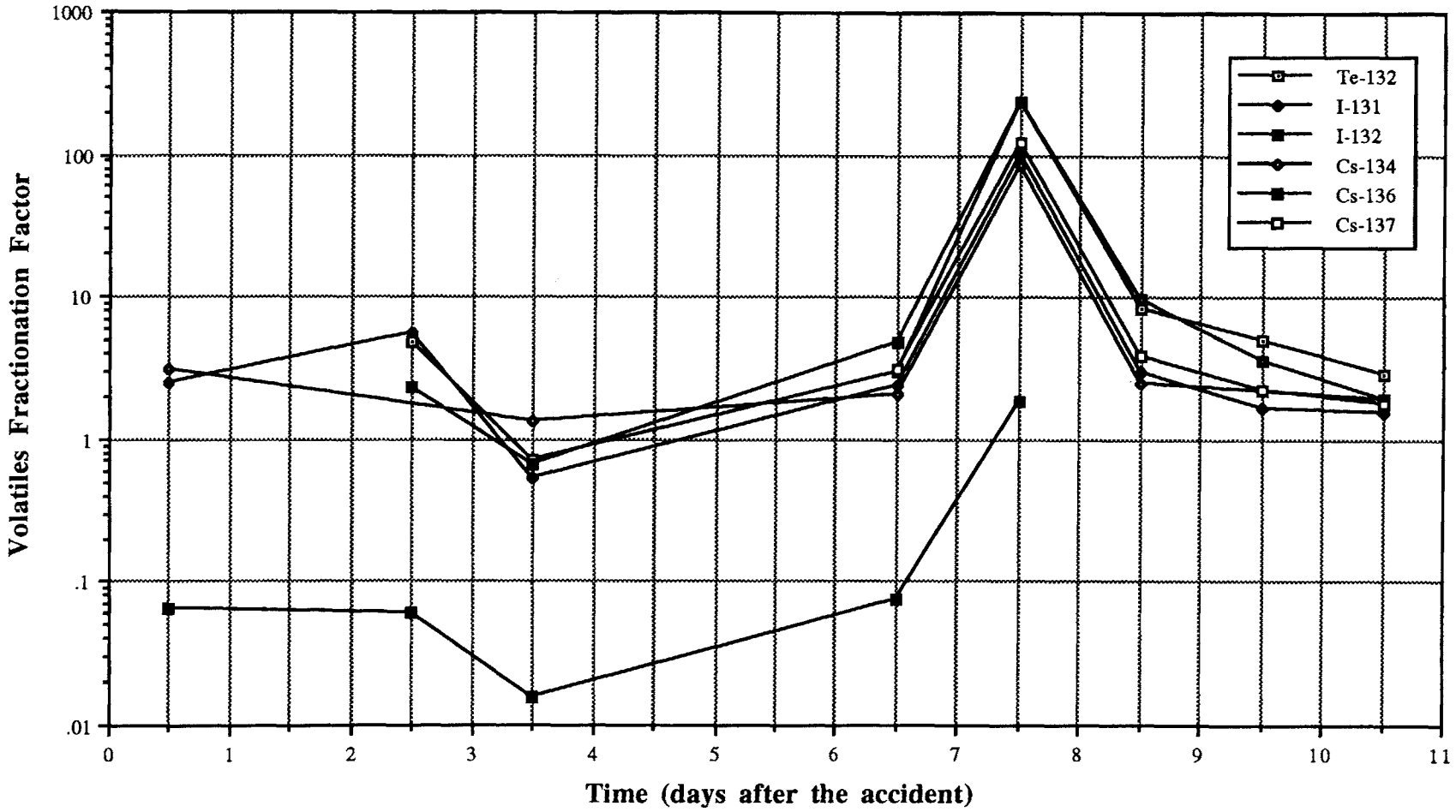


Figure VI.9

Fractionation Factor, $k_{i\text{-}95}$, for the Refractory Metals Over the Period of the Active Phase

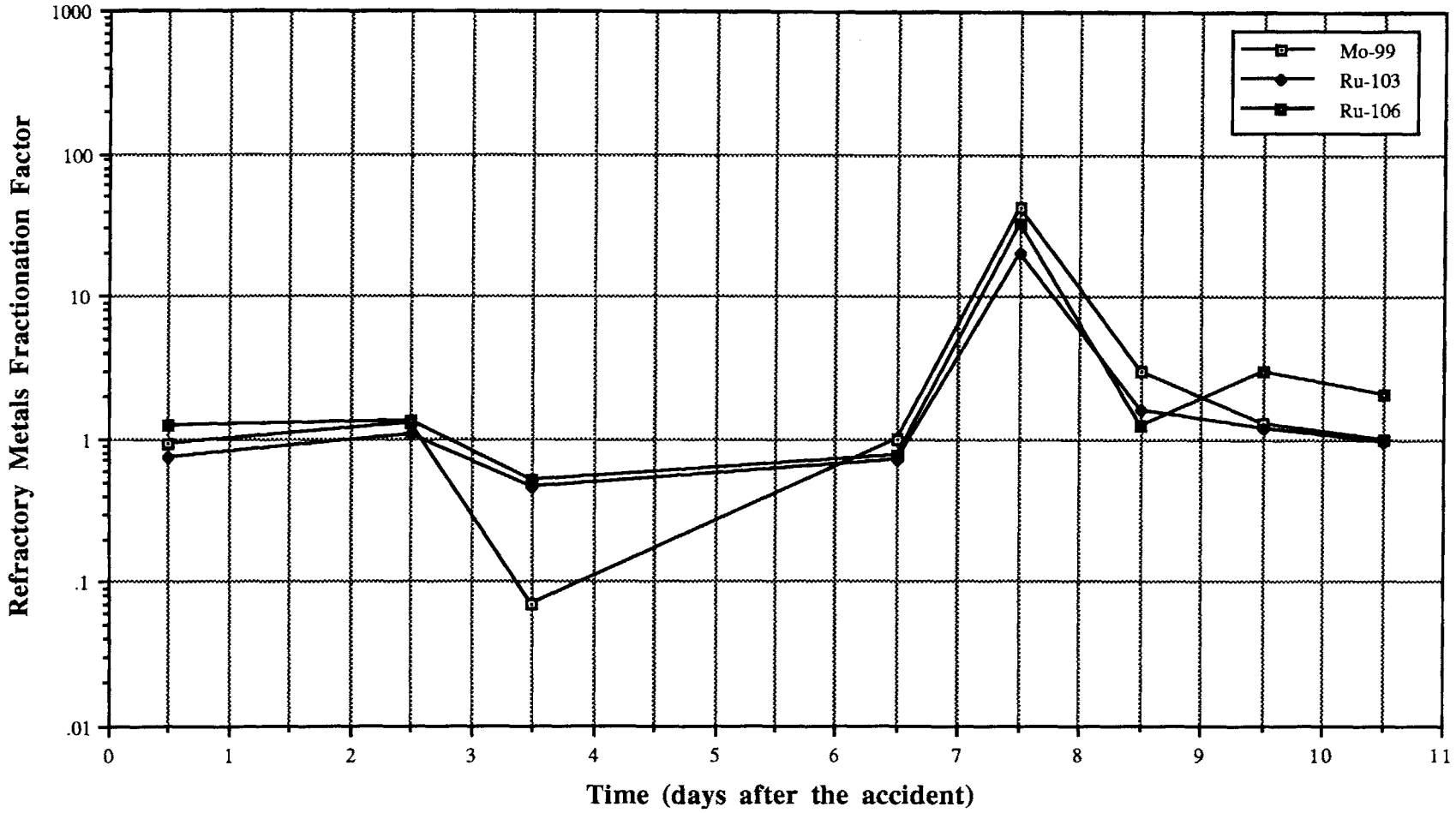
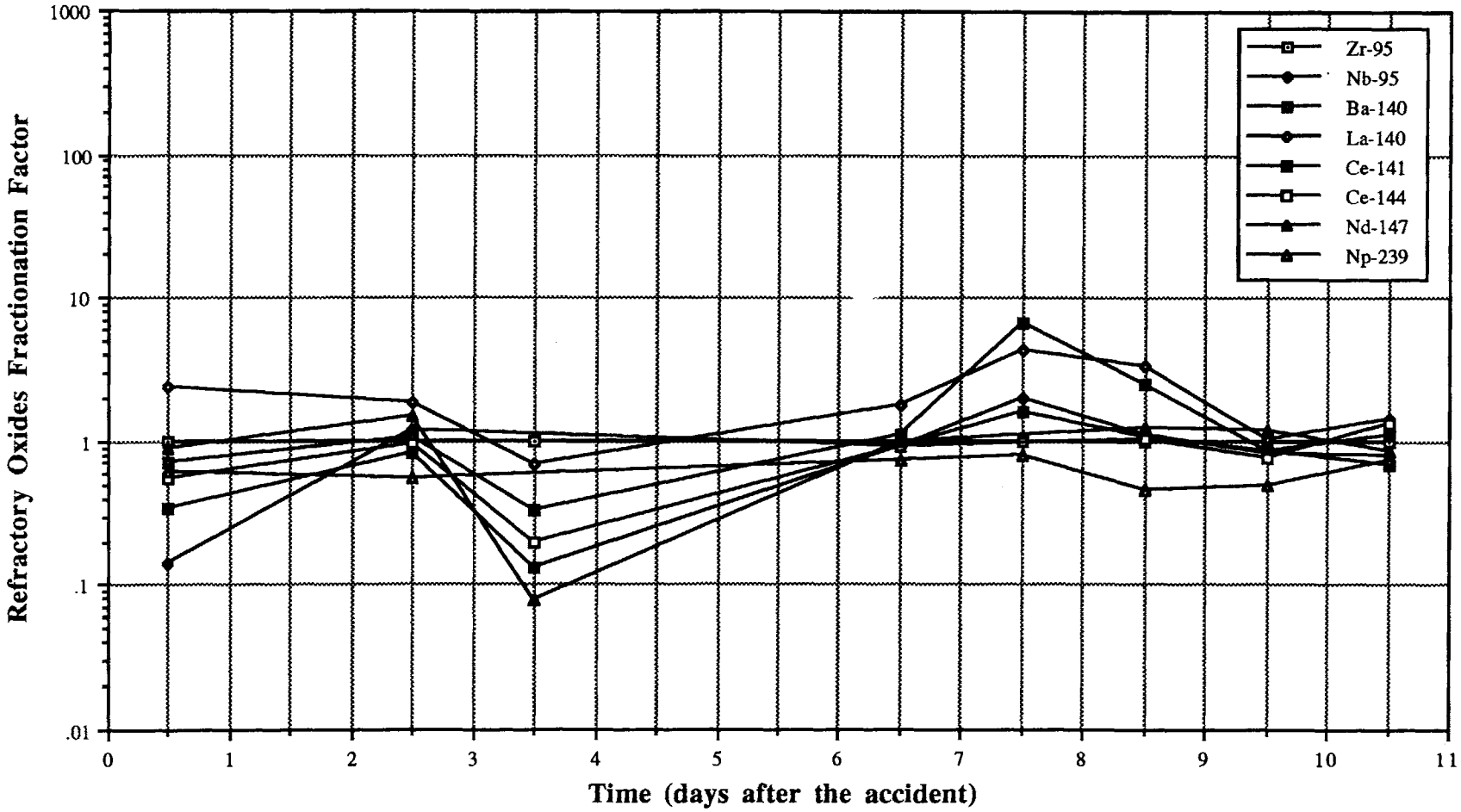


Figure VI.10

Fractionation Factor, $k_{i\text{-}95}$, for the Refractory Oxides Over the Period of the Active Phase



Certain trends are apparent from the figures of fractionation factors. First, as expected, generally the less volatile an element, the lower its $k_{i\text{-}95}$ value (i.e., the lower its efficacy for release with respect to Zr-95.) However, the difference in magnitudes of releases between the three groups is significantly less than expected. In fact, the differences between the volatiles and refractory oxides (which both roughly bound the refractory metals) are within an order of magnitude of each other. (Again, the behavior of Cs-136, because of reasons discussed above and according to Figure VI.8 which shows its fractionation factor to be more than an order of magnitude lower than Zr-95, can be discounted.) It then appears from the fractionation factor values that some unknown mechanism is limiting the release of the volatiles during the Active Phase; and this supports findings in Chapter V that an average 35% of the Cs-137 inventory in the corium was retained.

Although it is difficult to determine conclusively (because there is no data available for the period between days 3.5 and 6.5 for comparison), it is clear that some as yet unknown peculiarity on April 28–29 (day 3.5) sharply decreased the release efficacy of all the radioisotopes. Given the way air sampling was conducted (at one position in space and once per day), this may simply be a result of a wind shift at the time of the sampling.* Another possibility may be that a very small fraction of the material being dumped by the helicopters was actually able to enter the core shaft and disrupt the geometry enough to inhibit (for some reason) the release efficacy with respect to Zr-95. The effects of these possible scenarios cannot now be determined – without more information we can only speculate.

The normalized mass release curves of Figures VI.6 & VI.7 also show a decrease for all radioisotopes except for the tracer Zr-95 which increased substantially from day 2.5 to 3.5. Additionally (although bearing in mind the reliability of data for the first day is questionable), in Figure VI.10 Nb-95 shows an almost order of magnitude increase in its fractionation factor. It may be that because the core of a 1000 MWe RBMK contains approxi-

* In fact, it was on these days that a major shift in the wind occurred. During the first three days the prevailing winds were blowing toward the north-by-northeast carrying radioisotopes into Scandinavia. Afterwards the wind shifted to the southeast carrying the release plume over the Ukrainian capital Kyjiv.

mately 103 tonnes of Zircaloy-2.5 (Zr-2.5% Nb) in the channel pressure tubes and 74 tonnes of Zircaloy-1 (Zr-1.0% Nb) in the fuel rods[54] (yielding 173.5 tonnes of zirconium metal and 3.5 tonnes of niobium metal in the core), the relatively large release may be due to the excess presence of these metals. At the time of the accident, the fuel contained 5.8 and 3.9 kilograms of Zr-95 and Nb-95 respectively. Moreover, neutron activation could have produced significant amounts of these isotopes (relative to fission products produced in the fuel) in the fuel cladding and pressure tubes to explain such high $k_{i\text{-}95}$ values.†

As with the normalized mass release curves, the most prominent feature of the fractionation factor curves is the peak near the end of the Active Phase – the volatiles showing the greatest increase in efficacy of release while the refractory oxides show the least. However, in contrast to the former curves, the latter peak one day earlier at day 7.5. Figures VI.11 & VI.12 present the general trends of the isotope groups. (Note that these groups are averaged values of the mass release and fractionation factor intended only for illustrating general trends.) It is known that the dumping of materials into the reactor building stopped on May 2rd (day 6.5); but it is hardly likely this could have influenced the releases given the fact that the material did not cover the major part of the core (≈ 135 tonnes) still located in the reactor shaft. The difference in peak positions is more readily explained by the fact that according to the normalized mass release curves, Zr-95 has the second lowest value on day 7.5. Dividing by such low normalized value of activity to obtain the fractionation factors would artificially inflate the $k_{i\text{-}95}$ for the isotopes – especially in the cases of the volatiles. This is confirmed for day 8.5 where the fractionation factors return approximately to their day 6.5 values.

---

[54] Герасимов, А. С., Т. С. Зарицкая, А. П. Рудик, *Справочник по образованию нуклидов в ядерных реакторах*, Москва: Энергоатомиздат, (1989): 143.

† Detailed abundance and decay curves have been published for fission products (divided into nine chemical volatility groups) resulting from prompt or simultaneous fission that are typical of the spectrum from weapons tests or criticality accidents. From approximately one to two days after such an event, the niobium-zirconium group actually contributes more to the total activity than any other – and thus may be a contributing factor to the high $k_{i\text{-}95}$ values for these isotopes. [See Figure 1-8 in G. W. Parker & C. J. Barton, "Chapter 18 – Fission Product Release," *The Technology of Nuclear Reactor Safety*, Editors T. J. Thompson & J. G. Beckerley, Cambridge: The MIT Press, (1973): 538.

Figure VI.11

Average Normalized Mass Release Curves for the Volatiles and Non-Volatiles Over the Period of the Active Phase

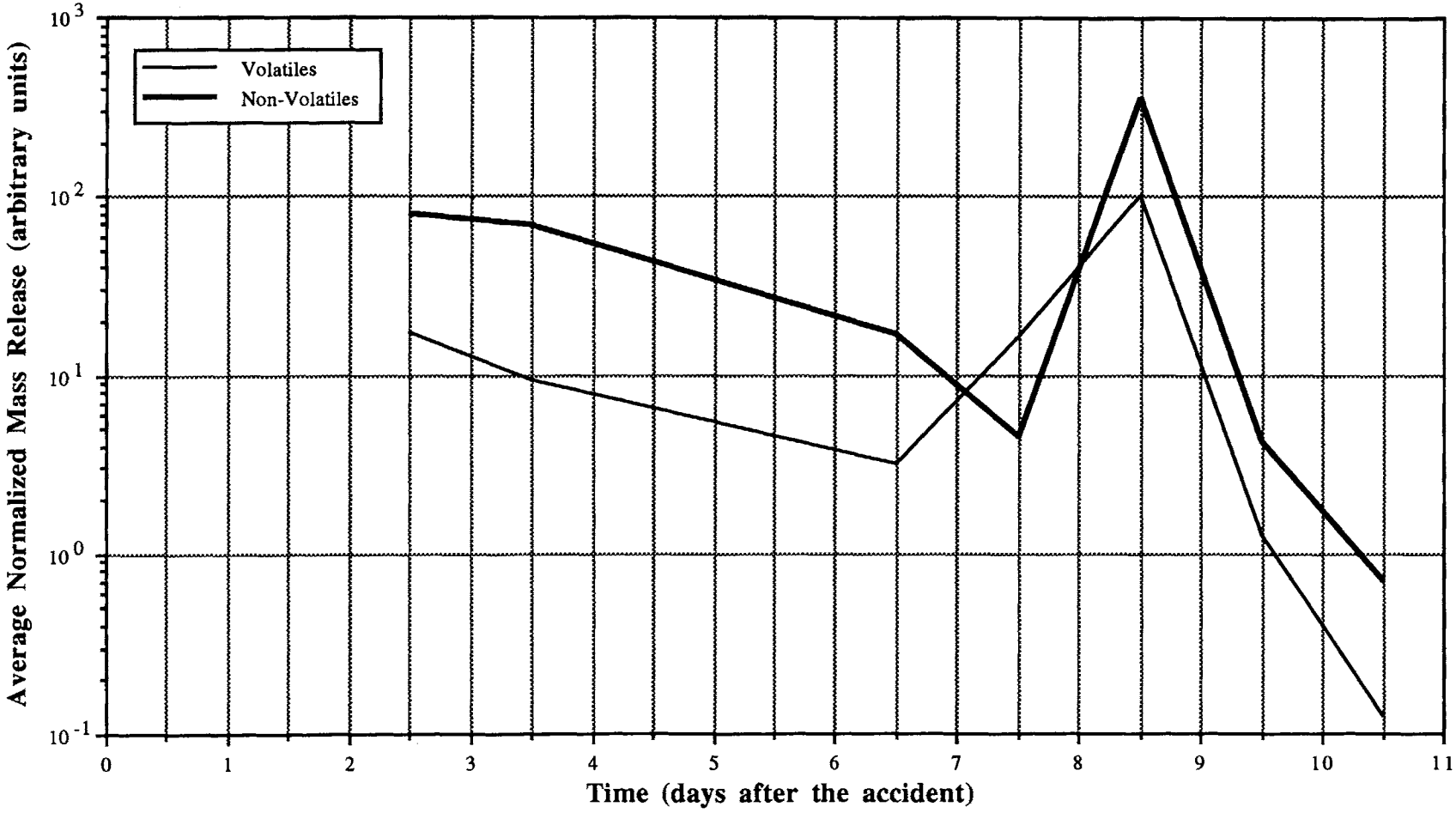
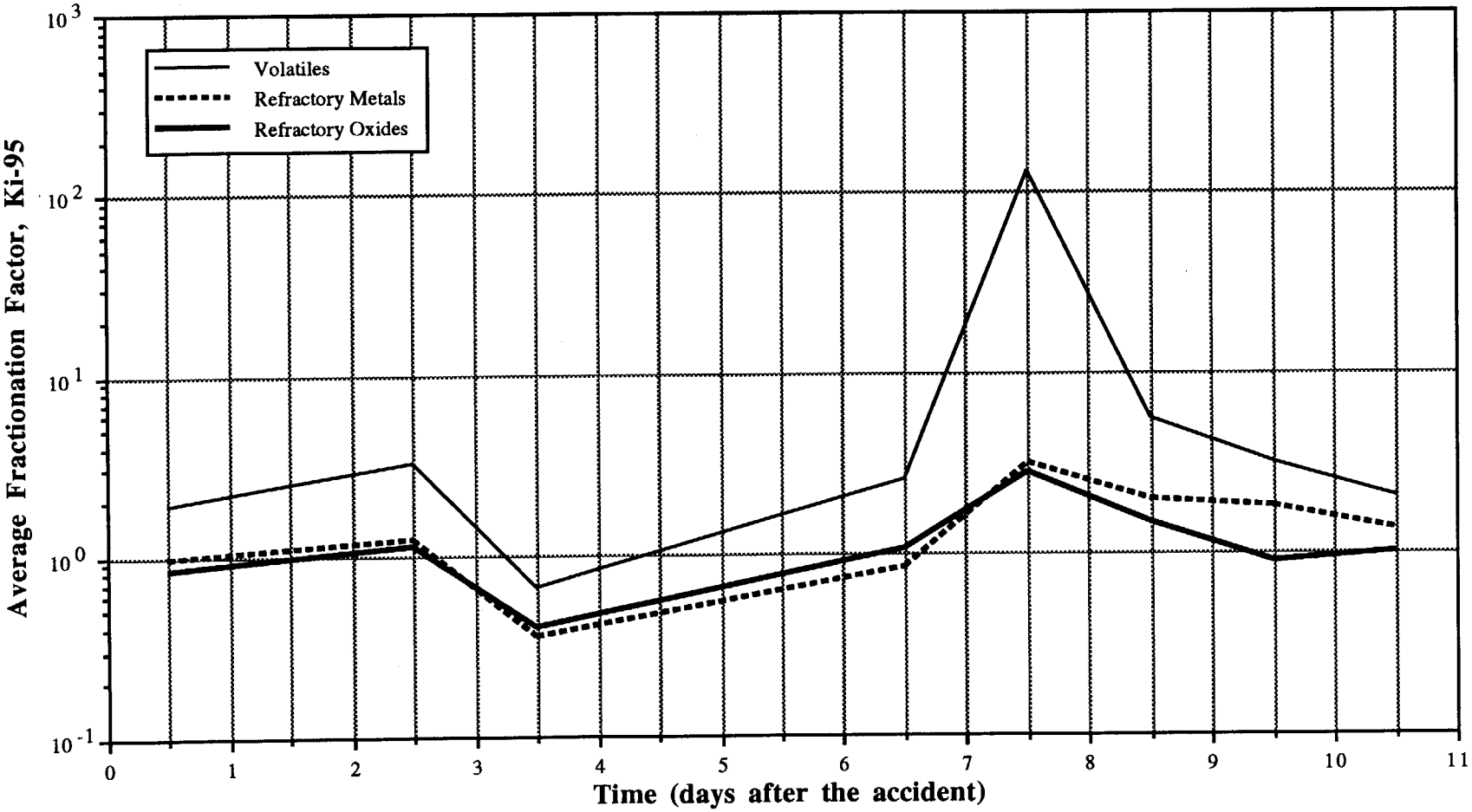


Figure VI.12

Average Fractionation Factor, $k_{i\text{-}95}$, for the Volatiles, Refractory Metals, and Refractory Oxides Over the Period of the Active Phase



Knowing the fractionation factor, little can be said about the absolute release rates for the radioisotopes in question because, recall, $k_{i\text{-}95}$ represents only the "efficacy" of isotope release relative to the Zr-95 tracer. Note also that in this study the methodology differs from a similar analysis in D. A. Powers et al,[55] where the data from Table 4.10 combined with Table 4.13 of the Soviet report[56] (the "bathtub" curve) was used to produce figures of fractional release rates for individual radioisotopes. (It has already been shown that the Soviet accounts of accident management actions and release data presented at Vienna are unreliable.) The results for the current analysis were obtained by combining newly-available PROBA data with the more precise core inventory calculations that provided the core inventory in intervals of twelve hours for 300 hours after the accident. Results from the normalized mass release curves show that radioisotope release rates remain more or less steady or even decrease with time – in contrast to D. A. Powers et al, where release rates are shown to increase significantly with time.

VI.3.4. Source Term Estimate

A non-rigorous but conservative estimate for volatile radionuclide and total releases from Chornobyl may be obtained by considering the results of radiochemical analyses of Fuel-Containing Masses (FCMs or "lava") and a preliminary material balance applied to the remaining fuel located within the sarcophagus – both presented in Chapter V – together with results of the source term analysis presented here. As mentioned Chapter V, analyses of the lava located in the lower regions of the reactor building show that the ratio of the measured activity of Cs-137 to the calculated (or "expected") activity, A_{meas}/A_{calc}, is 0.35 $\pm$ 0.11. Unfortunately, although Table V.2 presents a fuel material balance, the errors are large and some of the fuel is unaccounted for. The corium located in the lower regions of the reactor building has been studied and quantified more extensively than other forms of

[55] D. A. Powers, et al., 14–15.

[56] USSR State Committee, Part II, Appendix 4, (13, 20). The hypotheses presented in section 4.3 of the report, concerning what may have been happening within to the core of the reactor within the reactor shaft during the Active Phase, are of course flawed.

the fuel. Even here, however, efforts to determine the amount of fuel present have not been very precise because the extreme radiation environment within the sarcophagus has forced researchers to employ rather ingenious methods (but without independent confirmation or testing) to locate and quantify fuel in inaccessible regions of the reactor building.[57] Moreover, there has been no positive confirmation (although it is fairly certain) that approximately eleven tonnes of nuclear fuel is located on the floor of the Central Hall of the reactor building beneath 5,020 tonnes of materials thrown from helicopters in an attempt to smother the burning core. However, even if eventually there is no fuel found there, the "missing mass" falls well within the bounds of uncertainty.

The volatile radionuclides are the halides (bromine and iodine), alkali metals (rubidium and cesium), along with the metals silver, tellurium,** and antimony. For a lower bound estimate, however, we will limit ourselves to iodine, cesium (most biologically hazardous), and tellurium. Moreover, out of these elements we will further limit ourselves to those with significant half-lives, i.e., those with half-lives on the order of one day or greater.[58] Knowing that approximately 65% of the cesium was released from the lava, we must also estimate the amount of iodine** and tellurium released – and all three subject to the actual amount released beyond the reactor building, i.e., a certain amount of the releases plated out onto debris surfaces in the damaged building. If we assume conservatively that 35% of the cesium from the lava was released to the atmosphere† (i.e., approximately half plated

---

[57] Borovoi, A. A., Ivanov, A. I., Sich, Alexander, "Use of Robotic Technologies and Remote Systems for Diagnostics and Research Within the Chornobyl Sarcophagus," *Proceedings of the ANS Fifth Topical Meeting on Robotics and Remote Systems*, Knoxville, April 25–30, 1993.

** Note tellurium's volatility will be depressed somewhat if it combines with metallic zirconium.

[58] We choose this $t_{1/2}$ = 1 day half-life limit because, although many of the shorter-lived isotopes do not represent a prolonged-exposure hazard, this time is significant over the 10 day period of the Active Phase, and because some residents of nearby villages (now located within the 30 km exclusion zone) were not evacuated until approximately 8.5 days after the accident. [Ю. В. Сивинцева и В. А. Качалова, общие редакторы, *Чернобыль: Пять трудных лет*, Москва: Издат, (1992): 251.]

** To confirm how much iodine was released from this portion of the fuel, in principle one could analyze the corium for the presence of I-129. However, it would be quite difficult to detect I-129 because of its long half-life (1.574×10^7 years) and because it emits a weak beta (0.15 MeV) and gamma (39.6 keV) that would be lost in the "noise" of other fission product decays in the corium.

† Recall the above review of release estimates seems to indicate that approximately one third of the core inventory Cs-137 was released.

out)[59] we may assume that 40% radiotellurium and 60% radioiodine were released.[††] Finally, consideration must be given to the approximately 14% (27 tonnes) of fuel which is likely located on the floor of the Central Hall. Because the helicopters did not start dropping materials onto this portion of the core until around 10:00 A.M. on Sunday, April 27th (at least 32 hours after the accident), and because visual evidence suggests that it was "burning" (the main reason for attempting to smother it with the materials), it is expected to have contributed significantly to overall releases – and the assumption is that releases from this portion of the core approximated that reported by the Soviets in Vienna, i.e., 13% Cs, 15% Te, 20% I. We will neglect as insignificant volatile radionuclide releases from large core fragments and microparticles.*

Given the available information and taking into account only the seven most significant volatile isotopes, Table VI.15 presents this study's volatile element release estimates. The most important result is that this analysis yields a conservative estimate for releases of approximately 185 MCi – implying the total release was probably over 200 MCi, or more than four times the 50 MCi release (excluding noble gases) claimed by the Soviet in Vienna. Even if the Soviet figures of 13% Cs, 15% Te, and 20% I are taken as correct (a grossly inaccurate assumption) and apply these figures to the current analysis, the "significant" volatiles alone yield a release of 72 MCi – again, more than the total Soviet release estimate.

---

[59] This is overly conservative. Directly in the path of the releases from the fuel, the Upper Biological Shield was being strongly heated from the molten fuel (decay heat, graphite oxidation, and other exothermic chemical reactions.) Moreover, recent experimental investigations conclude that, "...as a result of their high chemical reactivity, the alkali metals display different transport characteristics in steam and hydrogen. In reducing atmospheres, a major fraction of the cesium is condensible, but, *under oxidizing conditions, the aerosol forms predominate.* (emphasis added) [Morris F. Osborne and Richard A. Lorenz, "ORNL Studies of Fission Product Release Under LWR Severe Accident Conditions," *Nuclear Safety*, Vol. 33, No. 3 (July – September 1992): 362.

[††] The ratio of releases of these three elements (Cs/Te/I = 35/40/60) reflects roughly the release ratio as presented by the Soviets in Vienna (Cs/Te/I = 13/15/20). This is not a bad estimate and in fact may be conservative given the volatility of iodine and conditions for release ("dry" ambient conditions and no filtration). As volatiles are carried away from the bulk corium in an atmosphere of steam and hydrogen, some may condense on structural surfaces or on aerosols formed from vapors of structural materials. However, given the high ambient heating – especially in the region of the reactor shaft – little could have plated out on hot debris.

* Recent studies have shown that this may not be the case and releases may have been quite significant (relative to the bulk mass release).

One final point must be made about the Soviet claim that 3.5 ± 0.5% of the core *mass* (6660 ± 950 kg) was released beyond the bounds of the station. Using the core inventories of all twelve isotopes presented in Table VI.15, it is readily shown that the initial mass of these isotopes (1600 MCi activity) is 110 kilograms. The implication is that even if all these isotopes are considered and assuming all are 100% released from the core, this mass is lost in the "noise" of the 950 kg error in the Soviet estimate – further implying that considerable *activity* releases may have occurred that would be virtually undetectable in the *mass* release estimate. By emphasizing the 3.5 ± 0.5% release as correct (which it probably is), it was possible to focus attention away from biologically significant radioisotope releases – even though these releases are more than three times that reported by the Soviets in Vienna.

Table VI.15

Estimated Activity Releases from Chornobyl
[radionuclides with significant half-lives ($t_{1/2} \geq 1$ day)]

1	2	3	4	5	6	7	8	9	10	11	12	13
Basic / Initial (t = 0) Data				**Fuel-Containing Materials (FCMs)**				**Central Hall & Outside Reactor Building**				**Total**
Isotope	Half-life	Activity (MCi)	Mass (kg)	fractional contribution	fractional release	fractional (1 - plateout)	release (MCi)	fractional contribution	fractional release	fractional (1 - plateout)	release (MCi)	**Release (MCi)**
Ru-103	39.25 d	102	3.2	0.71	0.95	??	??	>0.2	??	??	??	**??**
Ru-106	372.56 d	23.2	7.0	0.71	0.95	??	??	>0.2	??	??	??	**??**
Te-129m	33.6 d	28.1	0.93	0.71	(0.50)	(0.5)	5	>0.2	(0.30)	(0.9)	1.5	**6.5**
Te-132	78.03 h	121	0.40	0.71	(0.50)	(0.5)	21.5	>0.2	(0.30)	(0.9)	6.5	**28**
Te-134	41.8 m	208	0.0062	0.71				>0.2				
I-129	1.57 e7 y	(2.0 e-6)	(11.3)	0.71	(0.50)	(0.5)	–	>0.2	(0.50)	(0.9)	–	**–**
I-131	8.04 d	83.2	0.67	0.71	(0.80)	(0.5)	23.6	>0.2	(0.50)	(0.9)	7.5	**31.1**
I-132	2.284 h	121	0.012	0.71				>0.2				
I-133	20.8 h	181	0.16	0.71	(0.80)	(0.5)	51.4	>0.2	(0.50)	(0.9)	16.3	**67.7**
I-134	52.6 m	208	0.0078	0.71				>0.2				
Cs-134	2.062 y	4.6	3.5	0.71	0.65	(0.5)	1.1	>0.2	(0.30)	(0.9)	0.2	**1.3**
Cs-136	13.16 d	169	2.3	0.71	0.65	(0.5)	39	>0.2	(0.30)	(0.9)	9.1	**48.1**
Cs-137	30.0 y	7	80.4	0.71	0.65	(0.5)	1.6	>0.2	(0.30)	(0.9)	0.4	**2**
Cs-138	32.2 m	177	0.0042	0.71				>0.2				
Cs-139	9.27 m	167	0.0011	0.71				>0.2				
Total		**1600**	**110**				**143**				**41.5**	**185**

NOTE: Figures in parentheses are conservative estimates; shaded radionuclides have ($t_{1/2} < 1$ day).

Columns 4 – 7 FCM = Fuel-Containing Materials, i.e., that portion of the core currently located in the lower regions of the reactor building.

Columns 8 – 11 Central Hall & Outside Reactor Building = that portion of the core located on the floor of the Central Hall, outside the reactor building but within the bounds of the station, and beyond the bounds of the station.

fractional contribution Mass fraction of the entire core contributing to this release.

fractional release Fractional release from that portion of the fuel (as obtained or estimated from chemical analyses).

fractional (1 - plateout) Fraction that escaped from the fuel and debris into the environment.

release = (Initial Activity) × (fractional contribution) × (fractional release) × (fractional (1 - plateout)).

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

VII.1. Introduction

Rather than simply an academic exercise, establishing the sequence of events or scenario for the Active Phase of the Chornobyl accident has important ramifications for western severe reactor accident and degraded core analyses, as well as for source term analyses. Moreover, based on the new data and information presented in previous chapters, a radically different account appears to be emerging as to what may have been happening to the Chornobyl Unit-4 core over the period of the Active Phase. This, in turn, has important safety ramifications and severe accident planning implications for the fourteen or so RBMK reactors operating in Lithuania, Russia, and Ukraine. It is therefore, the primary goal of this concluding chapter is to hypothesize what may have happened to the reactor core over the period of the Active Phase by assembling the evidence provided in previous chapters to synthesize and reconstruct the sequence of events.

The second half of Chapter IV revisited and reappraised Accident Management Actions (AMAs) taken to contain the release of radioisotopes into the environment during the Active Phase. In particular, it is clear that Soviet attempts to smother the fire by dumping materials onto the Central Hall failed to reach and cover the burning core. The implication is that the core burned virtually in the open – further implying substantially more radioactivity was released than reported by the Soviets at Vienna. Additionally, given that the other AMAs outlined in Chapter IV were also, for the most part, unsuccessful in containing that portion

of the core participating in the corium-Lower Biological Shield melt-through,* the Chornobyl accident may well define the upper bound for severe accident releases.

This conjecture is supported by results of radiochemical analyses of corium presented in Chapter V. Approximately 71% of the core (≈135 tonnes) melted through the Lower Biological Shield, flowed into the lower regions of the reactor building, and quickly solidified into several forms of ceramic glass and pumice-like substances. The amount of Cs-137 remaining within the corium matrix as a fraction of the initial inventory is approximately 0.35, i.e., approximately 65% of the initial inventory *of this portion of the core* (≈71%) may have been released. There are two curious features of this result. First, this clashes strongly with the 13 ± 6.5% Cs-137 release reported by the Soviets in 1986 at Vienna.† Second, that fully 35% of the initial inventory of Cs-137 was retained in the fuel is unexpected given the length the time this portion of the core may have been molten (approximately nine days) while exposed to strongly oxidizing conditions, expectations of Cs-137 retention based on elemental volatility, and the experience of TMI-2 where only between 3 and 19% of the inventory of Cs-137 was retained in the molten debris under *reducing* conditions. Unfortunately, it is not known in what chemical form the cesium is found. If it formed the non-volatile CsI (which is soluble in water), this may explain the relatively large fraction retained in the corium at Chornobyl and why so little was retained at TMI-2.

Finally, the fact that the Lower Biological Shield acted as a "core-retainer" – permitting fuel decay heat generation to decrease while complicating the chemistry of the corium-LBS mixture – effectively reduced the ability of the corium to interact with surrounding structural materials. Chapter V detailed the current state of the nuclear fuel located in the

---

* Recall that the approximately 135 tonnes of UO_2 fuel participating in the melt-through is equivalent to the full core load of a 1300 MWe western BWR.

† As shown in Chapter VI, a (0.65% release) x (0.71% of the core) x (a very conservative 50% plate-out) yields an approximate 23% release into the environment. This still does not account for the remaining 29% of core ejected into the upper regions of the Central Hall and outside the reactor building – which may bring the total Cs-137 release to a conservative 40%. And this in turn, calls into serious question the Soviet claim that only 20% of the core inventory of I-131 was released. The fact that the core burned in the open during the Active Phase may drive the final Cs-137 release figure to 50–60% of the initial core inventory.

lower regions of the reactor building, and showed quite clearly, albeit unexpectedly, that after having melted through the Lower Biological Shield the corium did relatively little damage even to surrounding metallic structures. This result appears to justify western efforts to design core-retention components as part of future LWR containment designs.* It may also eventually show that the infamous and somewhat exaggerated "China Syndrome" appears much less likely to occur – even for an accident as severe as Chornobyl.

Regarding safety considerations for currently operating RBMKs, although this type of reactor differs radically from western LWRs (both in design and construction) and that an accident such as Chornobyl in all probability could never transpire at nuclear power installations in the West, it is not precluded that a sever accident could occur at the fourteen operating or planned RBMKs in Russia and Lithuania (Sosnovyj Bor, Kursk, Smolensk, and Ignalina Stations).[1] The design-basis accident for an RBMK-1000 is the rupture of a maximum of two "technological" or fueled-coolant channels in the reactor core, where in the event of such accident the ECCS and pressure suppression system (bubbler pool underneath the reactor) are designed to contain the associated over-pressurization of the thin stainless steel shell that surrounds the core. If more than two of the 1661 technological channels fail, it is postulated that the Upper Biological Shield would be lifted upwards –

---

* Note that a typical 1000 MWe western PWR or BWR have a UO_2 fuel load of approximately 75 and 115 tonnes respectively – as compared to the RBMK-1000 with a 190.3 tonne UO_2 fuel load where, for the case of the Chornobyl accident, about 135 tonnes flowed into the lower regions of the reactor building.

[1] In addition to imposing a moratorium on the construction of new reactor units till the end of 1994 in the wake of the Chornobyl accident (now rescinded), the Ukrainian Rada (Parliament) voted to shutdown the entire Chornobyl Nuclear Power Station effective midnight on December 31, 1993 (also rescinded) – leaving Ukrainian with twelve operating VVER (PWR-type) reactors at four stations on its territory: at the *Rivne Station* – one operating VVER-1000, two operating VVER-440s, and one VVER-1000 near completion; at the *Khmel'nyts'kyj Station* – one operating VVER-1000 and one VVER-1000 near completion; at the *South Ukraine Station* – three operating VVER-1000s; and at the *Zaporizhzhja Station* – five operating VVER-1000s and one VVER-1000 near completion. Units 1 & 2 at the *Chornobyl Station* are 1st generation RBMK-1000s with no pressure suppression pool to contain a design-basis accident, and Unit-2 has been shutdown since a major fire that destroyed one of its turbines in October 1991. Unit-3 and the destroyed Unit-4 are 2nd generation RBMK-1000s with a pressure suppression pool and upgraded ECCS. Construction on Units 5 & 6 (30 and 75% complete respectively), located approximately 1.5 kilometers southeast of the original four units, was abandoned in April 1987. In 1992 nuclear power accounted for approximately 27% of Ukraine's electrical power generating capacity.

shearing more of the channels that would lead to a loss of coolant and fuel melting.[2] Despite certain design improvements implemented by the Lithuanians, Russians, and Ukrainians for *some* of their RBMKs, each reactor remains without an adequate containment.[3] For this reason alone, an accurate appraisal of the Chornobyl accident is essential for probabilistic safety analyses of operating RBMKs, major backfit and upgrade plans for these reactors, emergency response and evacuation procedures, or to assess whether RBMKs should continue to operate in the future.

VII.2. Active Phase Scenario

VII.2.1. Mechanical-Dynamic Stage

The starting moment for this stage (8604.626/01:23:39–40) is actually four to five seconds prior to the beginning of the Active Phase and is defined as the time at which the operator pressed the emergency scram (AZ-5) button – an action for which to this day the motivation has not been clearly established. Unknown to the operators, the effect of the reinsertion of this fully withdrawn control rod bank (AR and RR rods) was to add approximately +0.5β to an already out-of-control reactivity increase initiated by the coast-down of the main coolant pumps participating in the safety experiment. It is at this time that a significant event is witnessed by the Central Hall shift foreman who was located approximately 14.5 meters (Level 50 m) above the floor of the Central Hall: not only did he feel the strong and frequent shocks (as did the reactor operators located on Level 12.5 m), but in addition he noticed that the 2,488 fuel and control channel caps (each with a mass of 80 kilograms –

---

[2] There is already a precedent for coolant channel ruptures in the aging fleet of operating RBMKs in the CIS: Sosnovyj Bor (Leningrad) Station Unit-1 in 1975, Chornobyl Unit-1 in 1982, Chornobyl Unit-4 in 1986, and Sosnovyj Bor Unit-4 in 1992.

[3] There are studies currently underway to design a pressure containment system to mitigate against the rupture of one of the forty-four (twenty-two per loop) group-distribution header which distributes coolant water to approximately forty of the reactors 1661 coolant channels. If implemented (difficult at best considering Russia's current economic plight), this would certainly decrease the probability of a catastrophic failure – although the upper part of the reactor would still remain without effective containment. See: International Atomic Energy Agency, *Safety Assessment of Proposed Improvements to RBMK Nuclear Power Plants*, IAEA–TECDOC-694: Vienna, Austria, (March 1993).

located directly over the reactor at floor level in the Central Hall) were vibrating violently up and down (see Chapter IV.2).

Apparently by this time, more than one or two pressure tubes in the reactor had burst – releasing steam into the reactor space – overpressurizing the thin stainless-steel reactor pressure boundary, *Component KZh*.[4] Steam would then have entered the space above the Upper Biological Shield but below the floor-level shield blocks covering the pressure tube refueling connections. If the steam blow-down was rapid, some shield blocks could even have been ejected from the floor. Moreover, a breach of *Component KZh* would have permitted steam to easily lift the 2500 tonne-equivalent Upper Biological Shield (UBS) and its associated coolant piping.* Even a slight rise (1–2 centimeters) of the UBS would have sheared most of the channels at precisely the weakest point in the coolant circulation circuit – the zirconium-to-stainless steel transition weld located above the core. It is speculated here that the first "explosion" may have been the rise and fall of the very large and heavy UBS and the associated rapid blow-down of steam as it escaped from the reactor cavity.†

Also, by this time the fuel channels would have been sufficiently damaged as to inhibit or even block the further insertion of the emergency scram rods into the core. Additionally, with the shearing of the channels there would have been a rapid flashing to steam of coolant in the reactor and a severe over-pressurization of the reactor space and possibly adjacent

---

[4] "...vault rupture disks are designed to accomodate the rupture of only one pressure tube in [the] reactor... a LOCA to several tubes would be [considered] a severe accident." [*NUREG-1250*, 3-32] Any subsequent local power increase (due to voiding) in the affected channel(s) could propogate to other channels in the immediate area – although not to the degree of the affected channel – exacerbating the problem. Soviet designers consider rupture of a pressure tube inside he reactor vault [i.e., inside the graphite pile] to be beyond the design basis of the plant (based on "leak before break") – although a [*Component KZh*) rupture disc is based on one tube rupturing... "The rupture of more than one pressure tube is beyond the design basis of the RBMK-1000 reactor. Such an event would exceed the stated relief capacity of the reactor vault and could overpressurize it. Excess pressure might deform or rupture the vault, or it might lift the Upper Biological Shield enough to relieve pressure to the upper core exit piping region." [*NUREG-1250*, 3-52]

* A simple calculation, p = ma/A (using the values given in Appendix III.B), yields a pressure of only just over 0.1 MPa (approximately one atmosphere) needed to raise the UBS. *NUREG-1250* (2-43) states, "If the pressure exceeds 0.3 MPa (44 psi), the Upper Biological Shield will lift up. Since the fuel channels are welded to the upper shield, its upward movement will lead to massive tube failures. Furthermore, since the control rod channels are also connected to the UBS, the control rods will be lifted out of the core." In either case, relatively little pressure will lead to a catastrophic failure of the fueled channels.

† An everyday example of this is the cover of a violently boiling cooking pot "dancing" as steam built up on the inside overcomes the force (weight) of the cover and escapes to ambient.

compartments. It is conjectured here that the extremely rapid over-pressurization of the reactor space was subsequently followed by its explosive release – hurling the UBS approximately ten meters into the air and rotating its lower face partially upwards. Judging from the current state of the UBS and the belief that a significant amount of fuel (on the order of eleven tonnes, see Chapter V) may be located 15 meters to the east-southeast of the reactor cavity under the 5000-tonne pile of debris thrown from the helicopters vainly attempting to smother the "core," the UBS probably carried along with itself a small portion of the core still connected by pressure tubes that weren't severed (at the upper zirconium-to-stainless steel weld connection[††]) during the initial lifting of the UBS. This portion of the core was then ejected into the Central Hall – disconnecting from the UBS in mid-flight and landing approximately over the cover panels of the southern Spent Fuel Pool.

That a portion of the core may have landed in the Central Hall and the direction of core fragment ejection appear to be supported by three pieces of evidence. First, as viewed from above the damaged reactor, immediately after the accident core graphite moderator and reflector blocks along with their associated fuel lay scattered upon the roof of Unit-3 and the Auxiliary Building in a "preferred" direction to the east-by-southeast. In fact, before these roofs were decontaminated, a distinct "anti-shadow" lay behind the large ventilation chimney located on the roof of the Auxiliary Building where the chimney had blocked core debris from landing behind it in a east-by-southeast direction, while all around lay graphite blocks. Second, as described in the section on Accident Management Actions in Chapter IV, it is now clear that the infamous "red glow" – initially thought to be the burning core located inside the reactor cavity – was presumably only a small portion of the core located above the Southern Spent Fuel Pool.[**] Finally third, damage to the reactor building as evi-

---

[††] Recall that the same zirconium-to-stainless steel transition weld is found at the bottom of the core.

[**] An intriguing hypothesis states that the "red glow" was neither burning core graphite, burning bitumen from the roof, nor a hot, glowing portion of the core. Rather, it may simply have been the *image* of the exposed and very hot core still remaining in the reactor shaft *reflected* off the tilted Upper Biological Shield and onto debris located to the east of the reactor shaft. As helicopter crews attempted to bomb this "glow," the pile of materials would have been increasing in size thus presenting a larger and larger area upon which the image of the core could be reflected. Additionally, this would explain why the "glow" didn't disappear shortly after being bombed from the air, and would also explain why some witnesses stated they

denced by displaced structural members and heavy equipment displaced from their normal positions appears to indicate a particularly strong explosive pressure wave was directed toward the east-southeast – possibly partially reflected off the lower face of the UBS as it was in mid-flight. Interestingly, that the UBS was in the air for a certain period of time is evidenced by the fact that it is currently resting upon a damaged portion of the high-bay wall at the entrance to the reactor cavity in the southwest quadrant (Figures V.8 &V.9), and that other portions of panels from the high-bay wall are now located at the bottom of the reactor shaft on top of the remains of the Lower Biological Shield.

Particularly intriguing is how these high-bay wall panels ended up at the bottom of the reactor shaft – especially considering that the explosive release of steam (that hurled the UBS upwards and completely destroyed the upper parts of the Central Hall) was directed outwards as evidenced by the remains of the reactor building (see Figures II.1, V.4a, & V.5a). As mentioned in Chapter IV, it might be possible that a hydrogen-steam mixture entered the reinforced steam-drum separator chambers (Rooms 804/3 & 804/4 – by way of ducts along which the coolant piping exiting the top of the reactor eventually reaches the separators) and attained detonation concentrations on the order of four percent hydrogen. This would explain how the wall panels would have been blow in toward the middle of the Central Hall.[5]

---

saw the "glow" even after the bombing campaigns were stopped on May 2nd – seven days after the accident. This hypothesis appears to be credible for two reasons: (1) the operators that entered the Central Hall to appraise the damage shortly after the accident did not mention any burning or glowing mass located away from the reactor shaft, and (2) the thick "smoke" emanating from the Central Hall during the period of the Active Phase would have obscured visibility for the helicopter crews.

[5] Grigori Medvedev assertively conjectures that this "series of explosions destroyed the drum-separator compartments, as well as the drum-separators themselves... tearing them from their attachments and from the pipelines." In fact, although some of wall panels from the separator chambers facing inward toward the Central Hall are missing (apparently blown out), the steam drums themselves are *not* torn off their supports nor away from the coolant lines. Apparently, Medvedev assumes that whatever hydrogen was produced in the core traveled along the coolant channel piping into the steam drums themselves. Besides the fact that the steam drums are not heavily damaged, it is difficult to fully agree with this hypothesis because the channels in which hydrogen was being produced would have been destroyed – making it difficult for hydrogen transport along these channels. Moreover, it is easier to imagine that, rather than along the coolant channels, hydrogen would have traveled along the ducts containing the these channels. [Grigori Medvedev, *The Truth About Chernobyl*, New York: Basic Books, (1991): 81–82.]

Medvedev is convinced that the major explosion was the detonation of hydrogen, and that this is what destroyed the reactor building and hurled the UBS into the air: the detonation occurred in the reactor "which was full of hydrogen." There are at least two problems with this hypothesis. First, it is unclear if enough

VII.2.2. Source-Term Stage

The analysis now turns to the behavior of the core *after* the initial releases that resulted from the explosive nature of the core's destruction. It is clear that these short term initial releases are extremely difficult to model directly. By necessity they must be estimated from ground deposition measurements together with a thorough modeling of Active Phase release rates. It is beyond the scope of this dissertation to provide a rigorous model of these release rates. However, Chapter VI made some effort to clarify the behavior of certain radioisotopes over the course of the Active Phase; and it is hoped that future studies will be able to more accurately estimate these release rates. The intent here is to provide a reasonable account (hypothesis) of what may have transpired within the core shaft during the Active Phase based on information provided in Chapters IV – VI. There are several important points (conclusions drawn from preceding chapters) upon which the following hypothesis is based:

(1) Little or none of the materials thrown from helicopters during the first six days after the accident in an attempt to "smother" the burning core made it to that major portion of the core (≈71%) located within the reactor shaft. (Chapter IV)

(2) Results of radiochemical analyses indeed seem to confirm that essentially no lead or boron carbide made it into the core shaft. In addition, visual evidence (photographs) indicate that the materials thrown from the helicopters formed a pile located approximately 15 meters to the east of the core shaft, and that there is little of no evidence of these materials covering the opening to the reactor shaft or the Upper Biological Shield. (Chapter IV & V)

---

hydrogen was formed in the core to have produced this magnitude explosion. Recall from Chapter IV that apparently two narrow power surges occurred at 01:23:44 and 01:23:46. This is also the time at which the explosions were heard. Before the initial power surge the power was rising relatively slowly. It is therefore difficult to imagine that much hydrogen could have formed before 01:23:44. Second, even if a great deal of hydrogen was formed during and after the initial power surge, the detonation would have required the presence of oxygen in the core – also difficult to imagine.

Finally, as concerns the possibility for hydrogen detonation in the steam drum chambers, some time would have been required for any hydrogen produced in the core (together with oxygen from the same source) to have entered the chambers and to have attained detonation concentrations. This again leaves open the question of how the high-bay wall panels managed to enter the reactor shaft: If hydrogen explosions occurred in the steam drum chambers, they conceivably must have occurred *after* the major steam explosion that hurled the UBS into the air. If this is the case, how could the panels have entered the reactor shaft unless the UBS was in the air for a very long time?

(3) Nitrogen purging of the core region was apparently started after the Active Phase (Chapter IV). This, therefore, proved to be ineffective except as a back-up in the event that the hot corium continued its downward movement.

(4) A detailed description of the forms, compositions, and locations of the corium – the Lava-Like Fuel-Containing Materials (LFCMs) – permitted visualization of the dynamic behavior of the LFCMs. (Chapter V)

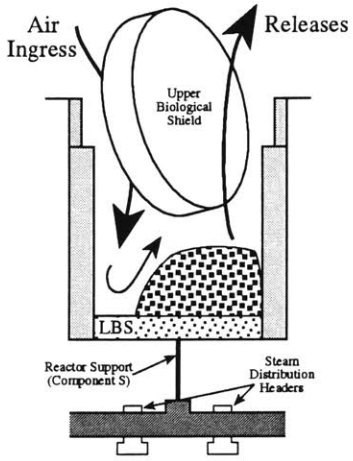
(5) New Soviet release data and an account of how data was collected permitted not only a reappraisal of the Soviet data, but also a better analysis of the behavior of seventeen isotopes whose chemical characteristics varied greatly. This in turn provided a rough notion of what may have been occurring within the reactor shaft over the period of the Active Phase. (Chapter VI)

VII.2.2.1. The Hypothesis

These revelations significantly alter conceptions of what may have been occurring in the core region during the Active Phase of the accident, and form the basis for the hypothesis. The hypothesis is presented as a sequences of events defined by a series of six stages (refer to Figure VII.1):

STAGE 1: The initial period after the explosive destruction of the core. The portion of the core that did not blow up and out of the core region eventually settled to the bottom of the core shaft on top of the Lower Biological Shield. The UO_2 and core metal structures (lower steel supports and Zircaloy tubing) also settled to the bottom and eventually melted. The vigorous oxidation (exothermic) of the graphite and zirconium (as evidenced by witnesses telling of a "howling" rush of air emanating from the mouth of the reactor cavity) together with decay heat generation (an integrated energy release estimate yields 8.5 GJoules over a ten day period) would have greatly suppressed the plateout of volatilized radionuclides or those carried by particulates. The heating of structures in the region (especially the lower portions of the Upper Biological Shield) would thus allow for significantly releases to occur.

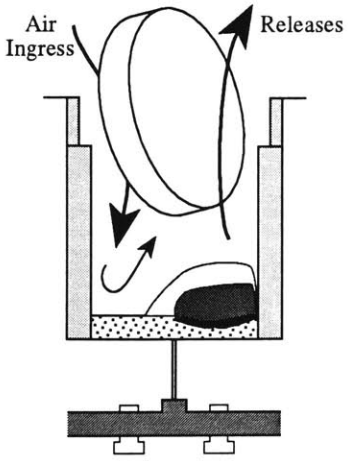
Figure VII.1
Hypothesized Accident-Progression Scenario During the Period of the Active Phase
(looking north)



April 26 ≈ 01:30
(Day 0+)

1

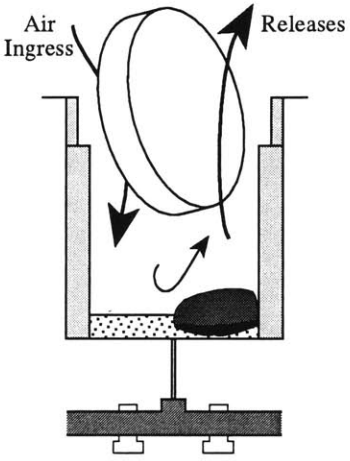
Core remains (pulverized fuel and graphite) settle on top of the Lower Biological Shield. Graphite oxidation and decay heat generation heats surrounding structures – greatly suppressing plateout onto these structures and thus increasing releases.



April 26 – May 2
(Day 0+ – Day 6.5–7)

2

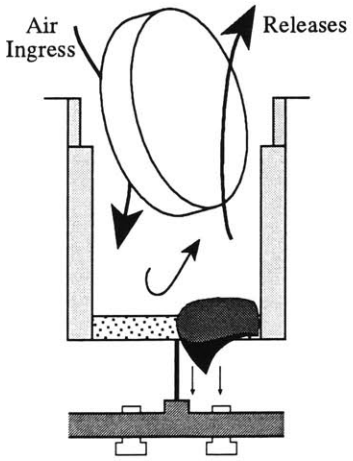
Melted fuel forming lower layer below graphite while interacting first with stainless steel plating of the LBS and later with serpentine filler and stainless steel coolant channels. Corium itself forming a lower metallic layer and upper ceramic/oxide layer and possibly a crust.



≈ May 2
(Day 6.5–7)

3

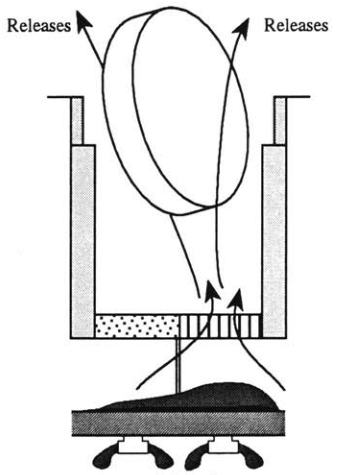
Upper graphite layer burns off enhancing volatile fission product releases. However, non-volatile fission product and actinide releases inhibited because less particulate releases are occurring.



May 3 – May 4
(Day 7.5 – 8.5)

4

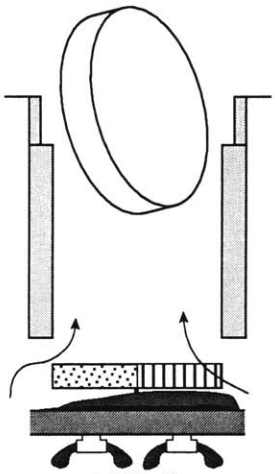
Melt-through: rapid downward and horizontal flows into the lower regions of the reactor building (not shown).



≈ May 4
(Day 8.5 – 9)

5

End of the Active Phase: releases drop by 2–3 orders of magnitude and continue to decrease. The corium has lost much of its ability to interact with surrounding materials and rapidly solidifies in mid-flow. (Decay heat is significantly lower, corium has spread out to provide a greater surface area for cooling, chemistry has been complicated by the interaction with the LBS.)



≥ May 5
(≥ Day 9)

6

The LBS (that which remains) decends ≈ 4 m. Decay heat heating of the stainless steel core support has lowered its yield point thus inducing creep under an approximately 800 tonne load.

STAGE 2: From the time of that the core and associated core structures settled to the bottom of the reactor shaft to approximately 6.5 – 7 days later, differences in the densities of the components of the pulverized graphite-corium mass would cause a differentiation and layering effect. The melted fuel would have first formed a lower layer below the graphite. There, it would interact initially with the stainless steel plating of the Lower Biological Shield, then with the stainless steel coolant piping and serpentine filler (recall, a hydrous magnesium silicate in the form of sand or small pebbles) within the LBS. Eventually, the fuel itself would differentiate to form a lower metal-enriched layer and a middle oxide layer – with the graphite forming the top layer only slightly insulating the rest of the corium. That a lower metal-rich layer was formed is evidenced by the current forms and locations of the LFCMs. Figure V.11 and the associated text indicate that a thin lower layer of highly radioactive solidified metal (especially enriched in Ru-103, Co-60, and other metals) exists under a thicker ceramic glass-like layer of corium in the Steam Distribution Corridor. What little (if any) sand or dolomite did get into the core – together with the serpentine and cast iron-pebble filler-material for the Lower Biological Shield – combined with the lava and increased the corium mixture's melting point – lowering its ability to interact and slowing the melting process. Heating of surrounding structures due to graphite oxidation and decay heat generation would continue to suppress radionuclide plateout.

STAGE 3: After approximately 6.5 days, the graphite associated with 71% of the core lying at the bottom of the reactor shaft (approximately 1340 tonnes) had burned off. There are three reasons to believe this. First, except for a few scattered blocks still located on top of the remaining portion of the Lower Biological Shield, there is no evidence of graphite remaining in the core region except for the charred and blackened southeast wall of the reactor shaft onto which some must have plated out. Second, there is no evidence of carbon or carbon-containing compounds in the results of radiochemical analyses of the corium. And third, there is a distinct deviation in behaviors of the volatile versus non-volatile radioisotopes as depicted in Figure VI.11 (average normalized mass release rate)

beginning around day 6.5 and ending around day 7.5. Up until that time the seventeen volatile and non-volatile radionuclides behaved quite similarly – indicating an isothermal process. A plausible explanation is that at that point the upper layer of graphite burned off. This would enhance the release of the volatiles because at the temperatures expected in the corium mass, the filtering effect of an (assumed) upper graphite layer would be gone. It would also decrease the releases of the non-volatiles because there would no longer be a particulate release mechanism available as a pathway to the environment.

STAGE 4: At approximately day 7.5–8, the corium melted through the Lower Biological Shield. Careful examination of the LBS shows that roughly its southeast quadrant is completely missing; while the remaining edges show signs of melting and sagging. The melt-through was followed by a rapid downward drop of the corium onto the floor of the Sub-Reactor Region where its momentum damages the wall between Room 305/2 and Room 304/3[†] – permitting corium to flow into Room 304/3, Corridor 301/5, and eventually southward down Corridor 301/6 (Figure V.10). The rapid (mechanical) redistribution of the corium and an increase in its surface area as it spreads horizontally substantially enhance radionuclide releases. This is also evidenced in Figure VI.11 where at day 7.5 there is a marked increase (by almost two orders of magnitude in the normalized mass releases of the non-volatiles and an order of magnitude increase in the release of volatiles to day 8.5. The corium also flowed downward into the Steam Distribution Corridor and Pressure Suppression Pool where it solidified into ceramic glass pumice-like formations (see figures in Chapter V). Still hot, the corium produced steam when it contacted whatever water remained in the Pressure Suppression Pool and caused an increase in the release of aerosols – which may also partly accounted for the peak in releases observed on day 8.5.

STAGE 5: At approximately 8.5 – 9 days after the accident, the Active Phase comes to an end. Releases drop by two to three orders of magnitude and continue to decrease. By this time the corium had lost much of its ability to interact with surrounding

[†] Note that the mass of corium has now substantially increased from 135 tonnes of fuel to a complex mixture of metals and serpentine with a mass of approximately 500 tonnes.

materials and rapidly solidified in mid-flow causing little if any damage even to metallic piping in the lower regions of the reactor building (Figures V.19 & V.20). Decay heat had dropped significantly, and the chemistry of the corium had been substantially altered (complicated) by the uptake of one quadrant (≈ 400 tonnes) of the LBS into the molten corium.

STAGE 6: Continued cooling of the solidified corium led to further reductions in releases – the hardened surface of the corium and reduced heated-air buoyancy effects suppress releases. At this point (beginning at about day 9), decay heat generation is 50 kWt/t U or about 3.75 MWt total heat generation. The approximately 75 tonnes of fuel contained in the corium located in Room 305/2 (Sub-Reactor Region) begins to heat the 110-tonne stainless steel reactor support, *Component S*, which at that point supports an approximately 800-tonne load. The combination of decay heat and loading stresses enhance creep in the reactor support; and eventually it compresses accordion-style – allowing the Lower Biological Shield to descend about four meters from its nominal position. The fact that the Lower Biological Shield descended slowly rather than as a result of the initial explosions that destroyed the core is evidenced by the quite smooth, drawn-out condition of the lower coolant channels to the north and south (Chapter V.2).

VII.2.2.1. Further Work to Confirm or Disprove the Hypothesis

Although the hypothesis presented above appears to agree well with the facts and data presented in preceding chapters, much remains to be studied to verify its plausibility and ultimate acceptance as a valid Active Phase scenario. There are five areas of research that should be pursued to confirm its validity. First, the melt-through of the Lower Biological Shield should be accurately modeled to establish a melting rate and time-frame for ultimate penetration of the LBS. This should incorporate, in particular, the effect of serpentine sparging (which contains more water of crystallization than regular concrete) on corium mixing and fission product transport mechanisms in the bulk material. Second, rigorous modeling is needed to determine the burn-off rate and ultimate loss of the approximately

1340 tonnes of well-rubblized graphite moderator and reflector that settled to the bottom of the reactor shaft together with the fuel-zirconium mixture.[6] Third, the effect of graphite as a particulate-transfer pathway for volatiles and non-volatiles should be studied to determine what mechanisms may inhibit the release of radionuclides, and to confirm the shape of release curves presented in Chapter V. Fourth, recent studies at INEL have confirmed that more cesium is retained in corium than previously thought (Chapter V). More attention should therefore be focused on understanding high-temperature chemistry effects on cesium and iodine volatility in degraded core analyses, and what role oxidizing graphite may have played in apparently suppressing the volatility of cesium. Finally fifth, because research conducted to date at Chornobyl has provided only a rather rough, descriptive account of the fuel and reactor building, a renewed effort, with the aid of western researchers, should be made to rigorously analyze the remains of Chornobyl Unit-4 as a basis for the above-recommend studies.

[6] This will be a particularly process to model precisely. Graphite burning is a rapid oxidation process at high temperatures. However, since it has a much higher thermal conductivity and no volatile carbon content as compared to coal, it is much more difficult to burn than coal. Whether graphite burning can be sustained is dependent on the presence of an external heat source (such as decay heat) or on a sufficient amount of heat available to maintain a high temperature from the oxidation reaction itself. Moreover, the geometrical configuration, the presence of sufficient quantities of oxygen, reaction product removal rates, the presence of chemical impurities, and vapor pressures all strongly influence the reaction rate. A brief summary of the literature concerning graphite loss rates under a variety of conditions is found in Pavel Hejzlar, Neil. E. Todreas, and Michael J. Driscoll, *Evaluation of Materials for the Fuel Matrix of a Passive Pressure Tube LWR Concept*, Program of Advanced Nuclear Power Studies, Massachusetts Institute of Technology, Report No. MIT-ANP-TR-017 (DOE/ER/75785-2), November 1993.

VII.3. Final Conclusions and Recommendations

VII.3.1. Results of the Investigation

The following is a brief summary of the conclusions contained in the more detailed discussions of Chapters IV–VI:

Results of Investigations and Analyses of the Nuclear Fuel

The behavior of Chornobyl corium (≈135 tonnes or ≈71% of the core's UO_2 fuel load) appears to indicate that "China Syndrome" scenario is much less likely to occur if a corium-retention system is implemented in containment designs:

(1) The corium melted through the ≈1200-tonne Lower Biological Shield (stainless steel construction with serpentine filler material) over a nine-day period. The corium lost much of its ability to interact with surrounding structures and quickly solidified because:

- Decay heat dropped to approximately 50 kWt/t U after nine days,
- The chemical system was complicated by the uptake of surrounding materials – especially the contribution of the LBS). This probably manifested itself as a change of the corium's melting temperature in various stratified layers.
- Rapid spreading over a distance up to 40 meters from the epicenter occurred after the corium had melted through the LBS,
- Little or no damage to the Pressure Suppression System piping and other structural components in the lower regions of the Unit-4 reactor building is evident.

(2) Retention of Cs-137 in the Chornobyl corium was 35% of the inital inventory of the fuel remaining in the core shaft. This is significantly higher than expected for highly-oxidizing conditions combined with the presence of burning graphite, that provided an additional particulate release (transport) mechanism over a nine-day period:

- The TMI accident released more cesium from the melted fuel than Chornobyl: 3% retained in the corium, 19% retained in the upper plenum debris.
- High-temperature chemical retention mechanisms for cesium ought to be investigated. Cesium may exist in low or mid-volatile chemical compounds at high temperatures.

Results of the Source Term Analysis

(1) Because the reactor had no containment, the release of fission products included an important component from the direct ejection of the fuel by the explosion.

(2) A new lower bound source term estimate for the volatile elements cesium, tellurium, and iodine indicates that on the order of four to five times more radioactivity was released into the environment that the 50 MCi (excluding nobles gases) reported by the Soviet at the IAEA Vienna Conference in August 1986.

(3) The fact that most of the core's iodine may have been released (as opposed to 20% I-131 reported by the Soviets in 1986) may provide a direct connection to the currently-observed very significant rise in childhood thyroid cancers in Belarus and Ukraine.

Accident Management Issues

Soviet attempts to contain the accident – especially during the initial nine to ten days when significant releases were occurring (the so called "Active Phase" of the accident) – now appear to have been ineffective or unfulfilled. The implication is that the accident shut itself down at the end of the Active Phase. It is hypothesized that the fuel melted through the Lower Biological Shield (while approximately 70% of the core's graphite burned away as it lay on top of the fuel), flowed into the lower regions of the reactor building, and quickly solidified.

(1) Little or none of the materials dropped from helicopters in an attempt to "smother" the fire actually made it into the core shaft.

(2) The *gaseous* nitrogen purging of the core was set up too late and would likely have proved ineffective given the conditions.

It appears that the Chornobyl Accident may well represent an upper bound for severe nuclear power plant accidents. As such, accident management analyses may be able to utilize the information to place conservative upper bounds on accident mangement planning strategies.

VII.3.2. General Conclusions

In a broader context, it appears that the efficacy of the Accident Management Actions, as previously concluded by the Soviets and subsequently by the IAEA, are now seriously in doubt. One might conclude, therefore, that there is little or nothing to be learned from them. However, re-examination was of value to identify the true lessons learned.

The IAEA's *International Chornobyl Project* should also be re-examined. This is particularly true given that it may now be possible to establish a direct link between the increased incidence of childhood thyroid cancers appearing in Belarus and Ukraine and the increased releases of the volatile I-131 as estimated and concluded here.[7] As explained in Chapter IV, it has been roundly criticized in Ukraine and the West – faulted for drawing specific conclusions from a study that a number of experts claim was limited in scope (neither the "liquidators" who worked to clean up and build the sarcophagus nor evacuees from the zone were studied) and partially biased because Moscow controlled access to data and people as opposed to the republics. Additionally, the IAEA's International Nuclear Safety Advisory Group (INSAG) should review conclusions in its original INSAG-1 report concerning the Accident Management Actions – with the intent of producing another reassessment similar to its INSAG-7 follow-up report on the causes of the accident.

Finally, with the new information presented here, it is clear that the governments of Ukraine – but especially Russia (and possibly Belarus) – should be pressed to make available *all* information on the extent and consequences of the accident. Without this information, it will be exceedingly difficult if not impossible to assess the impact of radioisotope releases upon the environment and the several million people living in areas affected by the fallout, as well as to properly analyze the Active Phase of the Accident.

---

[7] "According to Jack Sinnaeve of the European Community's radiation protection research unit, the scientific consensus is that there is a link between the accident and the increased number of cases of thyroid cancer that have been observed in recent years among children in contaminated regions of Belarus." ["Probably 42 Deaths Are Attributable to Chernobyl-4...," *Nuclear News*, Vol. 36, No. 15, (December 1993): 76.]

This Page Has Intentionally Been Left Blank

APPENDIX II

Chornobyl: A Nuclear or Non-Nuclear Explosion?[1]

The semantic argument over just what kind of explosion destroyed the Chornobyl reactor still persists today. This subject is debated in the press and in personal discussions – unfortunately never leading to a consensus even among experts. It has begun to take on the character of the well-known Berkelian paradox, "If a tree falls in the middle of a forest and no one is near to hear it, does it make a sound?" The same reasoning applies to the question of whether or not a *nuclear* explosion occurred at Chornobyl.

Note that a key word defining "explosion" is the *rate* at which energy is liberated during the process in question. For example, although difficult to classify as an explosion, the burning of a pound of coal releases far more energy than that released by the super-fast "burning" of a pound of TNT – despite the fact that no one would volunteer to stand next to a pound of dynamite sticks to witness them "burn" rather than cozying up next to a warm coal stove. Similarly, though one rarely thinks of rusty iron objects as "burning," for chemists the iron oxide (rust) that slowly appears on expensive cars involves an oxidation process. For the layman, it can be reason enough to invest in "Rusty Jones" undercoating for the family car.

Explosions are generally classified in two ways: by the *nature* of the energy contained or by the *mechanism* of its rapid release.

By the *nature* of the stored energy, one may enumerate as many types of explosions as there are types and forms of energy. All types of explosions occur as a result of physical

---

[1] For a short and excellent but slightly more technical comparison of the major differences between a nuclear bomb and a nuclear power reactor see Ronald Allen Knief, *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*, 2nd Ed., Washington, D.C.: Hemisphere Publishing Group, (1992): 156-157.

processes. This can include the explosion of a high-pressure gas tank after cracks appear in the casing, the explosion of a meteorite upon collision with a planet, the explosion of an electrical conductor subjected to a high-current impulse, the explosion of an aerosol can thrown into a fire. Chemical explosions occur as a result of the energy freed by the transfer of electrons between different chemical elements or compounds. In much the same way, a nuclear explosion is one in which the energy of atomic nuclei is freed with the rearrangement or release of neutrons and protons.

By the *mechanism* of energy release, explosions are further classified into two types: thermal and chain reaction-induced. The first occurs with the presence of positive feedback: the more energy freed, the higher the temperature; and the higher the temperature, the more energy is freed. Chain reaction-induced explosions are not *directly* a function of an increase in temperature, but come about in systems where energy is liberated through some elementary process that, in turn, initiates several more processes of the same kind, and so on. One well-known example is the fission reaction in a nuclear bomb. Another example of a chain reaction based on an elementary process is that of free radicals in chemical chain reactions.

In all official documents, the initial explosion that destroyed the Chornobyl reactor is classified as thermal. However this relates only to the mechanism, not to the nature of the energy that initiated the process. The *nature* of the explosion was nuclear. It was the consequence of a run-away nuclear reaction – the first energy liberated was that from the fission of uranium atoms.

At this point, we may elaborate more upon the *mechanism* that destroyed the Chornobyl reactor. To do this, the main difference between western nuclear reactors and the Soviet RBMK (Chornobyl-type) must be clarified. This concerns the effect of steam production within a reactor as coolant (water) flows past the nuclear fuel which heats it. Note that a fossil-fueled power plant operates by the same principle – water in the boiler is heated and turns to steam as it passes the burning fuel. The important difference is that a fossil-fuel power plant exhaust noxious waste (gases) into the air – nuclear plants do not.

In an RBMK, an increased production of steam indirectly increases *reactivity* (i.e., the efficiency of the fission process) and thus the power, so that the reaction feeds upon itself. For the water-graphite configuration of the RBMK design the water coolant acts as a "poison" – a kind of brake. But if the water is heated and begins to boil to form steam (i.e., if you have *less* of it), the reaction proceeds even more efficiently. In contrast, for western light-water reactors, in the event of a loss of cooling water (for instance, if the power is accidentally increased and more steam is produced), a physical process "poisons" (slows down) the reaction. In this sense, the inherent stability of western reactors is based upon physical principles – not upon man-made safety systems. On the other hand, because of its particular design, the RBMK is inherently unstable although based on the very same physical principles.* Such a design, therefore, requires that safety systems operate flawlessly at all times.

The fundamental safety assumption in the West is that mankind's technology will never be "perfect" and, as such, that accidents *do* occur. Western safety practices and systems are consequently designed with this in mind. Soviet safety policies, on the other hand, were formulated upon the less conservative assumptions regarding the ability of man-made safety systems to prevent a natural physical process from *ever* occurring.**

The fission process in nuclear power reactors (by which energy is transformed from nuclear into heat energy), even for the RBMK design, is actually inhibited slightly at the nuclear level by an increase in temperature. The explosion at Chornobyl began as a thermal one when the cooling system, by virtue of the physics of this type of reactor, was not ca-

---

* The positive void coefficient has nothing to do with the particular moderator material – graphite – used in the Chornobyl-type RBMK reactor. Rather, it is a strong function of the fuel-to-moderator ratio as specified in the design – in this case UO_2-to-graphite. An example of a stable reactor is the N-Reactor at Hanford which has a *negative* (stable) void coefficient even though its moderator is also graphite. Conversely, CANDU reactors have a positive (*unstable*) void coefficient even though there is no graphite in its core – its moderator is heavy water. For small variations in nominal operating conditions, the *overall power* coefficient for the CANDU reactor (which consists of the sum of all reactivity effects) is near zero.

** In the case of the RBMK, it appears the Soviets designed their reactor for safe operation at full power (where there was little need for a fast-acting control system), and assumed that little could happen at low power operation. The Chornobyl accident occurred when the reactor was at very low ($\approx$ 6%) power in violation of safe operating procedures.

pable of removing the heat generated by the "voiding-induced super-prompt critical power excursion." (Translating: as the amount of steam ("void") in the coolant increased, the neutron power increased with it.) Just before the accident, because of the high coolant flow rate and the precarious (in a nuclear physics sense) low-power state of the reactor, there was little or no boiling occurring in the core. Therefore, any increase in steam production relative to the core's no-boiling condition would have a large positive effect on the fission process.

Ironically, rather than countering the effects of increased steam production and thus increased power, the operators (unbeknownst to them[2]) exacerbated the problem by initiating the reinsertion of the control rods into an already neutronically-unstable core. As the poorly-designed and almost fully-withdrawn emergency control ("scram") assemblies entered the core of the reactor, the lower portions of these assemblies (made of graphite and known as "followers") *increased* the nuclear fission reaction rate in the lower portions of the core – actually making it possible for a local "critical mass" to form at the bottom of the reactor. (When water was pushed out of the bottom of the channel as the graphite followers dropped, the effect on the fission process was essentially the same as the effect of increased steam production, namely, less water was available to "poison" the reaction.) This increased the temperature of the fuel (and subsequently the water coolant which began boil and create steam) to the point where some of it fragmented, partially melted, and breached the walls of the fuel pins – bringing the fuel directly into contact with the water and causing the coolant to "flash" into steam. In the immediate region of the melted fuel and fuel pins, the fission chain reaction had most likely been terminated because the geometrical configuration of the fuel in relation to the graphite moderator had been altered to the point where the fission process could no longer be sustained. Additionally, the sudden increase of

[2] In their INSAG-7 report published January 1993, the IAEA's International Nuclear Safety Advisory Group identified the root cause of the Chornobyl accident as the RBMK reactor design, and firmly shifted the blame from the operators to the designers. Their original report, written on the basis of partial and slanted material provided by Soviet officials a few months after the accident, laid a large part of the blame on the Chornobyl Unit-4 operators. In fact, as concluded in INSAG-7, the operators were not fully trained to recognize the significance and seriousness of some of their actions that led to the accident.

steam allowed the reaction to proceed in other regions of the core. This, in turn, drove the fission power up all over the core with energy generation in these regions sustaining the increasing fission chain reaction. The stabilizing (or "negative") feedback within the fuel due to the increase in temperature was overcome by the "positive" feedback of heat-generated steam. The core, therefore, began to experience pressure pulses that compromised the structural integrity of the thin-walled stainless steel vessel surrounding it. The vessel was subsequently breached – allowing a release of the energy generated in a rapid, explosive manner.

But was it then a nuclear explosion? Nuclear explosions are defined characteristically by the presence of four striking elements: an intense nuclear shock wave, ionizing radiation, a blinding fireball, and radioactive fallout. There was no intense nuclear shock wave nor was there a blinding fireball at Chornobyl. The core and subsequently the reactor building were destroyed by a rapid release of *mechanical* energy when very high pressure steam was liberated. Additionally, a nuclear weapon has its somewhat more "exotic" fission products (radioactive elements) created at the moment of the explosion. At Chornobyl, the not-quite-so "exotic" (but still hazardous) fission products were created over a period of 865 days (2.4 years) *before* the accident as a result of slow and controlled reactions whose released energy was used to generate electricity.† Finally, to compare the immediate physical destruction at Chornobyl with that of Hiroshima is like comparing the energy of a burning match with the energy liberated by a hand grenade. On the other hand, by virtue of the amount of fission products accumulated over the several years of its operation, Chornobyl produced up to two hundred times more radioactive fallout than the bomb that devastated Hiroshima.††

---

† There were, however, additional primarily short-lived fission products produced by the fraction-of-a-second power pulse that eventually destroyed the reactor. These fission products, although adding to the "initial release" from Chornobyl, decayed to negligible levels within several minutes.

†† Not including the activation of surrounding material and the weapon's plutonium, a nuclear fission bomb releases approximately thirty-seven grams of fission products and transuranics per kiloton of explosive. For example, the Hiroshima bomb at 12.5 kilotons released almost one-half kilogram of radioactive materials.

How, then, should Chornobyl be classified? Was it a "half" nuclear explosion? It seems clear that Chornobyl does not lend itself to elementary classification. To call it a "nuclear explosion" without further elucidation, or to make simple-minded and categorical comparisons of Chornobyl with Hiroshima is to depart from the truth no less than denying the nuclear nature of this accident. The hazards from Chornobyl are not connected with a cataclysmic nuclear explosion wrecking tremendous destruction, but with the escape of radioactive materials into the surrounding environment. In and of itself this is a sufficiently serious threat to stimulate us to approach the nuclear energy debate more soberly and with less obfuscation than is currently done by pundits on both sides of the issue.

APPENDIX III.A

Text of a State Security Committee (KGB) Memorandum Concerning Construction Flaws at the Chornobyl Nuclear Power Station†

Not For Publication **SECRET**

21 February 1979 05363

Return to the General Section of
the Central Committee of the CPSU

CENTRAL COMMITTEE OF THE CPSU

USSR COMMITTEE OF STATE SECURITY [KGB]
February 21, 1979 No. 346-A
Moscow

RE: Construction flaws at the Chornobyl Nuclear Power Plant [AES]

According to data in the possession of the KGB of the USSR, design deviations and violations of construction and assembly technology are occurring at various places in the construction of the second generating unit of the Chornobyl AES, and these could lead to mishaps and accidents.

The structural pillars of the generator room were erected with a deviation of up to 100 mm from the reference axes, and horizontal connections between the pillars are absent in places. Wall panels have been installed with a deviation of up to 150 mm from the axes. The placement of roof plates does not conform to the designer's specifications. Crane tracks and stopways have vertical drops of up to 100 mm and in places a slope of up to 8 degrees.

Deputy head of the Construction Directorate, Comrade V. T. Gora, gave instructions for backfilling the foundation in many places where vertical waterproofing was damaged. Similar violations were permitted in other sections with the knowledge of Comrade V. T. Gora and the head of the construction group, Comrade Yu. L. Matveev. Damage to the waterproofing can lead to ground water seepage into the station and radioactive contamination of the environment.

The leadership of the Directorate is not devoting proper attention to the foundation, on which the quality of the construction largely depends. The cement plant operates erratically, and its output is of poor quality. Interruptions were permitted during the pouring of especially heavy concrete causing gaps and layering in the foundation. Access roads to the Chornobyl AES are in urgent need of repair.

Construction of the third high-voltage transmission line is behind schedule, which could limit the capacity utilization of the second unit.

As a result of inadequate monitoring of the condition of safety equipment, in the first three quarters of 1978, 170 individuals suffered work-related injuries, with the loss of work time totaling 3,366 worker-days.

The KGB of Ukraine has informed the CPSU Central Committee of these violations. This is for your information.

Chairman of the Committee [KGB] [signed] Yu. Andropov

† Made available by Valentine M. Smith (CDELL@VAX1.UMKC.EDU) over the BITNET computer network on August 7, 1992.

This Page Has Been Left Intentionally Blank.

APPENDIX III.B

Chornobyl Nuclear Power Station Unit-4 Parameters

The sources listed below were consulted to review and systematize the nominal Chornobyl Unit-4 RBMK-1000 reactor parameters *prior to the accident.* They are presented in tables beginning on the following page. Note slight variations exist between different sources that, unfortunately, appear as inconsistencies in the tables.

1) U.S.S.R. State Committee on the Utilization of Atomic Energy (comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Part I: General Material,* report presented at the International Atomic Energy Agency Expert's Meeting, August 25–29, 1986, Vienna.

2) U. S. Nuclear Regulatory Commission, comp. *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250). Washington, DC: U.S. Government Printing Office, 1987.

3) Дементьев, Б. А. *Ядерные энергетические реакторы: Учебник для вузов.* Москва: Энергоатомиздат (1990).

4) Герасимов, А. С., Т. С. Зарицкая, А. П. Рудик. *Справочник по образованию нуклидов в ядерных реакторах.* Москва: Энергоатомиздат, 1989.

5) Безбатченко, Н. И., Г. А. Котельников, Л. Н. Нефедова, А. Г. Мотлич, К. П. Чечеров. *Моделирование аварии на ЧАЭС: Обзор по материалам зарубежной печати.* Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990.

6) Доллежаль, Н. А., И. Я. Емельянов. *Канальный ядерный энергетический реактор.* Москва: Атомиздат, 1980.

7) *Техническое Обоснование Радиационной Безопасности Объекта «Укрытие».* Чернобыль, Украина; Минск, Беларусь: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, Институт радиоэкологических проблем при АН Беларусь, 1992.

8) Внучков. *Техническое описание конструкции реактора РБМК-1000.* Москва.

9) Гострой СССР. *Чертежи ВНИКИЭТа.* Москва. Ноябрь 1976, Октябрь 1979.

10) Personal coversations with scientists and engineers in Chornobyl, Kyjiv, and Moscow, October 1991 – March 1993.

REACTOR

Parameter	Magnitude	Unit
Thermal Power	3140	MWt
Electrical Power Generation – Turbo-Generator	2 x 500	MWe
Electrical Power (Gross / Net)	1000 / 925	MWe
Efficiency (Gross / Net)	31.8 / 29.5	%
Refueling	On Line	—
Core Height	7.0	m
Core Azimuthal Linear Extrapolation Distance	0.6	m
Core Equivalent Diameter	11.8	m
Core Volume	765.5	m^3
Number of Graphite Columns	2488	#
Number of Control Rod Channels	211	#
Number of Technological Channels [TC]	1661	#
TC Pitch	250 x 250	mm
TC Height	8	m
TC (Pressure Tube) Outer Diameter	88	mm
TC (Pressure Tube) Thickness	4	mm
TC (Pressure Tube) Material	Zr–2.5% Nb	—
Stainless Steel Inlet & Outlet Tube Material (transition weld)	08Cr18Ni10Ti	—
Stainless Steel Inlet Tube Dimensions (OD x t)	5.7 x 0.35	cm
Stainless Steel Outlet Tube Dimensions (OD x t)	7.6 x 0.40	cm
Graphite Pile (Moderator & Reflector) Height	8	m
Graphite Lateral Graphite Reflector True/Equivalent Thickness	1.00 / 0.88	m
Upper & Lower Graphite Reflector Thickness	0.5	m
Graphite Pile Mass	1885.4	tonne
Graphite Block Dimensions – Type 1	250 x 250 x 600	mm
Graphite Block Dimensions – Type 2	250 x 250 x 400	mm
Graphite Block Dimensions – Type 3	250 x 250 x 300	mm
Graphite Block Dimensions – Type 4	250 x 250 x 200	mm
Graphite Block Inner Channel Diameter	114	mm
Reactor Concrete Containment Shaft Dimensions	21.6 x 21.6 x 21.5	m

POWER GENERATION

Parameter	Magnitude	Unit
Average Coolant Pressure Across Core	6.8	MPa
Core Entrance / Exit Coolant Temperatures	270 / 284	°C
Maximum Calculated Channel Power	3.250	kWt
Maximum / Average Channel Power	2.61/1.89 = 1.38	[kWt]
Average Specific Heat Generation	17.8	kWt/kg U
Maximum / Average Discharge Burnup	28 / 20	GWt·d/t U
Average Volumetric Channel Heat Generation	4.1	MWt/m^3
Average Fuel Rod Surface Heat Flux	350	kWt/m^2
Maximum / Average Linear Heat Generation Rate	41/29 = 1.41	[kWt/m]
Heat Generation in Graphite Pile at 100% Power	188.4	MWt
Graphite Temperature Maximum / Average	750 / 600	°C
Axial Peak / Average Power Ratio Range	1.26 – 1.33	—
Radial Peak / Average Power Ratio Range	1.27 – 1.40	—
Heat Generation Nonlinearity Coefficient – Core Radial	1.48	—
Heat Generation Nonlinearity Coefficient – Core Axial	1.40	—
Heat Generation Nonlinearity Coefficient – Channel Radial	1.06	—

Coolant Flow Area in Channel	24.12×10^{-4}	m^2
Assembly Hydraulic Perimeter	1060	mm
Assembly Hydraulic Diameter	8.57	mm
Average Channel Mass Velocity	4.73	kg/sec
Coolant Enthalpy at Core Entrance	1160	kJ/kg
Coolant Saturation Parameters at Average Core Pressure 6.8 MPa		
Temperature	295	°C
Liquid Enthalpy	1318	kJ/kg
Latent Heat of Vaporization	1440	kJ/kg
Liquid Density	674	kg/m^3
Vapor Density	43	kg/m^3
Liquid Dynamic Viscosity	88×10^{-6}	Pa·sec
Vapor Dynamic Viscosity	19.5×10^{-6}	Pa·sec
Liquid Surface Tension	15.5×10^{-3}	N/m
Prandlt Number	0.891	—
Thermal Conductivity	0.556	W/(m·K)
Coolant Enthalpy at Core Exit	1534	kJ/kg
Boiling Elevation (from Core Entrance)	2.2 – 2.5	m
Effective Heat Transfer Coefficient, Fuel to Coolant	1.563	kWt/m^2 °K
Effective Heat Transfer Coefficient, Control Assembly to Coolant	0.161	kWt/m^2 °K
Steam Quality (Average / Maximum)	14.5 / 20.1	%

TECHNOLOGICAL (FUELED) CHANNELS

Parameter	Magnitude	Unit
Fuel Type	UO_2	—
Core Fuel Mass (1661 Assemblies) – Full/Maximum (Initial) Load	190.5	tonne
Assembly Fuel Mass – Fresh, Initially Loaded	114.7	kg
Assembly Total Mass	≈ 260	kg
Mass of Stainless Steel per Assembly	≈ 80	kg
Mass of Zirconium per Assembly	≈ 65	kg
Mass of Zirconium per TC Pressure Tube	≈ 55.4	kg
Mass (Total) of Zirconium per Channel	≈ 120.4	kg
Overall Assembly Length	10014	mm
Overall Assembly Width	79	mm
Fuel Assembly Pitch	250	mm
Fuel Enrichment	1.8 / 2.0 / *(2.4)*	w/o
Fuel Cassettes per Assembly	2 (stacked)	#
Fuel Rod Spacer Grids per Cassette	10	#
Fuel Rods per Cassette	18	#
Fuel Rod Outer Diameter	13.6	mm
Fuel Rod Length	3644	mm
Calculational Rod Cell	Triangular	—
Fuel Cladding Material	Zr–1.0% Nb	—
Fuel Cladding Wall Thickness	0.825	mm
Active Fuel Length per Cassette	3490	mm
Fuel Pellet Initial Diameter	11.48	mm
Fuel Pellet Initial Height	15.0	mm
Pellet Density (% theoretical)	94	%
Maximum Fuel Temperature	2640	°C
Fuel Cladding Maximum Temperature (Max / Inner / Outer)	350 / 325 / 295	°C
TC Plenum Length	120	mm
Channel Operating Pressure	6.8	MPa
RBMK-1000 Average Discharge Burnup	18.1	MW·d/kg U
RBMK-1500 Average Discharge Burnup	21.6	MW·d/kg U
Maximum Assembly Burnup	33.0	MW·d/kg U
Fuel Assembly Campaign (@ 24,000 MWt·d/t U)	1700	days
Fuel Assembly Service Period (@ 85% utilization)	1470	days
Isotopic Content of Discharged (18.6 GWd/t U) Fuel: U-235	4.1	kg/t U
" " " U-236	2.1	kg/t U
" " " U-238	969.3	kg/t U
" " " Pu-239	2.4	kg/t U
" " " Pu-240	1.7	kg/t U
" " " Pu-241	0.5	kg/t U
" " " Pu-242	0.3	kg/t U
Average Plutonium Production Rate (at 100% Power)	4.1	kg/yr

CONTROL SYSTEM

Parameter	Magnitude	Unit
Number of Control Assemblies	211	#
Control Assembly Spacing	500 x 500	mm
Control Assembly Material	Aluminum Alloy	—
Control Assembly Poison	B_4C	—
Number of Manual Regulation Assemblies [RR]	139	#
of these, Local Emergency Assemblies [LAZ]	*24*	#
SCRAM Assemblies [AZ] (Nominally Withdrawn)	24	#
Axial Power Regulation Rods [APR] (Shortened)	24	#
Automatic Regulation [AR]	24	#
of these, Local Automatic Regulation [LAR]	*12*	#
of these, Mid-Range Power Regulation [MPR]	*12*	#
Control Assembly Cooling	downward external, upward internal	—
Control Assembly Coolant Flow Rate	4.3 – 5.4	m^3/hr
Control Assembly Insertion Speed	0.4	m/sec
Control Assembly Insertion Time	20	sec
90% Reactivity Insertion Time	10	sec
Reserve Reactivity (Equivalent to 30 RR Assemblies)	1.8	Δk/k
Criticality Reserve Coefficient	1.25	—
Minimum Effectiveness of Control Assemblies	10.5	(Δk)%
Effectiveness of RR Assemblies	7.5	(Δk)%
Effectiveness of LAR Assemblies,		
Insertion / Withdrawal Speed Limitation	0.2	m/sec
Reactivity Insertion Rate for 12 Assemblies (@ 0.2 m/sec)	-0.7	β_{eff}/sec
Total Effectiveness of All Control Assemblies,		
for Hot Reactor	9.4	(Δk)%
for Cold Reactor with Coolant	6.5	(Δk)%
for Cold Reactor without Coolant	8.3	(Δk)%
Fuel Assembly Replacement Effectiveness (Burned – Fresh)	0.02	(Δk)%
Void Coefficient of Reactivity, α_φ	2×10^{-6}	% vol.
Prompt Power Coefficient of Reactivity, α_w	-0.5×10^{-6}	MWt^{-1}
Temperature Coefficient of Reactivity, α_T	-1.2×10^{-5}	$°C^{-1}$
Graphite Temperature Coefficient of Reactivity, $\alpha_{T,G}$	6×10^{-5}	$°C^{-1}$
Void Reactivity Effect	≈ 5	β_{eff}

RBMK Core at Initial 2.0% U-235 Enrichment					
Exposure (GWt·d/t U)	10	10.3	Exposure (GWt·d/t U)	10	10.3
Reactivity/$ (β)	0.0042	0.0048	Coolant Void (Δρ/Δα)	$+9.2\times10^{-3}$	$+2.0\times10^{-4}$
Number of Equivalent Rod Worths	20	30	Graphite Temperature (ρ/°C)	$+5.4\times10^{-5}$	$+6.0\times10^{-5}$
			Water Temperature (ρ/°C)	$+5.0\times10^{-5}$	—
Number of Supplemental Absorbers	0	1	Fuel Temperature (ρ/°C)	-1.1×10^{-5}	-1.2×10^{-5}
			Fuel Density (ρ/gm/cm³)	-1.3×10^{-2}	—

COOLING CIRCUIT

Parameter	Magnitude	Unit
System Material	Austenitic S.S.	—
Number of Independant Coolant Loops	2	#
Total Reactor Coolant (Water) Mass Flowrate	37,600	t/hr
Coolant Flowrate through Core	14	m^3/sec
Coolant Mass Flowrate through Channel at 100% Power	8.5	kg/sec
Core Entrance / Exit Coolant Temperatures	270 / 284	°C
Core Operating Pressure	6.8	MPa
Core Entrance or Exit Maximum Flow Speed	18.5	m/sec
Total Steam Flowrate (Production)	5800	tonne/hr
Maximum / Average Core Exit Steam Content	20 / 14.5	%
Number of Steam-Drum Separators [SDS]	4 (2 per circuit)	#
SDS Inner Diameter	2.3	m
SDS Length	30.7	m
SDS Wall Thickness	104	mm
SDS Mass	200	tonne
SDS Steam Pressure (Nominal)	6.85	MPa
SDS Feedwater Inlet Temperature	165	°C
Steam Humidity upon Exit from SDS	0.02	%
Number of Main Coolant Pumps [MPC] (Including 2 Backup)	8	#
MCP Nominal Pumping Rate	8000	m^3/hr
MCP Pumping Capacity	5,500 – 12,000	m^3/hr
MCP Nominal Pumping Capacity	7,000 – 9,000	m^3/hr
MCP Mass	100	tonne
MCP Dynamic Head	1.96	MPa
MCP Entrance Pressure	7.2	MPa
MCP Net Positive Suction Head	0.6	MPa
MCP Suction and Discharge Header Diameters	900	mm
MCP Braking (Rundown) Time for Full Stop	15	sec
MCP Shaft Speed	50	rev/sec
MCP Motor Power	5.5	MWe
Number of Group Dispensing Headers [GDH] per Loop	22	#
GDH Pressure	8.27	MPa
Pressure Drop in Piping	0.66	MPa
Feedwater Flow Rate	1.5	m^3/sec
Feedwater Temperature	165	°C
Feedwater / Steam Mass Flow Rate	15 / 25	kg/sec
Maximum / Nominal Steam Mass Flow Rate Through One Turbine	2902 / 2890	t/sec
Steam Pressure upon Entrance to Turbine	6.59	MPa
Steam Temperature upon Entrance to Turbine	280.4	°C
Maximum / Nominal Turbine Power	550 / 510	MWt
Condensor Pressure	4.9×10^{-3}	MPa

REACTOR SHAFT CONSTRUCTION

Parameter	Magnitude	Unit
Core		
Mass of Graphite Stack	1885.4	tonne
Mass of Zircaloy in Channels	103	tonne
Mass of Zircaloy in Assemblies	74	tonne
Mass of UO_2 Fuel (Full Charge with no Absorbers – 1661 TCs)	190.52	tonne
Mass of Aluminum (Control Assembly Material)	??	tonne
Mass of B_4C (Control Assembly Poison)	2.3	tonne
Mass of Steel	??	tonne

Component E (Upper Biological Shield)		
Diameter	17	m
Height	3	m
Total Equivalent Mass (includes weld connections & pipes, etc.)	≈ 2500	tonne
Total Mass (superstructure, filler, & internal piping)	≈ 2000	tonne
Mass of Superstructure (cylinder and compensator region only)	451.87	tonne
Metal Plate Covering Material	10XH1M	—
Thickness	40	mm
Serpentenite Filler Material ["rocks" ≈ 60%; "pebbles" ≈ 40%]	$Mg_6[Si_4O_{10}][OH]_8$	—
Theoretical (Microscopic) Density	2.5 – 2.7	t/m^3
Bulk (Macroscopic) Density ["rocks" ≥ 1.5; "pebbles" ≥ 1.3]	≈ 1.7	t/m^3
Specific Heat, $C_p = 1.12x10^{03}(1 + 0.507x10^{03}T[^\circ C])$	—	kJ/kg °C
Volume	590	m^3
Mass	1005	tonne
Internal Metal Piping	08X18H10T	—
Mass	≈ 500	tonne

Component L (Lateral Biological Shield – Lower)		
Outer Diameter	19	m
Inner Diameter	16.6	m
Height	11	m
Thickness	30	mm
Mass (without water)	556.6	tonne
Material (низколегированый сталь перлитного класса)	10ХСНД	—
Volume of Water	??	m^3

Component D (Lateral Biological Shield – Upper)		
Outer Diameter	19	m
Inner Diameter	18	m
Height	3	m
Thickness	30	mm
Mass (without water)	222.62	tonne
Material (низколегированый сталь перлитного класса)	10ХСНД	—
Volume of Water	??	m^3

Component OR (Lower Biological Shield [LBS] – Primary)		
Diameter	14.5	m
Height	2	m
Total Mass	1593.8	tonne
Metal Plate Covering Material	10XH1M	—
Thickness	40	mm
Mass (Cylinder and Compensator Only – 286.24 tonnes)	670.4	tonne
Serpentenite Filler Material ["rocks" ≈ 60%; "pebbles" ≈ 40%]	$Mg_6[Si_4O_{10}][OH]_8$	—
Theoretical (Microscopic) Density	2.5 – 2.7	t/m^3
Bulk (Macroscopic) Density ["rocks" ≥ 1.5; "pebbles" ≥ 1.3]	≈ 1.7	t/m^3
Specific Heat, $C_p = 1.12x10^{03}(1 + 0.507x10^{03}T[^\circ C])$		kJ/kg °C
Volume	250	m^3
Mass	489	tonne
"Black" Steel Mass	232.8	tonne
Internal Metal Piping	08X18H10T	—
Mass	201.6	tonne

Component OR (LBS – Thermal Compensator Region)		
Outer Diameter	16.6	m
Inner Diameter	14.5	m
Zone Zh Filler ("rocks" 20–40 mm diameter, $\rho = 1.4$ t/m^3)	Serpentenite	—
Mass	0.14	tonne
Zone Z Filler ("pebbles or sand" 2–3 mm diameter, $\rho = 4.2$ t/m^3)	Cast Iron Nuggets	—
Mass	68	tonne
Zone I Filler ("rocks" 20–40 mm diameter, $\rho = 1.7$ t/m^3)	Serpentenite	—
Mass	128	tonne
Total Mass of Fillers	196.14	tonne

Component KZh (Reactor Outer Membrane and Pressure Boundary)		
Outer Diameter	14.52	m
Height	9.75	m
Thickness	16	mm
Mass	69.73	tonne
Material	10XH1M	—

Component S (Reactor Support)		
Height	5.3	m
Thickness	≈ 40	mm
Mass	109.37	tonne
Material	10XH1M	—

Component NES & SES (Alignment & Emergency Support)		
Height	??	m
Thickness	??	mm
Mass	??	tonne
Material	10XH1M	—

Component G (Floor Shielding Blocks in Central Hall)		
Filler Material (Serpentine Pebbles 14% Mass; Cast Iron Pebbles 86% Mass, 2–3 mm diameter)		
Total Filler Material Volume	210	m^3
Density	3.8	t/m^3
Total Superstructure Mass (without filler)	587.29	tonne
Total Filler Material Mass	800	tonne

Reactor Shaft – General		
Dimensions (L x W x H)	21.6 x 21.6 x 25.5	m
Wall Thickness	2	m
Heavy Concrete Density	4.5	gm/cm^3
Hydrogen	0.5	wt. %
Oxygen	11.7	wt. %
Aluminum	0.35	wt. %
Silicon	4.75	wt. %
Calcium	2.7	wt. %
Iron	80.0	wt. %
Light Concrete Density	2.3	gm/cm^3
Hydrogen	0.25	wt. %
Oxygen	53.9	wt. %
Aluminum	4.41	wt. %
Silicon	31.75	wt. %
Calcium	7.66	wt. %
Iron	2.03	wt. %
Filler Material (Between Shaft Walls & Component L)		
Sand	SiO_2	—
Volume	2500	m^3
Mass	3250	tonne
Serpentenite	$Mg_6[Si_4O_{10}][OH]_8$	—
Volume (pebbles 20–40 mm diameter)	15	m^3
Mass	21	tonne

Serpentenite Filler Material Composition (Equivalent)		
Serpentenite	$Mg_6[Si_4O_{10}][OH]_8$	—
MgO	43	wt. %
SiO_4	44	wt. %
H_2O	13	wt. %
Serpentenite + Cast Iron Mixture (Only in Component G)		
SiO_2	3.81	wt. %
Al_2O_3	0.38	wt. %
Fe_2O_3	1.12	wt. %
BaO	30.33	wt. %
CaO	0.81	wt. %
MgO	3.55	wt. %
Cast Iron	60.0	wt. %

Chemical Composition of Four Soviet Concretes† (weight percent)

COMPOUND	CONCRETE TYPE			
	Basaltic	Regular	Heavy	Serpentine
Fe_2O_3	6.26	14.4	5.1	1.2
TiO_2	1.05	0.18	—	0.12
K_2O	5.39	1.22	0.77	0.68
Na_2O	1.8	0.08	0.77	0.08
CaO	8.82	31.3	12.1	45.4
MgO	6.16	0.48	1.35	5.67
SiO_2	54.84	35.8	66.1	3.6
Al_2O_3	8.32	3.6	5.5	1.6
CO_2	15	21.15	1.4	35.7
H_2O (entrained vapor)	3.86	2.7	4.4	3.94
H_2O (crystallization)	2	2	2.5	2
Cr_2O_3	—	0.014	—	0.004
MnO	—	0.03	0.016	0.01
Total	**113.50**	**112.954**	**100.006**	**100.004**

Another source†† provides the following chemical compositions for Soviet concretes:

Concrete	ρ (gm/cm³)	Elemental Composition (w/o)					
		H	O	Al	Si	Ca	Fe
Light	2.3	0.25	53.9	4.41	31.75	7.66	2.03
Heavy	4.5	0.50	11.7	0.35	4.75	2.70	80.0

† Панитков, Ю. С., И. А. Банель, А. М. Бернадская, В. П. Бескоровайный, Н. В. Горбачева, Н. М. Груша, В. В. Котович, Л. Н. Козловская, В. Г. Молодых, Н. К. Мышкина, Н. В. Нитей, В. В. Ничипор, Т. А. Павлина, В. В. Скурат, Л. А. Станкевич, Э. М. Тащилова, *Отчёт о научно-исследовательской работе: Восстановление динамики разрушения 4-го блока ЧАЭС на основе физического и математического моделирования: Разработка физичес-кой модели чернобыльской катастрофы*, Минск, Беларусь: Академия Наук Беларуси, (1991): 165. It is not clear why the components of the basaltic and regular concretes do not add up to 100 weight percent.

†† А. А. Дубинин, ред., *Вторичное Гамма-Излучение в Радиационной Защите*, Москва: Энергоатомиздат, (1984): 127. For substantially more information on Soviet concretes see also U.S. Department of Energy, *Department of Energy's Team's Analyses of Soviet Designed VVERs*, (DOE/NE-0086) Washington, D.C.: U.S. Department of Energy.

Composition of Soviet Stainless Steels Used In High-Temperature, High-Corrosion Environments

Steel	C	Si	Mn	Ni	Cu	Cr	Ti	S	P
10ХСНД	≤0.12	0.8-0.11	1.3-1.65	≤0.3	0.15-0.30	≤0.3	—	—	—
10ХН1М	≤0.12	0.8-0.11	1.3-1.65	≤1		≤0.3	—	—	—
1Х18Н9Т	≤0.12	≤0.8	≤2.0	8-9.5	—	17-19	0.4-0.8	≤0.02	≤0.035
1Х19Н10Т	≤0.12	≤0.8	≤2.0	9-11	—	17-19	0.4-0.8	≤0.02	≤0.035
0Х18Н10Т	≤0.08	≤0.8	≤2.0	9-11	—	17-19	0.4-0.8	≤0.02	≤0.035
0Х18Н12Т	≤0.08	≤0.8	≤2.0	11-13	—	17-19	0.4-0.6	≤0.02	≤0.035

10ХСНД σ_y = 400 MPa σ_u = 520–540 MPa

0Х18Н10Т $\sigma_y \geq$ 210 MPa $\sigma_u \geq$ 520 MPa

This Page Has Been Left Intentionally Blank.

APPENDIX III.C

CIS Nuclear Power Reactors

KEY

ATC	**A**tomic **T**hermal-**C**enter a reactor (usually a VVER) dedicated to supply district or industrial heating needs only
ATET(s)	**A**tomic **T**hermo-**E**lectric **C**enter a reactor (usually a VVER) dedicated both to district heating and electrical power production
BN	literally: **F**ast **N**eutrons – the Russian acronym for a Fast Breeder Reactor
FBR–BN	**F**ast **B**reeder **R**eactor liquid sodium moderated fast reactor
GLWR	**G**raphite-Moderated, Pressurized **L**ight **W**ater-Cooled **R**eactor heat-and-power-producing units (mettalic uranium fuel at Bilibino)
LWGR	**B**oiling **L**ight **W**ater-Cooled, **G**raphite-Moderated **R**eactor example is the Chornobyl RBMK (see below)
OMR	**O**rganically **M**oderated **R**eactor
RBMK	literally:**R**eactor of **G**reat **P**ower – **C**hannel Type The RBMK is the Russian acronym for the West's LWGR. It is a heterogeneous, thermal neutron, graphite-moderated, channel-type boiling-water nuclear reactor with on-line refueling
VVER	**W**ater-Cooled, **W**ater-**M**oderated **E**nergy **R**eactor essentially quivalent to a western Pressurized Water Reactor (PWR) except for hexagonal lattice and horizontal steam generators
VVER—es	A VVER with improved (**E**nhanced) **S**afety systems
VVER—ps	A VVER with **P**assive **S**afety systems

NOTE:

••Data for Ukraine includes both the initial criticality and full power operation dates

••Reactor Units with all fields greyed-out means that it is shutdown or abandoned

••Reactor Units with only the first field (i.e., "Station Name") greyed-out are planned or under construction

APPENDIX III.C

CIS Nuclear Power Reactors

Station Name	Unit–#	Station Geographic Location	Population Center	City Georgrahic Location	Reactor Type	Gross / Net (MWe)	Grid Startup
ARMENIA							
Armenian	1	40° 08′ N / 044° 07′ E	Oktemberjan Metsamor	40° 08′ N / 044° 02′ E 40° 04′ N / 044° 17′ E	VVER-440 V230	408 / 376	12/76
	2	40° 08′ N / 044° 07′ E	Oktemberjan Metsamor	40° 08′ N / 044° 02′ E 40° 04′ N / 044° 17′ E	VVER-440 V230	408 / 376	12/79
BELARUS							
Minsk	1	53° 54′ N / 027° 34′ E			VVER-1000 ATET		
Minsk	1	53° 54′ N / 027° 34′ E			VVER-1000 ATET		
LITHUANIA							
Ignalina	1	55° 21′ N / 026° 10′ E	Ignalina		RBMK-1500	1500 / 1380	12/83
Ignalina	2	55° 21′ N / 026° 10′ E	Ignalina		RBMK-1500	1500 / 1380	08/87
Ignalina	3	55° 21′ N / 026° 10′ E	Ignalina		RBMK-1500	1500 / 1380	

The Armenian reactor Units 1 & 2 were shutdown on 02/89 and 03/89 respectively.

Plans for the Minsk Station were abandoned in 1987.

Ignalina Unit-3 has been cancelled or indefinitely deferred.

RUSSIA

Station Name	Unit–#	Station Geographic Location	Population Center	City Georgrahic Location	Reactor Type	Gross / Net (MWe)	Grid Startup
Arkhangelsk	1		Arkhangelsk		ATC-500		?
Arkhangelsk	2		Arkhangelsk		ATC-500		?
Balakovo	1	50° 02´ N / 047° 35´ E	Balakovo Saratov		VVER-1000 V320	1000 / 950	12/85
Balakovo	2	50° 02´ N / 047° 35´ E	Balakovo Saratov		VVER-1000 V320	1000 / 950	10/87
Balakovo	3	50° 02´ N / 047° 35´ E	Balakovo Saratov		VVER-1000 V320	1000 / 950	12/88
Balakovo	4	50° 02´ N / 047° 35´ E	Balakovo Saratov		VVER-1000 V320	1000 / 950	1993
Balakovo	5	50° 02´ N / 047° 35´ E	Balakovo Saratov		VVER-1000es		by 2000
Balakovo	6	50° 02´ N / 047° 35´ E	Balakovo Saratov		VVER-1000es		by 2000
Bashkir	1		Bashkir ASSR		VVER-1000 V320	1000 / 950	
Bashkir	2		Bashkir ASSR		VVER-1000 V320	1000 / 950	
Belojarsk	1	56° 45´ N / 061° 20´ E	Zarechnyj Sverdlovsk	56° 48´ N / 061° 19´ E	LWGR	108 / 102	04/64
Belojarsk	2	56° 45´ N / 061° 20´ E	Zarechnyj Sverdlovsk	56° 48´ N / 061° 19´ E	LWGR	160 / 146	12/67
Belojarsk	3	56° 45´ N / 061° 20´ E	Zarechnyj Sverdlovsk	56° 48´ N / 061° 19´ E	FBR BN-600	600 / 560	04/80
Belojarsk	4	56° 45´ N / 061° 20´ E	Zarechnyj Sverdlovsk	56° 48´ N / 061° 19´ E	FBR BN-800	800 / 750	> 2000
Brjansk	1		Brjansk		ATC-500		—
Far East	1				VVER-600ps		~ 2010
Far East	2				VVER-600ps		~ 2010
Gorkij	1	56° 20´ N / 044° 00´ E			ATC-500		

Gorkij	2	56° 20′ N / 044° 00′ E			ATC-500		
Kalinin	1	57° 53′ N / 035° 01′ E	Udomlja Tver	57° 53′ N / 035° 01′ E	VVER-1000 V302	1000 / 950	05/84
Kalinin	2	57° 53′ N / 035° 01′ E	Udomlja Tver	57° 53′ N / 035° 01′ E	VVER-1000 V302	1000 / 950	12/86
Kalinin	3	57° 53′ N / 035° 01′ E	Udomlja Tver	57° 53′ N / 035° 01′ E	VVER-1000 V320	1000 / 950	~ 1993
Kalinin	4	57° 53′ N / 035° 01′ E	Udomlja Tver	57° 53′ N / 035° 01′ E	VVER-1000 V320	1000 / 950	~ 1995
Khabarovsk	1				ATC-500		~ 2010
Khabarovsk	2				ATC-500		~ 2010
Kola	1	67° 35′ N / 032° 30′ E	Northern Lights Murmansk	67° 28′ N / 032° 25′ E	VVER-440 V230	440 / 411	06/73
Kola	2	67° 35′ N / 032° 30′ E	Northern Lights Murmansk	67° 28′ N / 032° 25′ E	VVER-440 V230	440 / 411	12/74
Kola	3	67° 35′ N / 032° 30′ E	Northern Lights Murmansk	67° 28′ N / 032° 25′ E	VVER-440 V213	440 / 411	03/81
Kola	4	67° 35′ N / 032° 30′ E	Northern Lights Murmansk	67° 28′ N / 032° 25′ E	VVER-440 V213	440 / 411	10/84
Kola	5	67° 35′ N / 032° 30′ E	Northern Lights Murmansk	67° 28′ N / 032° 25′ E	VVER-630es		2001–2005
Kola	6	67° 35′ N / 032° 30′ E	Northern Lights Murmansk	67° 28′ N / 032° 25′ E	VVER-630es		2001–2005
Kola	7	67° 35′ N / 032° 30′ E	Northern Lights Murmansk	67° 28′ N / 032° 25′ E	VVER-630es		2006–2010
Kostroma	1	58° 29′ N / 041° 30′ E	Kostroma		VVER-1000 V320	1000 / 950	1999 ?
Kostroma	2	58° 29′ N / 041° 30′ E	Kostroma		VVER-1000 V320	1000 / 950	?
Kostroma	3	58° 29′ N / 041° 30′ E	Kostroma		VVER-1000 V320	1000 / 950	?
Kostroma	4	58° 29′ N / 041° 30′ E	Kostroma		VVER-1000 V320	1000 / 950	?
Krasnodar	1				VVER-1000	1000 / 950	
Kursk	1	51° 40′ N / 035° 45′ E	Kursk Kurchatov	51° 42′ N / 036° 12′ E 51° 39′ N / 035° 40′ E	RBMK-1000	1000 / 925	12/76

Kursk	2	51° 40′ N / 035° 45′ E	Kursk Kurchatov	51° 42′ N / 036° 12′ E 51° 39′ N / 035° 40′ E	RBMK-1000	1000 / 925	01/79
Kursk	3	51° 40′ N / 035° 45′ E	Kursk Kurchatov	51° 42′ N / 036° 12′ E 51° 39′ N / 035° 40′ E	RBMK-1000	1000 / 925	10/83
Kursk	4	51° 40′ N / 035° 45′ E	Kursk Kurchatov	51° 42′ N / 036° 12′ E 51° 39′ N / 035° 40′ E	RBMK-1000	1000 / 925	12/85
Kursk	5	51° 40′ N / 035° 45′ E	Kursk Kurchatov	51° 42′ N / 036° 12′ E 51° 39′ N / 035° 40′ E	RBMK-1000	1000 / 925	by 1995
Kursk	6	51° 40′ N / 035° 45′ E	Kursk Kurchatov	51° 42′ N / 036° 12′ E 51° 39′ N / 035° 40′ E	RBMK-1000	1000 / 925	
Magadansk	1	68° 03′ N / 166° 25′ E	Bilibino Chukhotka		LWGR	12 / 11	01/74
Magadansk	2	68° 03′ N / 166° 25′ E	Bilibino Chukhotka		LWGR	12 / 11	12/74
Magadansk	3	68° 03′ N / 166° 25′ E	Bilibino Chukhotka		LWGR	12 / 11	12/75
Magadansk	4	68° 03′ N / 166° 25′ E	Bilibino Chukhotka		LWGR	12 / 11	12/76
Magadansk	5	68° 03′ N / 166° 25′ E	Bilibino		GLWR-32		2001–2005
Magadansk	6	68° 03′ N / 166° 25′ E	Bilibino		GLWR-32		2001–2005
Magadansk	7	68° 03′ N / 166° 25′ E	Bilibino		GLWR-32		2006–2010
Melekess	1		Dimitrograd		OMR Arbus	5 / 1	1963
Melekess	2		Dimitrograd		BWR VK-50	62 / 50	01/66
Melekess	3		Dimitrograd		FBR BOR-60	15 / 12	1/70
Novovoronezh	1	51° 14′ N / 039° 12′ E	Novovoronezh	51° 19′ N / 039° 13′ E	VVER-220 V210	210 / 197	09/64
Novovoronezh	2	51° 14′ N / 039° 12′ E	Novovoronezh	51° 19′ N / 039° 13′ E	VVER-440	365 / 336	12/69
Novovoronezh	3	51° 14′ N / 039° 12′ E	Novovoronezh	51° 19′ N / 039° 13′ E	VVER-440 V230	417 / 385	12/71
Novovoronezh	4	51° 14′ N / 039° 12′ E	Novovoronezh	51° 19′ N / 039° 13′ E	VVER-440 V230	417 / 385	12/72
Novovoronezh	5	51° 14′ N / 039° 12′ E	Novovoronezh	51° 19′ N / 039° 13′ E	VVER-1000 V187	1000 / 950	05/80
Novovoronezh	6	51° 14′ N / 039° 12′ E	Novovoronezh	51° 19′ N / 039° 13′ E	VVER-1000es		~ 2000
Novovoronezh	7	51° 14′ N / 039° 12′ E	Novovoronezh	51° 19′ N / 039° 13′ E	VVER-1000es		~ 2000

Obninsk	1	55° 05´ N / 036° 40´ E	Obninsk Kaluga	55° 05´ N / 036° 37´ E	FBR-5	15 / 12	1959
Obninsk	2	55° 05´ N / 036° 40´ E	Obninsk Kaluga	55° 05´ N / 036° 37´ E	LWGR	5 / 5	12 / 54
Primorskaja	1				VVER-600ps		~ 2010
Primorskaja	2				VVER-600ps		~ 2010
Rostov	1	47° 32´ N / 042° 09´ E	Rostov na Donu	47° 14´ N / 039° 42´ E	VVER-1000 V320	1000 / 950	
Rostov	2	47° 32´ N / 042° 09´ E	Rostov na Donu	47° 14´ N / 039° 42´ E	VVER-1000 V320	1000 / 950	
Rostov	3	47° 32´ N / 042° 09´ E	Rostov na Donu	47° 14´ N / 039° 42´ E	VVER-1000 V320	1000 / 950	
Rostov	4	47° 32´ N / 042° 09´ E	Rostov na Donu	47° 14´ N / 039° 42´ E	VVER-1000 V320	1000 / 950	
Shevchenko	1		Shevchenko		FBR BN-350	150 / 135	7/73
Smolensk	1	54° 06´ N / 033° 20´ E	Smolensk Desnogorsk	54° 06´ N / 033° 20´ E	RBMK-1000	1000 / 925	12/82
Smolensk	2	54° 06´ N / 033° 20´ E	Smolensk Desnogorsk	54° 06´ N / 033° 20´ E	RBMK-1000	1000 / 925	05/85
Smolensk	3	54° 06´ N / 033° 20´ E	Smolensk Desnogorsk	54° 06´ N / 033° 20´ E	RBMK-1000	1000 / 925	06/90
Smolensk	4	54° 06´ N / 033° 20´ E	Smolensk Desnogorsk	54° 06´ N / 033° 20´ E	RBMK-1000	1000 / 925	
Sosnovyj Bor	1	59° 54´ N / 029° 07´ E	Sosnovyj Bor	59° 54´ N / 029° 07´ E	RBMK-1000	1000 / 925	12/73
Sosnovyj Bor	2	59° 54´ N / 029° 07´ E	Sosnovyj Bor	59° 54´ N / 029° 07´ E	RBMK-1000	1000 / 925	07/75
Sosnovyj Bor	3	59° 54´ N / 029° 07´ E	Sosnovyj Bor	59° 54´ N / 029° 07´ E	RBMK-1000	1000 / 925	12/79
Sosnovyj Bor	4	59° 54´ N / 029° 07´ E	Sosnovyj Bor	59° 54´ N / 029° 07´ E	RBMK-1000	1000 / 925	02/81
Sosnovyj Bor	5	59° 54´ N / 029° 07´ E	Sosnovyj Bor	59° 54´ N / 029° 07´ E	VVER-630es		~ 2010
Sosnovyj Bor	6	59° 54´ N / 029° 07´ E	Sosnovyj Bor	59° 54´ N / 029° 07´ E	VVER-630es		~ 2010
South Urals	1				BN-800	750 / 800	~ 2000
South Urals	2				BN-800	750 / 800	~ 2000
South Urals	3				BN-800	750 / 800	> 2000
Tatar	1	56° 08´ N / 054° 10´ E	Kama	56° 08´ N / 054° 10´ E	VVER-1000 V320	1000 / 950	
Tatar	2	56° 08´ N / 054° 10´ E	Kama	56° 08´ N / 054° 10´ E	VVER-1000 V320	1000 / 950	
Tatar	3	56° 08´ N / 054° 10´ E	Kama	56° 08´ N / 054° 10´ E	VVER-1000 V320	1000 / 950	
Tatar	4	56° 08´ N / 054° 10´ E	Kama	56° 08´ N / 054° 10´ E	VVER-1000 V320	1000 / 950	

Tomsk	1		Siberia		LWGR	200 / 190	
Tomsk	2		Siberia		LWGR	200 / 190	12/59
Tomsk	3		Siberia		LWGR	200 / 190	12/60
Tomsk	4		Siberia		LWGR	200 / 190	12/61
Tomsk	5		Siberia		LWGR	200 / 190	12/62
Troitsk	1		Cheljabinsk			100 / 90	
Troitsk	2		Cheljabinsk			100 / 90	
Troitsk	3		Cheljabinsk			100 / 90	
Troitsk	4		Cheljabinsk			100 / 90	
Troitsk	5		Cheljabinsk		LWGR	100 / 90	1/56
Voronezh	1	51° 38´ N / 039° 12´ E	Voronezh		ATC-500		~ 2000
Voronezh	2	51° 38´ N / 039° 12´ E	Voronezh		ATC-500		~ 2000

Summary of Russian Reactors
Shut-Down, Cancelled, or Suspended

Russian reactors shut down to date are as follows:	Belojarsk	Unit-1	Shut Down – 1983
	Belojarsk	Unit-2	Shut Down – 01/90
	Novovoronezh	Unit-1	Shut Down – 02/88
	Novovoronezh	Unit-2	Shut Down – 08/90
	Tomsk	Unit-1	Shut Down – 08/90
	Troitsk	Unit-1	Shut Down – 08/90
	Troitsk	Unit-2	Shut Down – 08/90
	Troitsk	Unit-3	Shut Down – 08/90
	Troitsk	Unit-4	Shut Down – 07/90
Russian reactors cancelled to date are as follows:	Gorkij	Unit-1	cancelled
	Gorkij	Unit-2	cancelled
	BN-1600	Unit-1	cancelled
	Kursk	Unit-6	cancelled
	Smolensk	Unit-4	cancelled
	Bashkir	Unit-1	cancelled
	Bashkir	Unit-2	cancelled
	Krasnodar	Unit-1	cancelled
	Tatar	Unit-1	cancelled
	Tatar	Unit-2	cancelled
	Tatar	Unit-3	cancelled
	Tatar	Unit-4	cancelled
Russian reactors suspended to date are as follows:	Rostov	Unit-1	suspended
	Rostov	Unit-2	suspended
	Rostov	Unit-3	suspended
	Rostov	Unit-4	suspended

UKRAINE

Station Name	Unit–#	Station Geographic Location	Population Center	City Georgrahic Location	Reactor Type	Gross / Net (MWe)	Grid / Power
Chornobyl	1	51° 22´ N / 030° 06´ E	Prypjat Chornobyl	51° 23´ N / 030° 03´ E 51° 15´ N / 030° 13´ E	RBMK-1000/1	1000 / 925	09/77 05/78
Chornobyl	2	51° 22´ N / 030° 06´ E	Prypjat Chornobyl	51° 23´ N / 030° 03´ E 51° 15´ N / 030° 13´ E	RBMK-1000/1	1000 / 925	12/78 05/79
Chornobyl	3	51° 22´ N / 030° 06´ E	Prypjat Chornobyl	51° 23´ N / 030° 03´ E 51° 15´ N / 030° 13´ E	RBMK-1000/2	1000 / 925	11/81 06/82
Chornobyl	4	51° 22´ N / 030° 06´ E	Prypjat Chornobyl	51° 23´ N / 030° 03´ E 51° 15´ N / 030° 13´ E	RBMK-1000/2	1000 / 925	12/83 05/84
Chornobyl	5	51° 22´ N / 030° 07´ E	Prypjat Chornobyl	51° 23´ N / 030° 03´ E 51° 15´ N / 030° 13´ E	RBMK-1000/3	1000 / 925	abandoned
Chornobyl	6	51° 22´ N / 030° 07´ E	Prypjat Chornobyl	51° 23´ N / 030° 03´ E 51° 15´ N / 030° 13´ E	RBMK-1000/3	1000 / 925	abandoned
Crimea	1	45° 20´ N / 035° 44´ E	Aktajsk Kerch	45° 20´ N / 035° 44´ E 45° 21´ N / 036° 28´ E	VVER-1000 V320		under review
Crimea	2	45° 20´ N / 035° 44´ E	Aktajsk Kerch	45° 20´ N / 035° 44´ E 45° 21´ N / 036° 28´ E	VVER-1000 V320		under review
Kharkiv	1		Kharkiv		VVER-1000 ATET		
Kharkiv	2		Kharkiv		VVER-1000 ATET		
Khmel'nyts'kyj	1	50° 18´ N / 026° 52´ E	Netishyn Slavuta	50° 18´ N / 026° 52´ E	VVER-1000 V320	1000 / 950	12/87 08/88
Khmel'nyts'kyj	2	50° 18´ N / 026° 52´ E	Netishyn Slavuta	50° 18´ N / 026° 52´ E	VVER-1000 V320	1000 / 950	(1995?)
Khmel'nyts'kyj	3	50° 18´ N / 026° 52´ E	Netishyn Slavuta	50° 18´ N / 026° 52´ E	VVER-1000 V320	1000 / 950	under review
Khmel'nyts'kyj	4	50° 18´ N / 026° 52´ E	Netishyn Slavuta	50° 18´ N / 026° 52´ E	VVER-1000 V320	1000 / 950	under review
Odesa			Teplodar	46° 28´ N / 030° 44´ E	VVER-1000 ATET		
Odesa			Teplodar	46° 28´ N / 030° 44´ E	VVER-1000 ATET		

Rivne	1	51° 23´ N / 025° 52´ E	Kuznetsovsk Saryn	51° 41´ N / 025° 52´ E 51° 20´ N / 026° 36´ E	VVER-440 V213	392 / 361	12/80 09/81
Rivne	2	51° 23´ N / 025° 52´ E	Kuznetsovsk Saryn	51° 41´ N / 025° 52´ E 51° 20´ N / 026° 36´ E	VVER-440 V213	416 / 384	12/81 07/82
Rivne	3	51° 23´ N / 025° 52´ E	Kuznetsovsk Saryn	51° 41´ N / 025° 52´ E 51° 20´ N / 026° 36´ E	VVER-1000 V320	1000 / 950	12/86 05/87
Rivne	4	51° 23´ N / 025° 52´ E	Kuznetsovsk Saryn	51° 41´ N / 025° 52´ E 51° 20´ N / 026° 36´ E	VVER-1000 V320	1000 / 950	(1994?)
South Ukraine	1	47° 50´ N / 031° 09´ E	Konstantinovka Yuzhno-Ukrajinsk	47° 50´ N / 031° 09´ E	VVER-1000 V302	1000 / 950	12/82 10/83
South Ukraine	2	47° 50´ N / 031° 09´ E	Konstantinovka Yuzhno-Ukrajinsk	47° 50´ N / 031° 09´ E	VVER-1000 V302	1000 / 950	01/85 04/85
South Ukraine	3	47° 50´ N / 031° 09´ E	Konstantinovka Yuzhno-Ukrajinsk	47° 50´ N / 031° 09´ E	VVER-1000 V320	1000 / 950	09/89 12/89
South Ukraine	4	47° 50´ N / 031° 09´ E	Konstantinovka Yuzhno-Ukrajinsk	47° 50´ N / 031° 09´ E	VVER-1000 V320		under review
Zaporizhzhja	1	47° 28´ N / 034° 50´ E	Enerhodar	47° 30´ N / 034° 28´ E	VVER-1000 V320	1000 / 950	12/84 04/85
Zaporizhzhja	2	47° 28´ N / 034° 50´ E	Enerhodar	47° 30´ N / 034° 28´ E	VVER-1000 V320	1000 / 950	06/85 10/85
Zaporizhzhja	3	47° 28´ N / 034° 50´ E	Enerhodar	47° 30´ N / 034° 28´ E	VVER-1000 V320	1000 / 950	12/86 01/87
Zaporizhzhja	4	47° 28´ N / 034° 50´ E	Enerhodar	47° 30´ N / 034° 28´ E	VVER-1000 V320	1000 / 950	12/87 01/88
Zaporizhzhja	5	47° 28´ N / 034° 50´ E	Enerhodar	47° 30´ N / 034° 28´ E	VVER-1000 V320	1000 / 950	08/89 10/89
Zaporizhzhja	6	47° 28´ N / 034° 50´ E	Enerhodar	47° 30´ N / 034° 28´ E	VVER-1000 V320	1000 / 950	(1994?)

APPENDIX V

Detailed Classification of Lava-Like Fuel Containing Materials and Results of Radiochemical Analyses

Data Group A.1
Sub-Reactor Region (305/2)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	Black, porous ceramic	11.28	5.86	5.90	0.35	0.150	0.55
2	Black, porous ceramic	12.44	5.82	5.87	0.39	0.090	0.59
3	Black, porous ceramic 16 cm below surface	11.94	3.78	4.02	0.09	0.020	0.57
$x \pm \sigma$		11.89 ± 0.48	5.15 ± 0.97	5.26 ± 0.88	0.28 ± 0.13	0.087 ± 0.053	0.57 ± 0.02

Data Group A.2
Sub-Reactor Region (305/2)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	Ce-144 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	4.200	7.700	1.480	2.000	1.100	1.510	3.300	1.800	1.930	6.600		
2	4.300	7.800	1.090	1.800	1.100	1.530	3.700	2.200	2.610	4.000		
3	3.030	6.368	1.180	1.344	0.746	0.986	0.560	0.321	3.532	0.554	0.157	
$x \pm \sigma$	3.84 ± 0.58	7.29 ± 0.65	1.25 ± 0.17	1.72 ± 0.27	0.98 ± 0.17	1.34 ± 0.25	2.52 ± 0.14	1.44 ± 0.81	2.69 ± 0.66	3.72 ± 2.48	0.16 ± 0.40	

Data Group B.1
Room 304/3

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	LFCM: 15 cm below surface	11.20	3.75	4.25	0.39	0.040	0.54
2	LFCM: 30 cm below surface, 13 m from 207/4	11.64	4.52	4.32	0.19	0.020	0.56
3	LFCM: 5 cm below surface	11.54	4.18	4.20	0.10	0.020	0.56
4	LFCM surface	12.10	3.73	4.42	0.17	0.020	0.58
5	piece from height 0 cm	11.53	4.52	4.55	0.26	0.090	0.56
6	piece from height 10 cm	12.18	5.80	5.84	0.30	0.080	0.58
7	piece from height 5 cm	11.77	4.88	4.92	0.37	0.020	0.57
8	LFCM	11.25	3.25	3.54	0.38	0.020	0.54
9	LFCM	10.80	4.05	4.38	0.39		0.52
10	LFCM	11.06	3.26	4.17	0.41		0.54
11	LFCM	11.36	3.43	4.12	0.43		0.55
12	black, course-grain porous lava with large gas voids 30 cm deep	11.08	3.69	4.80	0.23	0.050	0.54
13	black porous ceramic	12.01	4.82	4.86	0.33	0.050	0.58
14	black porous ceramic	11.51	4.09	4.13	0.41	0.010	0.56
15	black, porous lava with large gas inclusions 30 cm deep	11.60	4.25	4.20	0.37		0.56
16	black, porous lava with large gas voids 30 cm deep	10.98	3.33	5.47	0.24		0.53
17	black, medium-grain porous lava, 30 cm below surface	11.28	4.21	4.76	0.49		0.55
18	black, hard, brittle piece	11.07	4.32	4.60	0.40	0.020	0.54
19	black, hard, brittle piece	10.99	3.27	3.90	0.40	0.020	0.53
20	black, hard, brittle piece	11.38	3.23	3.90	0.40	0.020	0.55
21	black, hard, brittle piece	11.38	3.23	4.30	0.40	0.040	0.55
22	black, hard, brittle piece	10.81	4.34	4.40	0.43	0.020	0.53
23	black, hard, brittle piece	10.93	4.15	4.10	0.44	0.020	0.53
$x \pm \sigma$		11.37 ± 0.39	4.01 ± 0.64	4.44 ± 0.50	0.34 ± 0.10	0.033 ± 0.022	0.55 ± 0.02

Data Group B.2
Room 304/3

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	(36.16)?	(61.77)?	(31.43)?	(13.01)?	(7.214)?	0.966	2.302	1.248	4.884	1.150	0.543	
2	4.080	7.568	1.596	1.779	0.848	1.174	1.410	0.791	4.452	0.832	0.236	
3	3.599	6.756	1.321	1.595	0.724	1.083	0.662	0.368	5.999	0.636	0.180	
4	3.273	6.313	1.958	1.439	0.762	0.976	1.004	0.583	3.841	0.655	0.186	
5	3.550	12.50	1.350	0.722	1.470	1.170	1.870	1.040	2.860	2.940	2.470	
6	5.940	12.80	1.340	1.740	1.350	1.520	2.860	1.670	2.530	3.500	4.030	
7	3.530	11.80	1.290	0.805	1.560	1.270	2.930	1.660	2.230	0.625	2.570	
8	3.225	5.801	1.353	0.829	0.733	0.836	1.990	1.083		0.405		7.228
9	4.190	7.901	1.542	1.802	0.922	1.033	2.477	1.300				9.451
10	3.482	6.401	1.067	1.262	0.780	0.836	2.101	1.126				6.338
11	3.383	6.601	1.097	1.352	0.769	0.886	2.366	1.300				8.673
12	3.887	7.501	6.905	3.849	1.576	0.946	1.367	0.734		1.425		6.941
13	3.600	6.600	1.540		0.900	1.260	2.600	1.500	1.650	2.000		
14	3.600	6.500	0.306		0.900	1.060	2.700	1.500	2.120	0.440		
15	4.356	8.101	5.753		1.588	1.101	2.506	1.401				7.457
16	4.145	8.001	4.372	2.951	1.489	0.853	1.253	0.667				6.941
17	5.355	8.601	3.500		1.427	1.086	3.303	1.802				6.539
18	4.272	8.101	2.858		1.533	1.108	2.760	1.480		0.579		8.547
19	3.814	6.501	2.476	2.017	1.179	1.016	2.539	1.354		0.579		7.104
20	1.950	8.201	5.295	2.017	1.415	1.016	2.539	1.396		0.579		7.659
21	3.159	6.501	2.234	1.614	1.061	1.016	2.539	1.396		1.157		7.770
22	3.979	8.101	4.187	2.340	1.533	1.108	2.981	1.565		0.579		8.210
23	3.693	7.101	2.959	1.936	1.297	1.062	2.870	1.532		0.771		7.437
$x \pm \sigma$	3.82 ± 0.77	7.92 ± 1.93	2.56 ± 1.71	1.77 ± 0.76	1.17 ± 0.32	1.06 ± 0.15	2.26 ± 0.68	1.24 ± 0.37	3.40 ± 1.39	1.11 ± 0.87	1.46 ± 1.44	7.59 ± 0.84

Data Group C.1
Corridor 301/5

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	brown large-grained damp powder	11.62	3.04	3.93	0.39	0.020	0.56
2	dark-brown & brittle crumb	12.46	2.78	1.52	0.39	0.040	0.60
3	dull black ceramic with grey-brown inclusions	11.47	3.66	4.65	0.39	0.080	0.55
4	fragments of black lava with dull surface and shiny inside	11.40	3.06	4.46	0.19	0.030	0.55
5	black ceramic	11.27	4.80	5.16	0.40	0.030	0.55
6	black, course-grain, porous lava 10-15 cm from the surface	10.79	3.59	3.61	0.38		0.52
7	black lava	11.65	3.77	4.54	0.40	0.030	0.56
8	black lava, mid-grain porous with soot and ashes 1–10 cm from the surface	11.57	4.07	5.48	0.37		0.56
9	black, course-grain, flaky porous lava 0–15 cm from the surface	11.54	3.65	4.50	0.39		0.56
10	black-grey damp sand with shiny-grey droplet inclusions	11.58	2.65	4.03	0.29	0.030	0.56
11	black shiny pieces with stuck-on damp, grey grains	11.74	3.32	4.28	0.42	0.040	0.57
$x \pm \sigma$		11.55 ± 0.38	3.49 ± 0.59	4.20 ± 0.99	0.36 ± 0.06	0.038 ± 0.017	0.56 ± 0.02

Data Group C.2
Corridor 301/5

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	Ce-144 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	4.241	7.191	2.630		1.071	0.790	1.911	1.071		0.413		5.567
2	2.868	4.901	1.749	1.019	0.537	0.731	1.756	1.046	1.638	0.821		(4.75e-8)?
3	3.731	7.961	0.763		6.729	0.947	2.275	1.260		2.175		5.166
4	3.830	8.741	6.178		2.503	0.792	0.936	0.516		0.738		1.057
5	5.166	9.504	2.014	2.906	1.097	1.238	3.035	1.655		1.037		(5.66e-14)?
6	4.615	8.701	5.399		1.489	0.915	2.164	1.134				6.500
7	4.646	8.342	1.835	3.082	0.900	0.980	2.428	1.363		0.830		(5.66e-14)?
8	5.399	9.802	5.877	6.416	1.613	1.055	2.392	1.335				8.031
9	4.330	8.401	4.609	3.978	1.489	0.946	2.278	1.268				7.067
10	3.030	5.711	0.776		0.848	0.688	1.251	0.699		0.634		5.200
11	3.626	6.811	0.969		0.725	0.863	2.229	1.260		0.921		6.529
x ± σ	4.14 ± 0.77	7.82 ± 1.46	2.98 ± 2.02	3.48 ± 1.76	1.73 ± 1.66	0.90 ± 0.15	2.06 ± 0.55	1.15 ± 0.30	1.64 ± 0.01	0.95 ± 0.50		5.64 ± 1.96

Data Group D.1
Corridor 217/2 (undefined location)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	black lava	12.02	4.26	4.30	0.33	0.050	0.58
$x \pm \sigma$		12.02 ± 3.47	4.26 ± 2.06	4.30 ± 2.07	0.33 ± 0.58	0.050 ± 0.224	0.58 ± 0.76

Data Group D.2
Corridor 217/2 (undefined location)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	Ce-144 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	4.720	7.840	1.109	2.581	0.769	1.113	2.303	1.329		1.674		
$x \pm \sigma$	4.72 ± 0.01	7.84 ± 0.01	1.11 ± 0.01	2.58 ± 0.01	0.77 ± 0.01	1.11 ± 0.01	2.30 ± 0.01	1.33 ± 0.01		1.67 ± 0.01		

Data Group E.1
Corridor 217/2 ("Elephant's Foot")

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	"Elephant's Foot"	10.19	4.69	5.30	0.46	0.030	0.50
2	shiny black ceramic	10.95	5.31	5.36	0.38	0.050	0.53
$x \pm \sigma$		10.57 ± 0.38	5.00 ± 0.31	5.33 ± 0.03	0.42 ± 0.04	0.040 ± 0.010	0.52 ± 0.02

Data Group E.2
Corridor 217/2 ("Elephant's Foot")

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	Ce-144 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1						1.177	3.332	1.660		0.951		
2	5.300	9.700	1.440	1.900	1.200	1.360	3.200	1.700	1.910	1.900		
$x \pm \sigma$	5.30 ± 0.01	9.70 ± 0.01	1.44 ± 0.01	1.90 ± 0.01	1.20 ± 0.01	1.27 ± 0.09	3.27 ± 0.07	1.68 ± 0.02	1.91 ± 0.01	1.43 ± 0.47		

Data Group F.1

Corridor 217/2 (Stalagtite at [D 1/2, 43 1/2])

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 ($^w/_o$)	meas. UO_2 ($^w/_o$)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	black "Stalagtite" black hanging from ceiling	11.56	4.21	4.24	0.32	0.090	0.56
2	black "Stalagtite" black hanging from ceiling	11.37	5.30	5.00	0.30	0.020	0.55
3	black "Stalagtite" black hanging from ceiling	11.63	4.31	4.35	0.31	0.030	0.56
4	black "Stalagtite" black hanging from ceiling	11.92	4.79	4.83	0.35	0.060	0.57
5	black "Stalagtite" black hanging from ceiling	12.06	4.40	4.43	0.36	0.020	0.58
6	black "Stalagtite" black hanging from ceiling	11.50	5.10	5.14	0.42	0.020	0.55
7	black "Stalagtite" black hanging from ceiling	11.53	4.71	4.75	0.36	0.030	0.56
8	black "Stalagtite" black hanging from ceiling	11.38	4.30	4.33	0.47	0.060	0.55
9	dull black ceramic	12.35	4.87	4.91	0.28	0.030	0.59
$x \pm \sigma$		11.70 ± 0.32	4.67 ± 0.36	4.66 ± 0.31	0.35 ± 0.06	0.040 ± 0.023	0.56 ± 0.01

Data Group F.2

Corridor 217/2 (Stalagtite at [D $^1/_2$, 43 $^1/_2$])

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	Ce-144 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	3.770	8.330	1.270	0.889	1.150	1.090	2.170	1.210	1.610	2.750	2.210	
2	5.270	11.80	1.600	1.230	1.600	1.370	2.530	1.390	2.170	0.884	3.490	
3	3.050	9.250	1.400	0.495	1.160	1.120	2.140	1.200	2.000	1.100	2.760	
4	2.890	8.410	1.430	1.720	1.170	1.250	2.740	1.570	1.800	2.070	5.250	
5	3.470	7.880	1.400	0.629	0.790	1.150	2.540	1.470	2.020	0.752	3.200	
6	4.170	14.10	1.510	0.602	1.310	1.320	3.460	1.920	2.630	0.691	4.360	
7	3.890	9.500	1.170	1.060	1.550	1.220	2.750	1.530	1.710	1.160	4.060	
8	4.280	6.760	1.110	0.756	1.240	1.110	3.220	1.770	1.650	1.940	5.090	
9	4.600	8.400	1.150	1.500	1.000	1.280	2.200	1.300	2.070	1.100		
x ± σ	3.93 ± 0.71	9.38 ± 2.12	1.34 ± 0.16	0.99 ± 0.40	1.22 ± 0.24	1.21 ± 0.09	2.64 ± 0.44	1.48 ± 0.23	1.96 ± 0.30	1.38 ± 0.67	3.80 ± 1.01	

Data Group G.1
Corridor 217/2 (Stalagtite at [G, 43])

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	"flow stream" behind stalagtite – 0 cm deep	11.09	4.21	4.24	0.42	0.020	0.54
2	"flow stream" behind stalagtite – 2 cm deep	12.44	5.40	5.44	0.51	0.090	0.59
3	"flow stream" behind stalagtite – 4 cm deep	11.42	4.60	4.64	0.43	0.020	0.55
4	"flow stream" behind stalagtite – 6 cm deep	11.65	4.70	4.74	0.45	0.010	0.56
5	shiny black ceramic	11.51	4.79	4.83	0.35	0.050	0.56
$x \pm \sigma$		11.62 ± 0.45	4.74 ± 0.39	4.78 ± 0.39	0.43 ± 0.05	0.038 ± 0.029	0.56 ± 0.02

Data Group G.2
Corridor 217/2 (Stalagtite at [G, 43])

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	4.430	9.680	1.150	0.577	1.040	1.080	2.810	1.510	1.930	0.574	4.000	
2	5.090	12.90	1.280	2.430	1.190	1.420	4.490	2.670	3.220	3.560	3.760	
3	4.720	9.120	1.350	0.936	1.300	1.190	3.190	1.760	2.170	0.529	4.400	
4	3.060	7.690	1.210	0.706	0.868	1.220	3.420	1.920	2.820	0.511	3.830	
5	4.000	7.300	1.750	1.300	0.900	1.240	2.700	1.500	1.920	1.800		
$x \pm \sigma$	4.26 ± 0.70	9.34 ± 1.99	1.35 ± 0.21	1.19 ± 0.67	1.06 ± 0.17	1.23 ± 0.11	3.32 ± 0.64	1.87 ± 0.43	2.41 ± 0.52	1.40 ± 1.19	4.00 ± 0.25	

Data Group H.1

Corridor 217/2 ("Elephant's Foot" – 2nd Flow Stream)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	black lava	12.60	5.16	4.83	0.29	0.050	0.60
2	black, shiny, conglomerate mass	11.38	3.79	4.39	0.40	0.020	0.55
$x \pm \sigma$		11.99 ± 0.61	4.48 ± 0.69	4.61 ± 0.22	0.35 ± 0.06	0.035 ± 0.015	0.58 ± 0.03

Data Group H.2

Corridor 217/2 ("Elephant's Foot" – 2nd Flow Stream)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	4.683	7.865	0.871	1.882	0.765	1.360	2.462	1.481		1.885		5.410
2	4.069	6.601	0.322	1.622	0.857	0.980	2.444	1.344		0.474		6.448
$x \pm \sigma$	4.38 ± 0.31	7.23 ± 0.63	0.60 ± 0.27	1.75 ± 0.13	0.81 ± 0.05	1.17 ± 0.19	2.45 ± 0.01	1.41 ± 0.07		1.18 ± 0.71		5.93 ± 0.52

Data Group I.1
Corridor 217/2 (undefined location)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	"top" of droplet – black mass	11.27	3.96	4.19	0.41	0.020	0.55
2	"bottom" of droplet – shiny black, melted mass with greenish shimmer	11.36	4.01	4.57	0.40	0.020	0.55
$x \pm \sigma$		11.32 ± 0.05	3.99 ± 0.03	4.38 ± 0.19	0.41 ± 0.01	0.020 ± 0.000	0.55 ± 0.00

Data Group I.2
Corridor 217/2 (undefined location)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	4.008	6.661	0.632	2.027	0.656	1.021	2.601	1.418		0.500		
2	5.504	7.705	0.712	1.946	0.831	1.035	2.584	1.418		0.625		(6.33 e-14)?
$x \pm \sigma$	4.76 ± 0.75	7.18 ± 0.52	0.67 ± 0.04	1.99 ± 0.04	0.74 ± 0.09	1.03 ± 0.01	2.59 ± 0.01	1.42 ± 0.00		0.56 ± 0.06		

Data Group J.1
Corridor 017/2 (pieces laying on floor)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	small scone	12.05	4.90	4.94	0.41	0.010	0.58
2	10 cm scone	12.10	5.20	5.24	0.32	0.030	0.58
3	5 cm scone	11.15	4.78	4.82	0.29	0.020	0.54
$x \pm \sigma$		1..77 ± 0.44	4.96 ± 0.18	5.00 ± 0.18	0.34 ± 0.05	0.020 ± 0.008	0.57 ± 0.02

Data Group J.2
Corridor 017/2 (pieces laying on floor)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	3.050	9.150	1.440	9.390	1.320	1.280	3.250	1.880	3.080	0.539	5.950	
2	5.020	14.40	1.530	17.10	1.560	1.360	2.670	1.550	2.510	1.110	4.620	
3	4.860	16.30	1.320	9.450	1.530	1.230	2.240	1.210	2.460	0.589	3.000	
$x \pm \sigma$	4.31 ± 0.89	13.28 ± 3.02	1.43 ± 0.09	1.20 ± 0.36	1.47 ± 0.11	1.29 ± 0.05	2.72 ± 0.41	1.55 ± 0.27	2.68 ± 0.28	0.75 ± 0.26	4.52 ± 1.21	

Data Group K.1
Steam Distribution Corridor (210/7)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1		11.46	10.51	10.60	0.29	0.020	0.55
2		11.63	9.79	9.87	0.30	0.050	0.56
3		11.53	9.69	9.77	0.32	0.030	0.56
4	brown ceramic (SDH 4, tube 1)	11.78	10.96	8.19	0.17		0.57
5	brown chocolate ceramic	11.12	10.71	10.80	0.31	0.030	0.54
6	brown chocolate ceramic	12.83	10.59	10.70	0.31	0.030	0.61
7	brown chocolate ceramic	12.13	10.54	10.60	0.32	0.060	0.58
8	red lava from the floor	11.17	8.15	8.68	0.39	0.040	0.54
9	piece from surface	12.63	9.79	9.87	0.41	0.020	0.60
10	piece from 1 cm depth	11.82	10.41	10.50	0.36	0.050	0.57
11	dense dark-brown ceramic with metallic droplet inclusions	13.56	13.99	12.00	0.30	0.030	0.64
12	light-brown ceramic (SDH 4, tube 1)	11.43	9.65	8.22	0.13	0.040	0.55
13	dark-brown ceramic (SDH 4, tube 2)	11.52	9.04	7.98	0.15	0.140	0.56
14	black mass without metallic inclusions (SDH 4, tube 3)	10.60	9.05	8.26	0.09	0.060	0.52
15	elliptical piece to the side of great axis 2 cm	11.92	9.58	9.66	0.49	0.030	0.57
16	elliptical piece to the side of great axis 3 cm	12.02	10.49	1.0.6	0.46	0.070	0.58
17	elliptical piece to the side of great axis 4 cm	12.61	9.79	9.87	0.38	0.040	0.60
18	elliptical piece to the side of great axis 5 cm	11.84	10.40	10.50	0.49	0.020	0.57
19	elliptical piece to the side of great axis 6 cm	11.73	10.31	10.40	0.33	0.020	0.56
20	elliptical piece to the side of great axis 7 cm	11.05	10.10	10.20	0.32	0.010	0.54
$x \pm \sigma$		11.82 ± 0.67	10.2 ± 1.10	9.86 ± 1.05	0.32 ± 0.11	0.042 ± 0.028	0.57 ± 0.03

Data Group K.2
Steam Distribution Corridor (210/7)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	7.730	23.70	2.740	2.370	2.180	2.720	4.950	2.740	4.560	1.240	6.980	
2	6.320	16.80	2.350	3.040	3.230	2.540	4.710	2.640	3.920	3.770	6.300	
3	(98.50)?	29.70	3.060	2.540	2.450	2.510	4.960	2.760	3.690	2.470	8.690	
4	8.528	15.40	4.397	(34.33)?	0.194	2.853	3.036	1.721	11.54	0.209	0.241	8.456
5	11.00	20.00	2.110	4.000		2.750	5.200	2.800	4.300	2.600		
6	11.00	20.00	2.320	4.100	2.400	2.800	5.400	3.300	4.260	2.200		
7	11.00	20.00	1.660	5.000	2.700	2.760	5.500	3.200	3.390	4.600		
8	9.509	17.28	1.424	3.893	1.574	2.097	5.032	2.721		2.436		(1.24e-14)?
9	7.450	18.20	3.100	3.310	2.000	2.580	6.570	3.960	5.450	1.850	5.630	
10	10.10	26.80	2.450	3.190	1.850	2.710	6.050	3.440	4.460	3.620	7.400	
11						3.726	6.837	4.379		2.768		
12	9.667	16.78	5.406	(39.86)?	0.216	2.459	2.022	1.116	11.48	3.022	0.580	9.132
13	9.216	16.80	5.162	(35.44)?	0.205	2.343	2.239	1.245	9.568	9.893	0.999	8.343
14	7.830	14.07	3.292	(29.95)?	0.178	2.297	1.310	0.676	8.514	4.137	0.476	6.652
15	9.940	21.30	2.590	1.490	1.960	2.500	7.560	4.330	3.990	2.070	6.200	
16	8.000	18.00	2.750	2.550	2.090	2.740	7.760	4.480	5.120	5.900	10.30	
17	9.290	22.30	2.600	3.320	2.600	2.580	6.000	3.610	4.680	2.980	8.020	
18	8.880	22.80	3.000	3.250	2.560	2.710	8.270	4.710	4.340	1.270	5.510	
19	9.180	24.40	2.760	3.220	2.700	2.680	5.540	3.130	4.310	1.390	7.060	
20	7.780	30.80	3.500	1.420	2.620	2.590	5.060	2.710	4.560	1.070	7.970	
x ± σ	9.02 ± 1.30	20.80 ± 4.56	2.98 ± 1.01	3.11 ± 0.92	1.87 ± 0.97	2.65 ± 0.31	5.20 ± 1.83	2.98 ± 1.11	5.67 ± 2.57	2.98 ± 1.06	5.49 ± 3.19	8.15 ± 0.91

Data Group L.1

Steam Distribution Corridor (undefined location)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 ($w/_o$)	meas. UO_2 ($w/_o$)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	dark-grey dense mass without voids	11.77	5.12	7.49	0.68	0.360	0.57
$x \pm \sigma$		11.77 ± 3.43	5.12 ± 2.26	7.49 ± 2.74	0.68 ± 0.83	0.360 ± 0.600	0.57 ± 0.76

Data Group L.2

Steam Distribution Corridor (undefined location)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	6.278	11.29	1.352	3.514	1.485	1.333	5.595	3.170		14.26		(5.77e-14)?
$x \pm \sigma$	6.28 ± 0.01	11.29 ± 0.01	1.35 ± 0.01	3.51 ± 0.01	1.49 ± 0.01	1.33 ± 0.01	5.60 ± 0.01	3.17 ± 0.01		14.26 ± 0.01		

Data Group M.1
Pressure Suppression Pool – 2 (012/15)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 ($^w/_o$)	meas. UO_2 ($^w/_o$)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	brown lava from "pile"	11.81	7.26	9.80	0.58	0.100	0.57
2	dull brown ceramic	11.88	10.16	10.20	0.30		0.57
3	dull brown ceramic	11.24	11.65	11.70	0.31	0.040	0.54
4	brown fine-porous lava with streaks of pumice, 20 cm depth from surface	11.44	9.00	9.04	0.28	0.040	0.55
5	pile, selection from 0 cm depth	11.15	10.31	10.40	0.36	0.030	0.54
6	pile, selection from 2 cm depth	12.30	10.40	10.50	0.32	0.040	0.59
7	pile, selection from 5 cm depth	11.82	10.21	10.30	0.36	0.020	0.57
8	brown, fine-porous lava with black droplets, some spherical form	11.78	7.75	7.52	0.28		0.57
$x \pm \sigma$		11.68 ± 0.35	9.59 ± 1.38	9.93 ± 1.15	0.35 ± 0.09	0.045 ± 0.026	0.56 ± 0.02

Data Group M.2

Pressure Suppression Pool – 2 (012/15)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	7.898	13.70	3.558	4.257	0.229	1.891	6.755	3.839		5.383		
2	9.400	17.00	1.710	3.000	2.300	2.650	4.900	2.800	3.930			
3	9.400	17.00	2.860	3.300	2.300	3.000	5.700	3.100	4.140	3.600		
4	9.704	19.00	11.21	9.624	3.351	2.327	3.987	2.202		2.556		16.86
5	10.20	18.30	3.570	2.820	2.050	2.650	5.910	3.190	3.480	2.390	5.290	
6	7.860	31.30	3.460	2.770	2.060	2.730	5.330	3.140	4.840	3.090	10.50	
7	9.310	25.40	3.580	2.580	2.640	2.660	5.960	3.390	4.670	1.290	6.870	
8	7.843	14.00	8.343	7.057	2.482	2.017	3.531	2.002				13.54
$x \pm \sigma$	8.95 ± 0.88	19.46 ± 5.61	4.79 ± 3.03	4.43 ± 2.40	2.18 ± 0.83	2.49 ± 0.36	5.26 ± 1.01	2.96 ± 0.57	4.21 ± 0.50	3.05 ± 1.26	7.55 ± 2.18	15.20 ± 1.66

Data Group N.1

Pressure Suppression Pool – 2 (undefined location)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 ($w/_o$)	meas. UO_2 ($w/_o$)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	pumice	12.46	13.22	11.5	0.33	0.040	0.60
2	porous dark-brown material similar to slag	13.21	9.67	11.0	0.35	0.040	0.63
$x \pm \sigma$		12.84 ± 0.38	11.5 ± 1.78	11.25 ± 0.25	0.34 ± 0.01	0.040 ± 0.000	0.62 ± 0.02

Data Group N.2

Pressure Suppression Pool – 2 (undefined location)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	(4.654e-3)?	13.30		(2.834e-9)?	4.421	3.477	7.148	4.257		3.700		
2						2.566	5.481	3.434		2.681		
$x \pm \sigma$		13.30 ± 0.01			4.42 ± 0.01	3.02 ± 0.46	6.32 ± 0.83	3.85 ± 0.41		3.19 ± 0.51		

Data Group O.1
Pressure Suppression Pool – 1 (012/7)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 ($w/_o$)	meas. UO_2 ($w/_o$)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	brown ceramic from a pile	11.67	11.32	11.40	0.26	0.020	0.56
2	pile, selection from 0 cm deep	11.64	10.21	10.30	0.36	0.030	0.56
3	pile, selection from 10 cm deep	12.22	10.11	10.20	0.36	0.030	0.59
4	pile, selection from 15 cm deep	11.46	9.59	9.66	0.36	0.040	0.55
5	pile, selection from 5 cm deep	12.53	9.91	10.00	0.32	0.080	0.60
6	dark-brown lava, below: small pores, top: large, 50 cm depth	11.88	8.93	9.73	0.32		0.57
7	dark-brown, fine-porous lava 25 cm depth	11.83	8.34	9.70	0.30	0.040	0.57
8	dark-brown, fine-porous lava 25 cm depth	11.57	9.57	8.47	0.31		0.56
$x \pm \sigma$		11.85 ± 0.34	9.75 ± 0.83	9.93 ± 0.76	0.32 ± 0.03	0.040 ± 0.019	0.57 ± 0.02

Data Group O.2

Pressure Suppression Pool – 1 (012/7)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	10.00	(190.0)?	2.660	3.700	2.400	2.940	4.800	2.700	3.860	1.900		
2	11.00	22.10	2.830	2.160	1.950	2.650	5.830	3.270	4.800	2.550	7.590	
3	7.470	24.50	2.710	3.300	2.080	2.650	5.890	3.450	4.130	2.580	5.470	
4	6.920	14.00	2.920	2.000	1.850	2.480	5.530	3.060	4.370	2.560	5.890	
5	7.850	25.40	2.320	4.440	2.250	2.610	5.130	3.070	4.350	5.800	7.150	
6	9.646	18.00	11.69		3.475	2.327	4.556	2.603				16.52
7	9.646	16.30	5.659	7.699	2.854	2.172	3.987	2.269		2.703		15.60
8	9.647	17.00	3.574	5.004	2.358	2.482	4.784	2.669				13.77
x ± σ	9.02 ± 1.33	19.61 ± 4.06	4.30 ± 2.96	4.04 ± 1.81	2.40 ± 0.50	2.54 ± 0.22	5.06 ± 0.62	2.89 ± 0.37	4.30 ± 0.31	3.02 ± 1.27	6.53 ± 0.87	15 30 ± 1.14

Data Group P.1

Pressure Suppression Pool – 1 (undefined location)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	rust-colored pumice from a pile in the room	10.97	9.90	18.40	0.31	0.050	0.53
2	porous, non-homogeneous – similar to slag	11.79	10.50	10.00	0.31	0.030	0.57
$x \pm \sigma$		11.38 ± 0.41	10.20 ± 0.30	14.20 ± 4.20	0.31 ± 0.00	0.040 ± 0.010	0.55 ± 0.02

Data Group P.2

Pressure Suppression Pool – 1 (undefined location)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	9.080	17.52	(-5.13e+4)?	2.922	2.107	2.536	4.882	2.598		3.701		
2						2.733	5.246	2.976		2.621		
$x \pm \sigma$	9.08 ± 0.01	17.52 ± 0.01		2.92 ± 0.01	2.11 ± 0.01	2.64 ± 0.01	5.06 ± 0.18	2.79 ± 0.19		3.16 ± 0.54		

Data Group Q.1
Pressure Suppression Pool – 1 (012/5)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 ($^w/_o$)	meas. UO_2 ($^w/_o$)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	porous, highly-active FCM on top of metal structure	11.53	10.44	8.90	0.18	0.030	0.56
$x \pm \sigma$		11.53 ± 3.40	10.44 ± 3.23	8.90 ± 2.98	0.18 ± 0.42	0.030 ± 0.173	0.56 ± 0.75

Data Group Q.2
Pressure Suppression Pool – 1 (012/5)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	8.281	15.38	3.239	3.615	1.641	2.705	3.068	1.707	16.63	2.111	0.544	
$x \pm \sigma$	8.28 ± 0.01	15.38 ± 0.01	3.24 ± 0.01	3.62 ± 0.01	1.64 ± 0.01	2.71 ± 0.01	3.07 ± 0.01	1.71 ± 0.01	16.63 ± 0.01	2.11 ± 0.01	0.54 ± 0.01	

Data Group R.1

Pressure Suppression Pool – 1 (012/8)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	porous, highly-active FCM on top of metal structure	11.59	10.14	8.16	0.23	0.030	0.56
$x \pm \sigma$		11.59 ± 3.40	10.14 ± 3.18	8.16 ± 2.86	0.23 ± 0.48	0.030 ± 0.173	0.56 ± 0.75

Data Group R.2

Pressure Suppression Pool – 1 (012/8)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	8.340	15.62	4.348	3.748	2.041	2.630	3.776	2.111	15.09	2.450	0.578	
$x \pm \sigma$	8.34 ± 0.01	15.62 ± 0.01	4.35 ± 0.01	3.75 ± 0.01	2.04 ± 0.01	2.63 ± 0.01	3.78 ± 0.01	2.11 ± 0.01	15.09 ± 0.01	2.45 ± 0.01	0.58 ± 0.01	

Data Group S.1
Steam Distribution Corridor (210/6)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	grey droplets/inclusions in black-brown lava	12.50	4.96	4.13	0.51	0.100	0.60
2	shiny black ceramic	12.94	4.61	4.65	0.52	0.140	0.62
3	black ceramic	11.87	6.84	6.00	0.57	0.140	0.57
4	black lava	11.74	10.38	7.67	0.35	0.020	0.57
5	black lava	12.25	6.03	5.25	0.60	0.090	0.59
6	black lava (SDH 3, tube 1)	12.77	6.29	6.32	0.52	0.070	0.61
7	black lava (from tail) with a mettlic sheen	11.42	5.94	6.77	0.38	0.130	0.55
8	black lava (SDH 4, tube 2)	11.52	5.35	8.20	0.24	0.080	0.56
9	black-brown lava	12.41	5.45	7.23	0.60	0.150	0 59
10	slag-form, solid, black color (SDH 3, tube 1)	12.16	6.77	7.66	0.53	0.150	0.58
$x \pm \sigma$		12.16 ± 0.49	6.26 ± 1.54	6.39 ± 1.30	0.48 ± 0.11	0.107 ± 0.041	0.58 ± 0.02

Data Group S.2
Steam Distribution Corridor (210/6)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	4.763	8.478	3.524	1.942	1.150	1.306	4.125	2.464	3.894	3.972	0.649	
2	4.800	8.700	1.320	1.700	1.400	1.220	3.900	2.400	2.460	5.000		
3						1.783	6.282	3.584		7.182		
4	8.600	14.35	3.634	5.515	1.983	2.699	5.766	3.260		1.481		(7.81e-14)?
5	6.259	10.85	3.826	2.715	1.571	1.582	5.877	3.450	6.824	4.119	0.875	
6	6.538	10.89	2.529	2.753	1.368	1.662	5.304	3.227		3.581		9.016
7	6.239	10.57	1.981	(25.00)?	0.138	1.536	3.632	2.003	6.705	6.081	0.618	6.201
8	9.653	16.70	4.772	4.003	0.224	1.385	2.017	1.121		3.289		9.268
9	7.341	12.08	3.025	2.714	1.574	1.432	5.316	3.154	5.760	6.215	0.800	
10	6.413	11.31	1.908	(24.31)?	0.144	1.772	5.807	3.385	8.532	7.738	0.891	7.892
x ± σ	6.73 ± 1.51	11.55 ± 2.45	2.95 ± 1.04	3.05 ± 1.22	1.06 ± 0.67	1.64 ± 0.40	4.80 ± 1.27	2.81 ± 0.75	5.70 ± 2.00	4.87 ± 1.84	0.77 ± 0.11	8.09 ± 1.21

Data Group T.1
Pressure Suppression Pool – 1 (012/6)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	porous, highly-active FCM on top of metal structure	10.98	9.05	8.61	0.16	0.030	0.53
$x \pm \sigma$		10.98 ± 3.31	9.05 ± 3.01	8.61 ± 2.93	0.16 ± 0.40	0.030 ± 0.173	0.53 ± 0.73

Data Group T.2
Pressure Suppression Pool – 1 (012/6)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	7.490	14.06	3.379	3.397	1.734	2.318	2.309	1.230	12.77	1.878	44.33	
$x \pm \sigma$	7.49 ± 0.01	14.06 ± 0.01	3.38 ± 0.01	3.40 ± 0.01	1.73 ± 0.01	2.32 ± 0.01	2.31 ± 0.01	1.23 ± 0.01	12.77 ± 0.01	1.88 ± 0.01	0.44 ± 0.01	

Data Group U.1

Steam Distribution Corridor (undefined location)

1	2	3	4	5	6	7	8
#	Description	Burnup (MW·d/kg·U)	calc. UO_2 (w/o)	meas. UO_2 (w/o)	Cs-137 A_m/A_c	Ru-106 A_m/A_c	Cs-134/Cs-137
1	red ceramic	12.11	7.43	6.11	0.28	0.100	0.58
2	pieces of ceramic	10.66	8.26	6.19	0.18	0.010	0.52
3	black ceramic	10.48	5.00	5.14	0.32	0.050	0.51
$x \pm \sigma$		11.08 ± 0.73	6.90 ± 1.38	5.81 ± 0.48	0.26 ± 0.06	0.053 ± 0.037	0.54 ± 0.03

Data Group U.2

Steam Distribution Corridor (undefined location)

1	2	3	4	5	6	7	8	9	10	11	12	13
	α					γ						β
#	Pu-238 (Bq/g e+5)	Pu-239+240 (Bq/g e+5)	Am-241 (Bq/g e+5)	Cm-242 (Bq/g e+7)	Cm-244 (Bq/g e+5)	C44 (Bq/g e+9)	Cs-137 (Bq/g e+7)	Cs-134 (Bq/g e+7)	Eu-155 (Bq/g e+6)	Ru-106 (Bq/g e+7)	Sb-125 (Bq/g e+6)	Sr-90 (Bq/g e+7)
1	5.996	10.07	1.689	1.980	1.254	1.944	3.337	1.939	4.489	5.893	0.266	
2	6.802	12.41	2.864	2.094	1.207	2.098	2.321	1.203	11.18	0.697	0.246	
3	4.034	7.653	1.042	1.378	0.846	1.265	2.502	1.278	4.923	1.761	0.183	
$x \pm \sigma$	5.61 ± 1.16	10.04 ± 1.94	1.87 ± 0.75	1.82 ± 0.31	1.10 ± 0.18	1.77 ± 0.36	2.72 ± 0.44	1.47 ± 0.33	6.86 ± 3.06	2.78 ± 2.24	0.23 ± 0.04	

APPENDIX VI.A

Chornobyl Unit-4 Core Technological (Fueled) Channel Burnup Figures at 8604.626/01:22:00

Position Coordinate	Channel 1 Burnup (MW·d/kg U)	Channel 2 Burnup (MW·d/kg U)	Channel 3 Burnup (MW·d/kg U)	Channel 4 Burnup (MW·d/kg U)	Channel 5 Burnup (MW·d/kg U)	Channel 6 Burnup (MW·d/kg U)	Channel 7 Burnup (MW·d/kg U)
1							
2							
3							
4							
5							
6							
7							
8							8.7
9						8.9	10.0
10					8.8	9.9	
11				8.1	9.9		10.1
12				9.2		11.0	11.1
13			8.5	5.1	10.7	6.9	11.3
14			8.9	9.7	10.5	11.2	
15		8.1	8.9	10.0	10.7	11.1	11.0
16		8.7	9.8	10.4		0.4	11.4
17		8.6	10.3	10.7	11.3	6.4	7.6
18	7.9	9.4		10.4	11.0	0.0	
19	4.2	9.4	9.8	2.0	10.2	11.2	11.3
20	8.2	9.5	10.2	9.9		11.2	11.1
21	8.4	11.5	10.7	0.9	11.2	7.5	12.2
22	8.8	10.0		11.0	11.4	12.2	
23	4.7	10.2	10.7	3.0	11.7	12.0	11.7
24	9.2	10.6	11.3	11.5		12.1	11.9
25	9.3	10.0	11.8	0.2	12.0	6.2	12.2
26	9.1	10.6		11.0	11.5	11.9	
27	8.1	9.9	10.3	1.2	10.6	11.5	11.8
28	6.3	9.5	10.3	10.1		0.1	11.5
29	7.7	7.4	10.2	0.8	11.1	8.3	11.5
30	7.3	8.9		10.6	10.9	11.3	
31	9.2	8.3	9.5	2.8	11.0	11.2	10.8
32		7.9	9.2	10.1		11.4	11.4
33		6.9	8.9	3.8	10.8	5.6	11.7
34		6.9		9.0	10.3	0.0	
35			7.2	11.6	9.9	11.1	11.7
36			7.0	8.1		11.6	12.0
37				8.3	10.1	7.5	11.8
38				7.8	9.2	10.6	
39					8.4	5.1	9.7
40						8.5	9.1
41							8.7
42							
43							
44							
45							
46							
47							
48							

Position Coordinate	Channel 8 Burnup (MW·d/kg U)	Channel 9 Burnup (MW·d/kg U)	Channel 10 Burnup (MW·d/kg U)	Channel 11 Burnup (MW·d/kg U)	Channel 12 Burnup (MW·d/kg U)	Channel 13 Burnup (MW·d/kg U)	Channel 14 Burnup (MW·d/kg U)
1							
2							
3						8.4	9.0
4				7.6	8.8		10.1
5			7.3	8.9	9.7	10.5	6.8
6		8.0	9.2		10.3	10.8	11.3
7	4.7	9.3	10.3	10.6	2.3	11.2	11.4
8	9.5		11.6	11.6	11.5		11.9
9	10.5	11.5	10.8	12.0	0.7	12.0	6.4
10	10.8	11.3	11.9		11.2	11.4	11.6
11	3.1	11.4	11.6	11.1	1.7	10.5	11.3
12	11.2		0.6	11.4	10.5		0.1
13	0.7	11.5	4.8	11.9		11.3	7.5
14	11.0	11.5	12.0		11.7	11.5	12.2
15	2.4	11.5	12.0	11.8	2.5	11.9	11.8
16	11.4		12.6	12.1	11.6		0.1
17	1.1	12.6	8.9	12.4	0.5	11.9	6.3
18	11.6	12.1	12.4		11.3	11.5	11.9
19	4.4	11.5	11.9	11.4	1.3	10.6	11.5
20	11.3		11.7	11.6	10.6		11.3
21	0.6	11.7	5.4	12.1	0.3	11.2	8.9
22	11.8	12.0	12.3		11.8	11.3	12.0
23	1.8	11.9	12.3	12.0	2.2	11.2	11.6
24	11.8		12.7	12.1	11.3		11.5
25	1.3	12.6	11.3	12.2	0.7	11.5	7.0
26	12.1	12.0	12.2		11.1	11.3	11.6
27	3.7	11.6	11.7	11.2	2.3	10.5	11.4
28	11.4		11.5	11.4	10.5		11.4
29	0.6	11.4	5.2	11.5	0.8	11.5	3.2
30	10.9	11.4	11.7		11.6	11.8	12.5
31	1.4	11.5	4.5	11.9	12.5	12.2	12.2
32	11.4		0.1	12.3	12.3		12.3
33	1.1	12.6	11.5	12.4	0.8	12.3	6.4
34	12.1	12.4	12.3		11.3	11.5	11.7
35	3.8	12.1	11.9	11.1	1.6	10.4	11.3
36	11.9		11.9	11.4	10.4		11.1
37	0.5	11.7	5.0	11.8	0.9	11.2	7.7
38	10.9	11.4	11.8		11.7	11.5	12.0
39	11.6	10.9	11.6	11.7	3.3	12.0	12.0
40	9.8		0.3	12.0	11.9		0.5
41	9.5	10.7	10.2	11.8	0.8	12.0	6.3
42	8.7	9.5	10.2		10.6	11.2	11.5
43		8.1	4.9	8.9	1.2	10.2	10.9
44			7.6	8.3	8.8		10.7
45				7.5	8.3	9.4	7.3
46						8.8	8.9
47							
48							

Position Coordinate	Channel 15 Burnup (MW·d/kg U)	Channel 16 Burnup (MW·d/kg U)	Channel 17 Burnup (MW·d/kg U)	Channel 18 Burnup (MW·d/kg U)	Channel 19 Burnup (MW·d/kg U)	Channel 20 Burnup (MW·d/kg U)	Channel 21 Burnup (MW·d/kg U)
1				6.9	7.4	7.7	8.3
2	7.9	8.3	8.4	8.8		8.6	9.2
3	9.5	7.8	10.5	9.9	9.6	1.2	9.3
4	10.6	11.1		0.1	10.7	9.8	
5	11.2	0.2	11.5	5.5	11.0	0.8	11.2
6		11.0	11.3	11.3		11.2	11.5
7	11.1	11.6	11.4	11.7	11.4	5.2	3.1
8	11.6	11.5		0.4	11.9	11.9	
9	11.7	1.1	12.5	9.3	12.3	0.9	12.1
10		11.6	12.1	12.2		4.2	7.7
11	11.4	4.3	11.8	11.8	11.0	1.5	10.6
12	11.8	11.8		11.8	11.5	10.5	
13	12.3	0.8	10.9	5.6	12.0	10.6	11.3
14		11.7	11.7	12.1		11.9	11.6
15	11.6	1.9	11.0	11.8	11.9	3.4	11.8
16	11.6	11.0		11.7	11.8	11.7	
17	11.9	1.3	11.7	4.1	11.6	0.9	11.9
18		11.9	11.6	11.6		10.7	11.4
19	11.9	4.0	11.9	11.7	10.8	2.1	10.5
20	12.1	12.2		0.0	11.6	10.6	
21	12.3	0.6	12.2	6.1	12.1	1.0	11.4
22		11.7	12.0	12.2		11.8	11.6
23	11.4	1.6	11.7	12.0	11.7	3.0	11.6
24	11.5	11.5		12.5	11.4	11.4	
25	11.7	1.1	12.3	8.8	10.7	0.9	11.5
26		11.7	11.8	11.0		9.6	10.9
27	11.7	4.8	11.9	11.2	9.8	2.0	10.1
28	12.0	12.2		0.6	10.9	10.1	
29	12.5	0.7	12.1	5.9	11.1	10.7	11.1
30		11.7	11.5	0.0		11.1	6.4
31	11.7	1.6	10.8	11.3	11.1	3.3	12.0
32	11.8	11.0		0.2	11.7	12.0	
33	11.9	1.0	11.8	11.0	12.3	0.9	12.1
34		11.8	11.8	12.4		11.1	11.6
35	11.5	4.7	10.8	2.2	11.5	2.1	10.6
36	11.5	12.1		11.0	11.8	10.0	
37	11.9	0.5	12.2	5.9	11.7	1.0	11.4
38		11.4	11.8	11.8		11.4	11.6
39	11.5	1.9	11.6	11.8	11.5	3.2	12.0
40	12.1	11.6		12.5	11.9	12.0	
41	12.0	1.2	12.5	3.1	12.0	0.5	12.2
42		11.6	11.9	0.0		10.7	11.3
43	10.8	4.1	11.3	11.4	10.5	1.7	10.3
44	10.7	10.7		11.1	11.0	10.1	
45	10.5	10.5	10.6	4.6	10.9	0.8	10.6
46		9.9	10.0	10.1		10.1	10.3
47	7.9	5.4	8.8	9.0	9.0	11.9	9.5
48				7.7	7.7	7.6	8.4

Position Coordinate	Channel 22 Burnup (MW·d/kg U)	Channel 23 Burnup (MW·d/kg U)	Channel 24 Burnup (MW·d/kg U)	Channel 25 Burnup (MW·d/kg U)	Channel 26 Burnup (MW·d/kg U)	Channel 27 Burnup (MW·d/kg U)	Channel 28 Burnup (MW·d/kg U)
1	7.9	9.1	9.0	9.2	5.8	9.0	8.5
2	9.9		10.1	10.1	10.5		9.3
3	10.3	10.7	3.6	11.1	11.0	10.5	2.2
4	10.9	11.5	11.6		11.7	11.3	10.4
5	3.1	12.0	0.5	12.0	5.8	11.7	0.9
6	12.3		11.7	11.8	11.9		11.0
7	12.2	11.8	2.3	11.3	11.6	11.2	
8	12.2	12.1	11.4		0.5	11.6	11.3
9	6.4	11.9	10.6	12.1	11.1	12.4	11.9
10	11.7		11.6	11.7	12.4		11.6
11	11.4	11.4	3.9	11.3	11.7	7.2	1.0
12	11.3	11.6	11.2		11.2	11.4	10.6
13	8.1	12.0	0.6	11.2	1.5	11.7	0.3
14	12.1		11.4	11.5	11.8		11.8
15	12.0	11.6	2.1	11.5	11.9	11.9	3.4
16	12.0	11.9	11.6		0.2	12.1	11.8
17	7.3	12.0	1.1	12.5	9.2	12.1	0.6
18	11.8		11.8	12.1	12.1		10.9
19	11.6	11.7	4.7	11.8	11.6	10.8	2.1
20	11.4	12.0	11.8		0.1	11.1	10.3
21	9.4	12.3	0.7	11.7	11.4	11.6	1.0
22	12.2		11.7	11.6	11.7		11.5
23	11.9	11.7	5.2	10.9	11.6	11.6	3.0
24	0.3	11.6	11.1		11.6	11.9	11.8
25	7.3	11.9	1.3	11.8	11.1	12.4	0.9
26	11.6		11.9	11.9	12.5		11.5
27	11.2	11.7	4.7	12.0	12.1	11.7	2.2
28	11.1	11.9	11.9		0.1	11.5	10.5
29	9.0	12.1	0.8	11.9	6.0	11.4	0.9
30	12.0		11.5	11.7	11.5		11.3
31	12.0	11.5	1.8	11.6	11.7	11.5	3.4
32	12.3	11.9	11.6		0.2	12.1	12.2
33	6.6	11.8	1.3	12.5	9.8	12.5	0.8
34	11.6		11.5	12.0	12.2		11.3
35	11.3	11.3	4.0	11.2	11.6	8.5	2.1
36	11.3	11.5	11.2		11.3	11.4	10.5
37	8.0	12.1	0.7	11.3	5.7	11.7	0.9
38	12.3		11.5	11.5	11.8		11.5
39	12.2	11.7	1.5	11.1	11.7	11.7	3.2
40	12.3	11.1	11.2		12.0	12.1	12.0
41	6.6	11.9	1.3	12.1	11.2	12.6	0.8
42	11.6		11.7	11.8	12.5		11.5
43	11.1	10.3	3.5	11.7	11.8	11.3	2.4
44	11.0	11.3	11.4		11.4	11.2	10.3
45	7.3	11.7	0.1	11.3	4.6	11.0	0.8
46	11.2		11.6	11.1	10.8		10.1
47	10.2	10.6	11.6	10.5	10.0	9.4	11.5
48	9.0	9.3	9.3	9.2	8.7	8.3	7.6

Position Coordinate	Channel 29 Burnup (MW·d/kg U)	Channel 30 Burnup (MW·d/kg U)	Channel 31 Burnup (MW·d/kg U)	Channel 32 Burnup (MW·d/kg U)	Channel 33 Burnup (MW·d/kg U)	Channel 34 Burnup (MW·d/kg U)	Channel 35 Burnup (MW·d/kg U)
1	8.3	8.0	7.6				
2	9.3	9.4		8.2	7.8	7.4	
3	9.6	10.0	9.3	1.4	9.1	8.7	9.8
4		0.6	10.6	10.4		10.0	9.5
5	11.1	8.1	11.1	11.0	11.0	4.4	10.5
6	11.0	0.0		10.8	11.2	11.4	
7	11.2	11.6	11.2	2.5	11.4	11.8	11.9
8		12.0	5.5	11.6		0.4	12.3
9	12.1	6.9	12.0	1.3	11.8	11.2	12.1
10	11.6	11.7		11.8	12.0	12.0	
11	2.0	11.5	11.5	3.5	11.3	2.4	10.9
12		11.5	11.7	11.2		11.4	11.3
13	11.5	7.8	12.3	0.5	11.5	5.4	12.1
14	11.7	12.4		11.7	11.8	12.3	
15	11.9	12.1	11.8	1.9	11.2	12.0	12.3
16		12.1	11.8	11.1		12.1	12.5
17	11.9	7.4	11.5	1.0	11.9	11.3	12.6
18	11.2	11.3		11.4	11.8	12.5	
19	10.5	11.1	11.2	3.9	9.4	12.2	11.6
20		11.2	11.7	11.9		12.0	11.6
21	11.2	8.9	12.1	0.7	12.0	6.0	11.9
22	11.4	12.0		11.6	11.8	12.1	
23	11.6	11.7	11.4	1.6	11.6	11.9	11.7
24		0.3	11.5	11.4		12.3	11.8
25	12.0	7.0	11.4	1.1	12.4	10.8	12.1
26	11.4	11.2		11.4	12.1	12.3	
27	10.4	11.1	11.2	4.7	12.0	12.0	11.3
28		11.0	11.5	11.9		12.1	11.6
29	11.1	8.7	11.5	0.5	12.1	6.2	11.8
30	11.3	11.5		10.9	11.5	11.9	
31	12.0	11.8	10.9	1.4	11.0	11.7	11.8
32		12.3	11.6	11.0		12.0	12.3
33	12.3	7.1	11.8	1.2	11.9	11.1	12.4
34	11.6	11.6		11.6	11.8	12.5	
35	10.5	11.3	11.4	4.8	12.0	12.1	11.4
36		0.2	11.7	11.9		12.1	11.8
37	11.3	7.9	12.2	0.7	12.0	5.9	12.1
38	11.5	12.2		11.6	11.8	12.0	
39	11.9	12.0	11.4	2.1	11.4	11.8	11.7
40		0.6	11.4	11.1		12.3	11.8
41	12.1	6.1	11.0	0.9	12.0	8.5	12.0
42	11.3	0.1		10.7	11.4	11.9	
43	10.4	1.8	10.5	10.1	11.0	11.2	10.5
44		10.6	10.8	10.7		10.9	10.6
45	10.5	7.0	11.0	10.7	10.6	2.6	9.9
46	9.9	10.4		10.2	9.7	9.2	9.0
47	8.9	9.1	9.0	5.1	8.4	8.0	
48	7.8	7.6	7.1				

Position Coordinate	Channel 36 Burnup (MW·d/kg U)	Channel 37 Burnup (MW·d/kg U)	Channel 38 Burnup (MW·d/kg U)	Channel 39 Burnup (MW·d/kg U)	Channel 40 Burnup (MW·d/kg U)	Channel 41 Burnup (MW·d/kg U)	Channel 42 Burnup (MW·d/kg U)
1							
2							
3	7.6						
4	9.0		7.4				
5	10.1	9.7	8.3	8.0			
6	11.0	10.5	10.3		8.5		
7	2.8	11.4	11.1	10.7	7.7	8.5	
8	12.1		0.2	11.3	10.6		7.9
9	0.9	12.0	5.7	11.4	1.0	10.1	5.1
10	11.0	11.3	11.5		10.9	10.3	9.8
11	1.8	10.3	11.2	11.3	4.2	10.7	10.4
12	10.5		11.0	11.5	11.3		10.9
13	0.8	11.2	7.3	11.4	0.7	11.4	4.7
14	12.0	11.6	11.8		11.1	11.4	11.6
15	2.8	11.9	11.8	11.1	1.8	11.4	11.8
16	12.1		0.2	11.6	11.6		0.1
17	0.9	12.3	6.4	12.0	0.8	12.4	4.3
18	11.6	11.7	11.3		11.7	12.1	12.0
19	1.4	10.6	11.5	11.5	4.1	11.8	11.6
20	10.6		11.3	11.9	11.7		0.5
21	0.3	11.2	7.7	12.4	0.8	11.7	5.2
22	11.6	11.3	12.1		11.7	11.6	11.6
23	2.1	11.0	11.7	11.6	1.8	11.1	11.7
24	11.0		11.5	11.6	11.2		0.3
25	0.7	11.4	7.0	12.1	1.3	12.1	11.3
26	11.0	11.3	11.9		12.0	12.1	12.8
27	2.3	10.5	11.4	11.7	3.7	12.2	12.3
28	10.6		11.2	11.6	11.8		0.5
29	0.9	11.3	7.9	11.8	0.5	11.9	5.5
30	11.7	11.5	12.0		11.2	11.4	11.2
31	2.9	12.1	11.9	11.2	1.9	11.0	11.4
32	12.3		12.1	11.6	11.3		0.3
33	0.8	12.4	6.3	11.6	0.9	12.4	9.1
34	11.4	11.8	11.6		11.5	12.0	12.0
35	1.7	10.6	11.3	11.4	3.9	11.6	11.4
36	10.8		11.4	11.8	11.7		11.3
37	0.9	11.5	8.0	12.3	0.6	11.5	4.8
38	11.8	11.6	12.2		11.3	11.1	10.8
39	3.4	11.8	11.8	11.3	1.5	10.4	10.1
40	11.7		11.8	11.2	10.4		9.4
41	0.8	11.8	5.0	10.9	10.1	9.3	5.5
42	10.8	11.0	10.9		9.5	8.4	
43	1.2	10.1	10.1	9.5	4.8		
44	9.8		9.4	8.4			
45	9.2	9.1	8.1				
46	8.6						
47							
48							

Position Coordinate	Channel 43 Burnup (MW·d/kg U)	Channel 44 Burnup (MW·d/kg U)	Channel 45 Burnup (MW·d/kg U)	Channel 46 Burnup (MW·d/kg U)	Channel 47 Burnup (MW·d/kg U)	Channel 48 Burnup (MW·d/kg U)	
1							
2							
3							
4							
5							
6							
7							
8							
9	3.4						
10		7.8					
11	10.0	4.9	7.5				
12	10.5	9.7					
13	11.0	0.6	9.3	8.0			
14		10.4	9.4	8.5			
15	11.3	2.2	9.8	8.9	7.4		
16	11.9	10.0		9.4	7.6		
17	11.8	1.5	10.8	5.3	5.5		
18		10.8	10.6	10.3		7.8	
19	11.0	2.2	10.1	10.3	9.8	8.2	
20	11.0	10.5		10.3	12.0	8.6	
21	11.4	0.8	10.8	6.4	10.2	8.7	
22		11.2	10.9	11.0		8.7	
23	11.6	5.0	11.2	10.8	10.1	11.4	
24	10.0	11.7		10.3	9.7	8.4	
25	12.1	0.8	11.5	4.8	9.5	8.2	
26		11.4	10.9	10.3		8.5	
27	11.6	1.8	9.8	10.0	9.5	10.8	
28	11.4	10.2		9.9	9.4	8.2	
29	11.0	1.0	10.4	6.9	9.7	8.3	
30		10.6	10.5	10.6		7.3	
31	10.9	3.1	10.7	10.3	9.5	8.0	
32	11.4	11.0		10.0	9.0		
33	11.8	0.2	10.4	7.1	8.1		
34		10.1	9.6	8.6	7.6		
35	10.5	1.2	8.8	8.1			
36	10.7	9.4		7.6			
37	10.5	9.5	8.5				
38		9.3	7.8				
39	9.6	8.4					
40	8.5						
41							
42							
43							
44							
45							
46							
47							
48							

SOURCE: Панитков, Ю. С., И. А. Банель, А. М. Бернадская, В. П. Бескоровайный, Н. В. Горбачева, Н. М. Груша, В. В. Котович, Л. Н. Козловская, В. Г. Молодых, Н. К. Мышкина, Н. В. Нитей, В. В. Ничипор, Т. А. Павлина, В. В. Скурат, Л. А. Станкевич, Э. М. Тащилова, *Отчёт о научно-исследовательской работе: Восстановление динамики разрушения 4-го блока ЧАЭС на основе физического и математического моделирования: Разработка физической модели чернобыльской катастрофы,* Минск, Беларусь: Академия Наук Беларуси, (1991): 28.

This Page Has Been Left Intentionally Blank.

APPENDIX VI.B

Initial Core Inventory Data for Sixty-Five Selected Radioisotopes for Chornobyl Unit-4 at the Time of the Accident

This listing of sixty-five radioisotopes (presented in order of ascending atomic mass units) represents those with significantly long half-lives taken from a group of 112 for which activity and specific heat generation were calculated as a function of time using the codes CACHE and WIMS (see Section VI.2.2.2.) The additional data and information have been taken from a number sources[1,2,3,4,5] for convenience and to add completeness to the table. A key to the various columns is as follows:

Isotope — The radionuclide in question. Metastable nuclides, of higher energy than the ground state, are characterized by the letter "m" following the mass number.

Mass — The radioisotopes mass in *atomic mass units* (amu), relative to C-12, whose mass is defined as 12.0000.

Half-life — The half-life of a particular radioisotope is designated by one of the following abbreviations for a unit of time: y, year; d, day; hr, hour; m, minute; s, second. To conserve space, certain very large or very small numbers (as throughout the rest of the table) are written in exponential notation used in computer calculations and printouts. For example, the half-life of Np-237, 2.14×10^6 years, is written as 1.26e06 y.

---

[1] Edgardo Browne and Richard B. Firestone, Virginia S. Shirley, ed. *Table of Radioactive Isotopes.* (New York, NY: John Wiley & Sons, 1986).

[2] Manson Benedict, Thomas H. Pigford, and Hans Wolfgang Levi, *Nuclear Chemical Engineering,* 2nd. Edition, (New York, NY: McGraw-Hill Book Company, 1981), pgs. 937–978.

[3] Benjamin M. Ma, *Nuclear Reactor Materials and Applications,* (New York, NY: Van-Nostrand Reinhold, 1983), pgs. 594–596.

[4] *CRC Handbook of Chemistry and Physics, 1991–1992,* "The Elements and Inorganic Compounds."

[5] GE Nuclear Energy Operations, *Nuclides and Isotopes: The Chart of the Nuclides* (14th Edition), General Electric Company: San Jose, California, (1989).

Decay Product [mode]

These are the product(s) of decay of the given radioisotope and the method of that decay. Note in some cases there was a very small percentage of spontaneous fission or electron captures, or positron emissions and these were not included. The following abbreviations are used for the mode of decay: β^- — beta decay, γ — gamma decay, IT — internal transition, α — alpha decay.

Total Energy per Decay

The fifth column gives the total effective energy in MeV emitted per decay. This is comprised of all forms of radiation that eventually degrade into heat – which includes alpha particles, electrons and positrons, all forms of electromagnetic radiation that arise from various nuclear transitions (IT, x-rays from orbital electrons capture, bremsstrahlung, etc.), neutrons, recoil nuclei, and fission fragments. Only neutrinos are excluded.

VALUES CALCULATED FOR TIME t = 0

Specific Heat Generation

Heat generation per unit mass of fuel (kWt/t U). At any time greater than zero this is the decay heat generated by the isotope in question.

Total Activity

The total activity of the isotope in question (Bq).

Specific Activity

Activity of the isotope in question per unit mass of fuel (Bq/gm U).

Mass

The total mass of the isotope in question (kg).

Predominant α

Predominant alpha decay energies (MeV) and occurance proportion.

β^-_{max}, $\langle\beta^-\rangle_{avg}$

Beta decay maximum and average energy (MeV).

Predominant γ

Predominant gamma decay energies (MeV) and occurance proportion.

Isotope	Mass (amu)	Half-life	Decay Product [mode]	Total Energy per Decay (MeV)	Specific Heat Generation (kWt/t U) [t = 0]	Activity (Bq) [t = 0]	Specific Activity (Bq/gm U) [t = 0]	Mass (kg) [t = 0]	Predominant α (MeV) [%/100]	β⁻ max; β⁻avg (MeV)	Predominant γ (MeV) [%/100]
Rb-86	85.911193	18.66 d	Sr-86 (s) [β⁻]	0.797	1.0e+00	1.6e+18	8.6e+09	5.5e-01		1.7743; 0.6670	1.0767 [0.088]
Kr-88	87.914270	2.84 h	Rb-88 [β⁻]	2.097	2.3e+00	1.2e+18	6.3e+09	2.5e-03		2.9130; 0.3590	0.1963 [0.260] 0.8349 [0.130]
Rb-88	87.911270	17.8 m	Sr-88 (s) [β⁻]	2.694	2.3e+00	1.0e+18	5.3e+09	2.3e-04		5.3160; 2.0680	0.8981 [0.141] 1.8361 [0.214]
Sr-89	88.907442	50.55 d	Y-89 (s) [β⁻]	0.607	1.9e+00	3.9e+18	2.1e+10	3.7e+00		1.4920; 0.5830	0.9092 [0.001]
Sr-90	89.907747	28.5 y	Y-90 [β⁻]	0.221	3.8e-02	2.3e+17	1.2e+09	4.5e+01		0.5462; 0.1960	
Y-90	89.907163	63.93 h	Zr-90 (s) [β⁻]	0.993	1.8e-01	2.3e+17	1.2e+09	1.1e-02		2.2815; 0.9340	2.1862 [>2e-06]
Y-91	90.907295	58.51 d	Zr-91 (s) [β⁻]	0.642	2.5e+00	4.9e+18	2.6e+10	5.4e+00		1.5456; 0.6030	1.2050 [0.003]
Sr-92	91.910980	2.71 h	Y-92 [β⁻]	1.500	2.6e+00	2.0e+18	1.1e+10	4.3e-03		1.8880; 0.1770	0.2416 [0.030] 1.3841 [0.900]
Y-92	91.908926	3.54 h	Zr-92 (s) [β⁻]	1.635	3.4e+00	2.4e+18	1.2e+10	6.6e-03		3.6120; 1.4350	0.9345 [0.139] 1.4054 [0.048]
Sr-93	92.914710	7.4 m	Y-93 [β⁻]	2.587	3.1e+00	1.2e+18	6.1e+09	1.1e-04		4.1140; 0.7570	0.1686 [0.180] 0.5902 [0.670] 0.7103 [0.213] 0.8759 [0.239]
Y-93	92.909552	10.25 h	Zr-93 (s) [β⁻]	1.249	3.4e+00	3.1e+18	1.7e+10	2.5e-02		2.8840; 1.1710	0.2669 [0.068] 1.9178 [0.014]
Zr-95	94.908035	64.02 d	Nb-95 [β⁻]	0.883	4.2e+00	5.8e+18	3.1e+10	7.3e+00		1.1243; 0.1170	0.7242 [0.441] 0.7567 [0.545]
Nb-95	94.906832	34.97 d	Mo-95 (s) [β⁻]	0.812	3.9e+00	5.7e+18	3.0e+10	3.9e+00		0.9256; 0.0435	0.7658 [0.998]
Nb-96	95.908056	23.35 h	Mo-96 (s) [β⁻]	2.730	9.7e+00	4.2e+18	2.2e+10	8.1e-02		3.1870; 0.2490	0.5687 [0.568] 0.7782 [0.969] 1.0913 [0.485]
Nb-97	96.908096	72.12 m	Mo-97 (s) [β⁻]	1.159	1.6e+00	1.7e+18	8.9e+09	1.7e-03		1.9338; 0.4670	0.6582 [0.983]
Mo-99	98.907720	65.76 h	Tc-99 [β⁻]	0.687	2.5e+00	5.3e+18	2.8e+10	3.0e-01		1.3570; 0.3900	0.1405 [0.907] 0.7395 [0.121]
Tc-99m		6.01 h	Tc-99 [γ]	0.143	4.9e+00	4.6e+18	2.4e+10	2.3e-02		0.4363; ??????	0.1405 [0.872]
Mo-101	100.910353	14.6 m	Tc-101 [β⁻]	2.080	2.1e+00	1.2e+18	6.3e+09	2.6e-04		2.8120; 0.4490	0.1919 [0.188] 0.5060 [0.118] 0.5909 [0.164] 1.0125 [0.128]

Isotope	Mass (amu)	Half-life	Decay Product [mode]	Total Energy per Decay (MeV)	Specific Heat Generation (kWt/t U) [t = 0]	Activity (Bq) [t = 0]	Specific Activity (Bq/gm U) [t = 0]	Mass (kg) [t = 0]	Predominant α (MeV) [%/100]	β⁻ max; β⁻avg (MeV)	Predominant γ (MeV) [%/100]
Tc-101	100.907326	14.2 m	Ru-101 (s) [β⁻]	0.824	8.3e-01	1.2e+18	6.3e+09	2.5e-04		1.6250; 0.4720	0.3113 [0.880] 0.5450 [0.060]
Ru-103	102.906306	39.25 d	Rh-103 (s) [β⁻]	0.556	1.7e+00	3.7e+18	2.0e+10	3.1e+00		0.7660; 0.0690	0.4971 [0.887]
Rh-103m		56.12 m	Rh-103 (s) [IT]	0.040	5.4e-03	3.7e+18	2.0e+10	3.1e-03			0.0027 [0.021] 0.0201 [0.021] 0.0202 [0.041]
Rh-105	104.905671	35.26 h	Pd-105 (s) [β⁻]	0.223	3.0e-01	1.6e+18	8.2e+09	4.9e-02		0.5660; 0.1520	0.3063 [0.051] 0.3192 [0.190]
Ru-106	105.907322	372.56 d	Rh-106 [β⁻]	0.010	7.2e-03	8.6e+17	4.5e+09	6.9e+00		0.0394; 0.0100	
Rh-106	105.907279	29.8 s	Pd-106 (s) [β⁻]	1.773	9.7e-01	7.1e+17	3.7e+09	5.4e-06		3.5400; 1.4110	0.5119 [0.207] 0.6219 [0.098]
Te-129m		33.5 d	Te-129 [0.64 IT] I-129 [0.36 β⁻]	0.335	2.7e-01	1.0e+18	5.4e+09	9.3e-01		1.6033; 0.2060	0.0272 [0.082] 0.0275 [0.153] 0.0310 [0.041]
I-131	130.906127	8.04 d	Xe-131 (s) [β⁻]	0.589	1.4e+00	2.9e+18	1.5e+10	6.4e-01		0.9708; 0.1820	0.2843 [0.061] 0.3645 [0.812]
Te-132	131.908523	78.03 h	I-132 [β⁻]	0.383	1.1e+00	4.0e+18	2.1e+10	3.6e-01		0.4930; 0.0590	0.0283 [0.204] 0.0286 [0.380] 0.2283 [0.882]
I-132	131.907981	2.284 h	Xe-132 (s) [β⁻]	2.907	9.0e+00	3.9e+18	2.0e+10	1.0e-02		3.5800; 0.4860	0.5227 [0.161] 0.6677 [0.987] 0.9546 [0.181]
I-133	132.907750	20.8 h	Xe-133 [β⁻]	1.177	4.0e+00	4.6e+18	2.4e+10	1.1e-01		1.7600; 0.4060	0.5299 [0.860] 0.8753 [0.045] 1.2982 [0.023]
Xe-133	132.905815	5.245 d	Cs-133 (s) [β⁻]	0.264	9.5e-01	6.2e+18	3.3e+10	8.9e-01		0.4270; 0.1000	0.0306 [0.141] 0.0310 [0.260] 0.0810 [0.370]
Te-134	133.911520	41.8 m	I-134 [β⁻]	2.800	1.6e+00	1.9e+18	9.8e+09	1.5e-03		1.5600; 0.2050	0.0795 [0.209] 0.2104 [0.223] 0.7672 [0.290]
I-134	133.909850	52.6 m	Xe-134 (s) [β⁻]	3.141	5.7e+00	2.1e+18	1.1e+10	2.1e-03		4.1500; 0.6080	0.8471 [0.954] 0.8841 [0.649] 1.0726 [0.150]

Isotope	Mass (amu)	Half-life	Decay Product [mode]	Total Energy per Decay (MeV)	Specific Heat Generation (kWt/t U) [t = 0]	Activity (Bq) [t = 0]	Specific Activity (Bq/gm U) [t = 0]	Mass (kg) [t = 0]	Predominant α (MeV) [%/100]	β^- max; β^-avg (MeV)	Predominant γ (MeV) [%/100]
Cs-134	133.906823	2.062 y	Ba-134 (s) [β^-]	1.787	2.5e-01	1.7e+17	8.9e+08	3.6e+00		2.0585; 0.1570	0.5693 [0.154] 0.6047 [0.976] 0.7959 [0.854]
Xe-135	134.907020	9.104 h	Cs-135 [β^-]	0.567	1.7e+00	3.5e+18	1.8e+10	3.7e-02		1.1600; 0.3030	0.2498 [0.900]
Cs-136	135.907340	13.16 d	Ba-136 (s) [β^-]	2.317	1.2e+01	6.0e+18	3.2e+10	2.2e+00		2.5485; 0.1000	0.3406 [0.486] 0.8186 [0.998] 1.0481 [0.797]
Cs-137	136.906770	30.0 y	Ba-137m [β^-] Ba-137 (s) [β^-]	0.662 0.276	3.7e-02	2.6e+17	1.4e+09	8.0e+01		1.1751; 0.1880	0.6617 [0.852]
Xe-138	137.913810	14.08 m	Cs-138 [β^-]	3.227	2.0e+00	1.3e+18	6.9e+09	3.7e-04		2.7700; 0.6280	0.2584 [0.315] 0.4346 [0.230] 1.7684 [0.167] 2.0159 [0.123]
Cs-138	137.910800	32.2 m	Ba-138 (s) [β^-]	3.227	4.4e+00	1.5e+18	7.7e+09	9.3e-04		5.3770; 1.2370	0.4628 [0.307] 1.0098 [0.298] 1.4358 [0.763] 2.2178 [0.152]
Cs-139	138.912900	9.27 m	Ba-139 [β^-]	2.077	2.0e+00	1.2e+18	6.5e+09	2.3e-04		4.2130; 1.6500	0.6724 [0.017] 1.2834 [0.077] 2.3501 [0.006]
Ba-139	138.908600	84.6 m	La-139 (s) [β^-]	0.935	1.5e+00	1.9e+18	1.0e+10	3.2e-03		2.3100; 0.8910	0.1659 [0.220]
Ba-140	139.910565	12.746 d	La-140 [β^-]	0.563	2.5e+00	5.9e+18	3.1e+10	2.2e+00		1.0340; 0.2760	0.0300 [0.136] 0.1627 [0.062] 0.5373 [0.024]
La-140	139.909438	40.16 h	Ce-140 (s) [β^-]	2.976	1.4e+01	6.0e+18	3.1e+10	2.9e-01		3.7610; 0.5250	0.3288 [0.207] 0.4870 [0.459] 0.8158 [0.236] 1.5965 [0.954]
La-141	140.910828	3.93 h	Ce-141 [β^-]	1.010	2.0e+00	2.3e+18	1.2e+10	1.1e-02		2.4460; 0.9830	1.3545 [1.000]
Ce-141	140.908219	32.5 d	Pr-141 (s) [β^-]	0.332	1.1e+00	5.5e+18	2.9e+10	5.2e+00		0.5813; 0.1450	0.0356 [0.091] 0.1454 [0.484]
La-142	141.913980	92.52 m	Ce-142 (s) [β^-]	3.279	5.5e+00	1.8e+18	9.6e+09	3.5e-03		4.5170; 0.8420	0.6413 [0.470] 2.3978 [0.148] 2.5427 [0.101]

Isotope	Mass (amu)	Half-life	Decay Product [mode]	Total Energy per Decay (MeV)	Specific Heat Generation (kWt/t U) [t = 0]	Activity (Bq) [t = 0]	Specific Activity (Bq/gm U) [t = 0]	Mass (kg) [t = 0]	Predominant α (MeV) [%/100]	β⁻ max; β⁻avg (MeV)	Predominant γ (MeV) [%/100]
Ce-143	142.912327	32.91 h	Pr-143 [β⁻]	0.840	2.6e+00	4.3e+18	2.3e+10	1.8e-01		1.4616; 0.4090	0.0356 [0.182] 0.0360 [0.330] 0.0574 [0.118] 0.2933 [0.420]
Pr-143	142.910990	13.58 d	Nd-143 (s) [β⁻]	0.366	1.5e+00	5.5e+18	2.9e+10	2.2e+00		0.9345; 0.3150	0.7420 [<2e-06]
Ce-144	143.913591	284.9 d	Pr-144 [β⁻]	0.138	3.7e-01	3.9e+18	2.0e+10	3.2e+01		0.3186; 0.0820	0.0356 [0.240] 0.0360 [0.044] 0.1335 [0.111]
Pr-144	143.913248	17.28 m	Nd-144 [β⁻]	1.307	4.0e+00	3.8e+18	2.0e+10	1.4e-03		2.9970; 1.2090	0.6965 [0.134] 0.8142 [0.007]
Nd-147	146.916074	10.98 d	Pm-147 [β⁻]	0.548	7.2e-01	2.1e+18	1.1e+10	7.0e-01		0.8953; 0.2330	0.0382 [0.133] 0.0387 [0.241] 0.0911 [0.280] 0.5310 [0.131]
Pm-148m		41.29 d	Pm-148 [0.046 IT] Sm-148 [0.954 β⁻]	2.091	2.9e+00	1.6e+18	8.4e+09	2.0e+00		2.6100; 0.1490	0.4141 [0.186] 0.5503 [0.944] 0.6300 [0.886] 0.7257 [0.327] 1.0138 [0.202]
Eu-154	153.923053	8.8 y	Gd-154 (s) [β⁻]	1.384	1.8e-02	1.4e+16	7.2e+07	1.4e+00		1.9689; 0.2270	0.1231 [0.405] 0.7234 [0.197] 1.2745 [0.355]
Eu-155	154.922930	4.96 y	Gd-155 (s) [β⁻]	0.142	1.2e-03	1.1e+16	6.0e+07	6.7e-01		0.2527; 0.0471	0.0430 [0.124] 0.0861 [0.340] 0.1053 [0.206]
Pu-236	236.046070	2.851 y	U-232 [α]	5.868	5.5e-07	1.1e+11	6.0e+02	5.8e-06	5.721 [0.317] 5.767 [0.681]		
Np-237	237.048056	2.14e06 y	Pa-233 [α]	4.956	1.1e-06	2.6e+11	1.4e+3	1.0e+01	4.639 [0.062] 4.664 [0.033] 4.766 [0.080] 4.771 [0.250] 4.788 [0.470]		0.0133 [0.192] 0.0166 [0.250] 0.0197 [0.058] 0.0294 [0.129] 0.0865 [0.126]
Np-239	239.052924	2.355 d	Pu-239 [β⁻]	0.690	2.0e+01	5.8e+19	3.1e+11	6.7e+00		0.7220; 0.2730	0.0181 [0.250] 0.1037 [0.239] 0.1061 [0.227] 0.2776 [0.142]

Isotope	Mass (amu)	Half-life	Decay Product [mode]	Total Energy per Decay (MeV)	Specific Heat Generation (kWt/t U) [t = 0]	Activity (Bq) [t = 0]	Specific Activity (Bq/gm U) [t = 0]	Mass (kg) [t = 0]	Predominant α (MeV) [%/100]	β^- max; β^-avg (MeV)	Predominant γ (MeV) [%/100]
Pu-239	239.052146	24,110 y	U-235 [α]	5.243	4.1e-03	9.5e+14	5.0e+06	4.1e+02	5.104 [0.106] 5.142 [0.151] 5.155 [0.732]		<6.6e-05> [<1e-05]
Pu-241	241.056737	14.4 y	U-237 [2.4e-05 α] Am-241 [0.999976 β^-]	0.007	8.1e-04	1.8e+17	9.6e+08	4.9e+01	4.853 [<1e-05] 4.896 [<1e-04]	0.0208; 0.0052	<1.35e-06> [<1e-05]
Am-241	241.056714	432.7 y	Np-237 [α]	5.640	7.7e-04	1.6e+14	8.7e+05	1.3e+00	5.443 [0.128] 5.485 [0.852]		0.0139 [0.130] 0.0176 [0.202] 0.0595 [0.357]
Pu-242	242.058725	376,300 y	U-238 [α]	4.980	1.2e-05	2.9e+12	1.5e+04	2.0e+01	4.856 [0.224] 4.900 [0.780]		0.0136 [0.033] 0.0171 [0.041]
Am-243	243.061367	7,380 y	Np-239 [α]	5.439	4.3e-05	9.7e+12	5.1e+04	1.3e+00	5.234 [0.110] 5.276 [0.880]		0.0435 [0.051] 0.0747 [0.600]
Cm-242	242.058788	162.94 d	Pu-238 [α]	6.217	2.2e-01	4.3e+16	2.3e+08	3.5e-01	6.069 [0.250] 6.112 [0.740]		0.0143 [0.040] 0.0181 [0.048] 0.0216 [0.011]
Pu-238	238.049511	87.74 y	U-234 [α]	5.592	6.0e-03	1.3e+15	6.8e+06	2.0e+00	5.456 [0.283] 5.499 [0.716]		0.0136 [0.042] 0.0171 [0.052]
Cm-244	244.062821	18.11 y	Pu-240 [α]	5.902	2.1e-03	4.3e+14	2.2e+06	1.4e-01	5.762 [0.236] 5.805 [0.764]		0.0143 [0.040] 0.0181 [0.040]
Pu-240	240.053882	6,563 y	U-236 [α]	5.255	6.4e-03	1.5e+15	7.8e+06	1.8e+02	5.123 [0.264] 5.168 [0.735]		<2.9e-05> [<1e-05]

This Page Has Been Left Intentionally Blank.

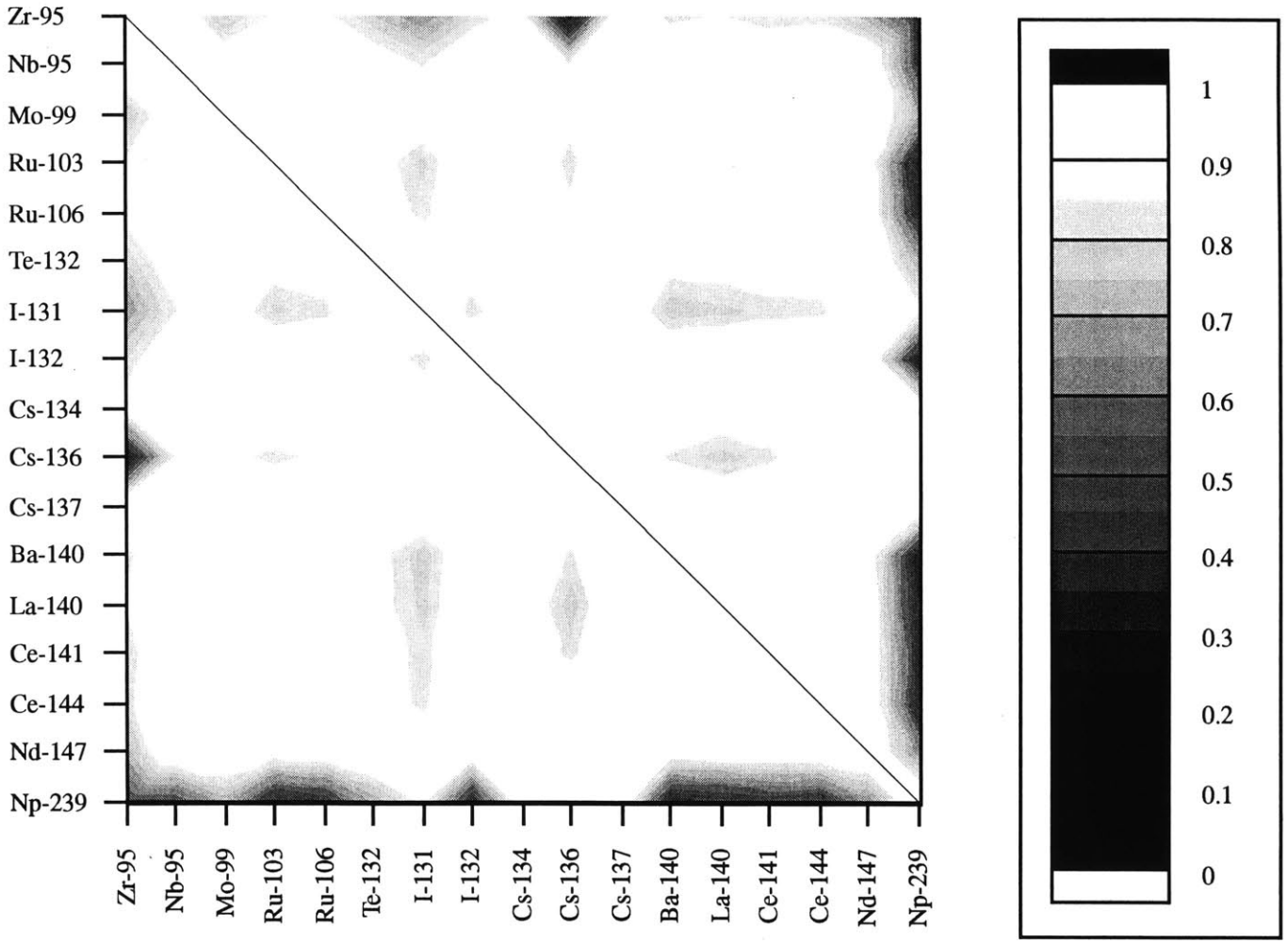
APPENDIX VI.C

Results of Correlation Analysis Applied to Fractional Mass Release Data
Derived from the Combined PROBA & Legasov Data Base (Table VI.12)

	Zr-95	Nb-95	Mo-99	Ru-103	Ru-106	Te-132	I-131	I-132	Cs-134	Cs-136	Cs-137	Ba-140	La-140	Ce-141	Ce-144	Nd-147	Np-239
Zr-95	1.000	1.000	0.716	0.868	0.883	0.752	0.651	0.791	0.900	0.336	0.976	0.824	0.858	0.807	0.818	0.725	0.531
Nb-95	1.000	1.000	0.964	0.990	0.986	0.943	0.840	0.975	0.976	0.855	0.978	0.989	0.995	0.999	0.999	0.979	0.532
Mo-99	0.716	0.964	1.000	0.914	0.926	0.990	0.953	0.936	0.944	0.895	0.996	0.914	0.919	0.947	0.950	0.998	0.715
Ru-103	0.868	0.990	0.914	1.000	0.993	0.916	0.784	0.985	0.981	0.820	0.992	0.994	0.997	0.986	0.992	0.931	0.432
Ru-106	0.883	0.986	0.926	0.993	1.000	0.942	0.827	0.983	0.995	0.882	0.998	0.975	0.983	0.971	0.986	0.940	0.495
Te-132	0.752	0.943	0.990	0.916	0.942	1.000	0.963	0.941	0.973	0.967	1.000	0.901	0.910	0.930	0.949	0.990	0.709
I-131	0.651	0.840	0.953	0.784	0.827	0.963	1.000	0.815	0.975	0.936	0.999	0.764	0.782	0.817	0.830	0.935	0.871
I-132	0.791	0.975	0.936	0.985	0.983	0.941	0.815	1.000	0.965	0.911	1.000	0.981	0.977	0.978	1.000	0.959	0.437
Cs-134	0.900	0.976	0.944	0.981	0.995	0.973	0.975	0.965	1.000	0.933	1.000	0.955	0.964	0.944	0.964	0.940	0.953
Cs-136	0.336	0.855	0.895	0.820	0.882	0.967	0.936	0.911	0.933	1.000	1.000	0.842	0.766	0.827	0.991	0.882	0.883
Cs-137	0.976	0.978	0.996	0.992	0.998	1.000	0.999	1.000	1.000	1.000	1.000	0.982	0.979	0.977	1.000	1.000	0.960
Ba-140	0.824	0.989	0.914	0.994	0.975	0.901	0.764	0.981	0.955	0.842	0.982	1.000	0.997	0.994	0.994	0.934	0.405
La-140	0.858	0.995	0.919	0.997	0.983	0.910	0.782	0.977	0.964	0.766	0.979	0.997	1.000	0.994	0.996	0.939	0.446
Ce-141	0.807	0.999	0.947	0.986	0.971	0.930	0.817	0.978	0.944	0.827	0.977	0.994	0.994	1.000	0.999	0.966	0.491
Ce-144	0.818	0.999	0.950	0.992	0.986	0.949	0.830	1.000	0.964	0.991	1.000	0.994	0.996	0.999	1.000	0.966	0.462
Nd-147	0.725	0.979	0.998	0.931	0.940	0.990	0.935	0.959	0.940	0.882	1.000	0.934	0.939	0.966	0.966	1.000	0.656
Np-239	0.531	0.532	0.715	0.432	0.495	0.709	0.871	0.437	0.953	0.883	0.960	0.405	0.446	0.491	0.462	0.656	1.000

Figure AVI.1

Contour Mapping of Correlation Analysis Results



SELECTED BIBLIOGRAPHY

I. Western Popular Press

Bandera, V. N. "Ukraine: Victim of Soviet Energy Program." *Soviet Ukrainian Affairs.* (Spring 1987): 9–10.

Bojcun, Marko and Viktor Haynes. *The Chernobyl Disaster.* London: The Hogarth Press, 1988.

Diuk, Nadia and Adrian Karatnysky. *The Hidden Nations: The People Challenge the Soviet Union.* New York: William Morrow and Company, Inc., 1990.

Feshbach, Murray and Alfred Friendly, Jr. *Ecocide in the USSR: Health and Nature Under Siege.* New York: Basic Books, Inc., 1992.

Freeland, Chrystia, "Waiting for the Next Chernobyl," *The Financial Times of London,* No. 32,043, Week 16, (April 21, 1993): 20.

Hawkes, Nigel, Geoffrey Lean, David Leigh, Robin McKie, Peter Pringle, and Andrew Wilson. *Chernobyl: The End of the Nuclear Dream.* New York: Vintage Books, 1986.

Jones, Ellen and Benjamin L. Woodbury, II. "Chernobyl' and *Glasnost*". *Problems of Communism,* Vol. XXXV, No. 6 (Nov – Dec 1986).

Kapitza, Sergei P. "Lessons of Chernobyl." *Foreign Affairs.* Vol. 72, No. 3 (Summer 1993): 7–11.

Karatnysky, Adrian. "The Ukrainian Factor." *Foreign Affairs,* (1992): 90 – 107.

Kramer, John M. "Chernobyl' and Eastern Europe." *Problems of Communism,* Vol XXXV, No. 6 (Nov – Dec 1986).

Kuts, Oksana. "Seven Years Later: Chornobyl Blows Out the Candle of Their Lives." *Buzzworm: The Environmental Journal.* Vol. V, No. 3 (May/June 1993): 26–28.

Marples, David R. "Chernobyl' and Ukraine." *Problems of Communism,* Vol XXXV, No. 6 (Nov – Dec 1986).

Marples, David R. *Chernobyl and Nuclear Power in the USSR.* New York: St. Martin Press, 1986.

Marples, David R. "The Chernobyl Disaster." *Current History,* Vol. 86, No. 522 (October 1987 – The Soviet Union, 1987): 325–328, 341–343

Marples, David R. *The Social Impact of the Chernobyl Disaster.* New York: St. Martin Press, 1989.

Marples, David R. "Chernobyl: Its Effects in the USSR." *Forum for Applied Research and Public Policy.* Summer 1990.

Marples, David R. *Ukraine Under Perestroika: Ecology, Economics, and the Worker's Revolt.* New York: St. Martin Press, 1991.

Marples, David R. "The Medical Consequences of Chornobyl: The Case of Belarus." *The Ukrainian Weekly*. Vol. LXI, No. 19 & 20 (May 9 & 16, 1993): 9 & 9.

Marples, David R. "Chernobyl's Lengthening Shadow." *The Bulletin of the Atomic Scientist.* Vol . 49, No. 7 (September 1993): 38–43.

Medvedev, Grigori. *The Truth About Chernobyl.* New York: Basic Books, Inc., 1991.

Medvedev, Zhores. *The Legacy of Chernobyl.* New York: W.W. Norton and Company, 1990.

Nahaylo, Bohdan. "Mounting Opposition in Ukraine to Nuclear Energy Programme." *Soviet Ukrainian Affairs.* (Spring 1988): 9–15.

Ramberg, Bennett. "Learning from Chernobyl." *Foreign Affairs*, Vol. 65, No. 2, (Winter 1986–87): 304–328.

Read, Piers Paul. *Ablaze: The Story of the Heroes and Victims of Chernobyl.* New York: Random House. 1993.

Shanahan, John. "Cuba's Potential Chernobyls." *The Wall Street Journal.* (August 5, 1992): A14.

Simes, Dimitri K. "America and the Post-Soviet Republics." *Foreign Affairs*, (1992): 73 – 89.

Strong, Maurice. "40 Chernobyls Waiting to Happen." *The New York Times.* Vol. CXLI, No. 48913, (Sunday, March 22, 1992): E15.

Sweet, William. "Chernobyl: What Really Happened." *Technology Review*, (July 1989): 42–52.

Thornton, Judith. "Chernobyl and Soviet Energy." *Problems of Communism,* Vol XXXV, No. 6 (Nov – Dec 1986).

Wilson, Richard. "How Dangerous Was [the] Chernobyl Accident?" *The Boston Globe.* (Saturday, May 24, 1986): 11.

"Chernobyls-in-Waiting." *The Economist.* Vol. 324, No. 7772, (August 15, 1992): 18.

"Too Little...." *The Economist.* Vol. 324, No. 7772, (August 15, 1992): 56.

II. Western Scientific & Technical

Accident Analysis Group of the Department of Nuclear Energy at BNL. *Independent Verification of Radionuclide Release Calculations for Selected Accident Scenarios.* (NUREG/CR-4629). Washington, DC: U.S. Government Printing Office. (July 1986).

Benedict, Manson, Thomas H. Pigford, and Hans Wolfgang Levi. *Nuclear Chemical Engineering*, 2nd. Edition. New York, NY: McGraw-Hill Book Company, 1981.

Benjamin M. Ma. *Nuclear Reactor Materials and Applications*. New York, NY: Van-Nostrand Reinhold, 1983.

Browne, Edgardo and Richard B. Firestone. *Table of Radioactive Isotopes.* Edited by Virginia S. Shirley. New York, NY: John Wiley & Sons, 1986.

Adamantiades, Achilles G., Chaim Braun, John E. Kenton, and Frank J. Rahn. *A Guide to Nuclear Power Technology: A Resource for Decision Making*. New York: John Wiley & Sons, 1984.

Bonell, P. G. "Analysis of the RBMK Against UK Safety Principles." *Nuclear Safety After Three Mile Island and Chernobyl*. Ed. G. M. Ballard. Elsevier Applied Science: London. (1988): 90–134.

Campbell, Robert W. *Soviet Energy Technologies*. Indiana University Press, 1980.

Chao, Jason, V. K. Chexal, William H. Layman, Gary Vine, Peter J. Jensen, and Adi R. Dastur. "An Analysis of the Chernobyl Accident Using RETRAN-02/MOD3." *Nuclear Technology*, Vol. 83 (December 1988): 928–301.

Clough, P. N. "Source Terms and the Chernobyl Accident." *Nuclear Safety After Three Mile Island and Chernobyl*. Ed. G. M. Ballard. Elsevier Applied Science: London. (1988): 306–353.

Cohen, Bernard L. "The Nuclear Reactor Accident at Chernobyl, USSR." *American Journal of Physics*, Vol. 55, No. 12 (December 1987): 1076–1083.

Cochran, Thomas B. and Robert Standish Norris. *Russian/Soviet Nuclear Warhead Production*. Washington D.C.: Natural Resources Defense Council. 8 September 1993.

Denton, Harold R. "The Causes and Consequences of the Chernobyl Nuclear Accident and Implications for U.S. Regulation of Nuclear Power Plants." An invited paper as a follow-up to the *International Energy Seminar on "Chernobyl: The Implications for Nuclear Power and the International Nuclear Regime."* The International Energy Program of the Johns Hopkins Foreign Policy Institute, Washington, D.C., July 9, 1986.

Dienes, Leslie and Theodore Shabad. *The Soviet Energy System: Resource Use and Policies*. Washington D.C.: V.H. Winston & Sons, 1979.

Duffy, Gloria. *Soviet Nuclear Energy: Domestic and International Policies*. A report prepared for the U.S. Department of Energy (R-2362-DOE). Santa Monica: The Rand Corporation, December 1979.

Elliot, Iain F. *The Soviet Energy Balance*. Praeger Publishers, 1974.

Hobbins, R. R., D. A. Petti, and D. L. Hagerman. "Fission Product Release from Fuel Under Severe Accident Conditions." *Nuclear Technology* (1992).

Idaho National Engineering Laboratory. *Assessment of Radionuclide Source Term Research*. (DOE/ID-10126(85)). Idaho Falls: INEL. (July 1985).

The International Advisory Committee, *The International Chernobyl Project: Assessment of Radiological consequences and Evaluation of Protective Measures – Conclusions and Recommendations*. IAEA/PI/D4E (May 1991.

International Atomic Energy Agency. *Safety Assessment of Proposed Improvements to RBMK Nuclear Power Plants: Report of the IAEA Extrabudgetary Programme on the Safety of RBMK Nuclear Power Plants*. Vienna, Austria: IAEA. (IAEA-TECDOC-694) March 1993.

The International Nuclear Safety Advisory Group (INSAG). *Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident*. August 30 – September 5, 1986, International Atomic Energy Agency (IAEA): Vienna, Austria, GLC(SPL.I)/3 Safety Series No. 75-INSAG-1, September 24, 1986.

The International Nuclear Safety Advisory Group (INSAG). *INSAG-7 –The Chernobyl Accident: Updating of INSAG-1*. International Atomic Energy Agency (IAEA): Vienna, Austria. Safety Series No. 75-INSAG-7, (1992).

Jankowski, M. W., D. A. Powers, and Kress, T. S. "Onsite Response to the Accident at Chernobyl (Accident Management)." *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 36–42.

Kao, Lainsu and Mujid S. Kazimi. "The Impact of Heat Transfer Models on Core/Concrete Interaction." *Nuclear Technology*, Vol. 78 (August 1987): 170–184.

Kazimi, Mujid S. and Neil E. Todreas. *Nuclear Systems I: Thermal Hydraulic Fundamentals*. New York: Hemisphere Publishing Corporation, 1990.

Kazimi, Mujid S. and Neil E. Todreas. *Nuclear Systems II: Elements of Thermal-Hydraulic Design*. New York: Hemisphere Publishing Corporation, 1990.

Kirchner, Gerald and Cornelius C. Noack. "Core History and Nuclide Inventory of the Chernobyl Core at the Time of Accident." *Nuclear Safety*, Vol. 29, No. 1 (January–March 1988): 1–5.

Knief, Ronald Allen. *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*. Hemisphere Publishing Corporation: Washington. (1992).

Kouts, Herbert. *Review of Research on Uncertainties in Estimates on Source Terms from Severe Accidents in Nuclear Power Plants*. (NUREG/CR-4883). Washington, D. C.: U.S. Government Printing Office. (April 1987).

Kress, T. S., M. W. Jankowski, J. K. Joosten, and D. A. Powers. "The Chernobyl Accident Sequence." *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 1–9.

Levine, S., G. D. Kaiser, V. C. Arcieri, H. Firstenberg, P. J. Fulford, P. S. Lam, R. L. Ritzman, and E. R. Schmidt. *Source Terms: An Investigation of Uncertainties, Magnitudes, and Recommendations for Research*. (NUS-3808). Rockville, Maryland: NUS Corporation. (March 1982).

Lewin, J. "The Russian Approach to Nuclear Reactor Safety." *Nuclear Safety*, Vol. 18, No. 4, (July – August 1977): 438 – 450.

Mabro, Robert, Ed. *World Energy Issues and Policies*. Oxford University Press, 1980.

McInall, Steven Gardiner. *Atmospheric Transport of Radionuclides Due to the Accident at the Chernobyl Unit-4 Nuclear Power Station*. Master of Science Dissertation. Department of Nuclear Engineering: Massachusetts Institute of Technology, (January 1988).

Nixon, W. and Egan, M. J. "Consequences of the Chernobyl Accident." *Nuclear Safety After Three Mile Island and Chernobyl*. Ed. G. M. Ballard. Elsevier Applied Science: London. (1988): 390–417.

Petti, D. A., Z. R. Martinson, R. R. Hobbins, and D. J. Osetek. "Results from the Power Burst Facility Severe Fuel Damage Test I-4: A Simulated Severe Fuel Damage Accident with Irradiated Fuel Rods and Control Rods," *Nuclear Technology*, Vol. 94, No. 313 (1991).

Powers, D. A. "Carburization as a Mechanism for the Release of Radionuclides During the Chernobyl Accident." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 113–125. Moscow, Russia: Nauka.

Powers, D. A., T. S. Kress, M. W. Jankowski. "The Chernobyl Source Term." *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 9–28.

Reisch, Frigyes. "Technical Note: How Chernobyl Happened: A Second Opinion." *Nuclear Safety*, Vol. 28, No. 1 (January–March 1987): 43–45.

Rasmussen, Dr. Norman. *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants* (WASH-1400). United States Nuclear Regulatory Commission: Washington D.C. (October 1975).

Stunkel, Kenneth R., Ed. *National Energy Profiles*. Praeger Publishers, 1981.

U.S. Central Intelligence Agency. *USSR Energy Atlas*. Washington, D.C.: U.S. Government Printing Office, 1985.

U.S. Department of Energy. *Report of the U.S. Department of Energy's Team Analyses of the Chernobyl-4 Atomic Energy Station Accident Sequence*. (DOE/NE-0076; DE87 003614) Washington, D.C.: U.S. Department of Energy. November 1986.

U.S. Department of Energy. *Department of Energy's Team's Analyses of Soviet Designed VVERs*. (DOE/NE-0086) Washington, D.C.: U.S. Department of Energy.

U. S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research. *Uncertainty Papers on Severe Accident Source Terms*. (NUREG-1265). Washington, D. C.: U.S. Government Printing Office. (May 1987).

U. S. Nuclear Regulatory Commission, comp. *Report on the Accident at the Chernobyl Nuclear Power Station* (NUREG-1250). Washington, DC: U.S. Government Printing Office, 1987.

Warman, Edward A. *Soviet and Far-Field Radiation Measurements and an Inferred Source Term From Chernobyl*. Presented at the New York Chapter Health Physics Society Symposium on the Effects of the Nuclear Reactor Accident at Chernobyl, April 3, 1987, Brookhaven National Laboratory.

Warman, Edward A. *Impact of Reduction of Source Terms for Reactor Accident Analysis (Draft)*. To be Presented at the 1983 Annual Conference of Southeastern Electric Exchange Engineering and Operation Division, April 14, 1983, New Orleans. (March 1983).

Wilson, Richard, et al. "Report to the American Physical Society of the Study Group on Radionuclide Release from Severe Accidents at Nuclear Power Plants." *Reviews of Modern Physics*, Vol. 57, No. 3, Part II (July 1985).

"Chernobyl: No Leukaemia Yet." *Nuclear Engineering International*. Vol. 38, No. 467 (June 1993): 8.

"Chernobyl Design Defects – The British View." *Nuclear Engineering International*, Vol. 32, No. 395 (June 1987): 21-22.

"World Nuclear Status Report 1991." *Nuclear Europe Worldscan: ENS World Yearbook* Vol. XII, No. 7–8 (July/August 1992): 39 – 57.

"Soviet Nuclear Power Plants," *USSR Technology Update*, Vol. 1, No. 12, (July 16, 1986).

III. Soviet Scientific & Technical (In English)

Adamov, Evgeni P. and Yuri Cherkashov. "The RBMK Reactor Improvement and Its Safety Increase," in *Nuclear Accidents and The Future of Energy: Lessons Learned from Chernobyl: Proceedings of the International Conference in Paris, France, April 15–17, 1991*, by the European Nuclear Society (ENS). Paris, France: European Nuclear Society, 1991, 55–69.

Adamov, E. O., V. P. Vasilevsky, A. A. Petrov, Yu. M. Cherkashov. "Operation of NPP With RBMK-Type Reactors and Measures to Be Taken to Improve Their Reliability and Safety." In *Proceedings of the*

First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989, edited by E. P. Velikhov and L. A. Bolshov, 76–90. Moscow, Russia: Nauka.

Adamov, E. O., V. P. Vasilevsky, A. A. Petrov, Yu. M. Cherkashov. "Feasibility Study of Safety of Uranium-Graphite RBMK-Type Reactors." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 90–102. Moscow, Russia: Nauka.

Adamov, E. O., V. V. Vazinger, V. P. Vasilevsky, Yu. V. Mironov, Yu. M. Nikitin, L. N. Podlazov, Yu. M. Cherkashov. "Estimation of Qualitative Effects of Possible Disturbances in Chernobyl-4." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 50–76. Moscow, Russia: Nauka.

Arutjunjan, R. V., V. V. Belikov, G. V. Belikova, L. A. Bolshov, V. V. Varenkov, V. M. Goloviznin, V. D. Kanukova, V. P. Kiselev, A. G. Popkov, V. F. Strizhov, V. V. Chudanov,. "Computer Code RASPLAV for Molten Core-Concrete Interaction Analyses." Preprint No. 16. Institute of Nuclear Safety of the Academy of Sciences of the USSR: Moscow, 1991.

Arutyunyan, R. V., L. A. Bolshov, A. A. Borovoi, B. Ya. Galkin, B. F. Petrov, L. A. Pleskachevsky, V. D. Popov. "4th Unit Barboter: Complex of Post-Accident Investigations." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 102–112. Moscow, Russia: Nauka.

Arutjunjan, R. V., L. A. Bolshov, V. V. Varenkov, V. M. Goloviznin, V. D. Kanukova, A. G. Popkov, V. F. Strizhov, V. V. Chudanov, T. A. Shipovskikh. "Modeling of SURC–4 Experiments." Preprint No. 17. Institute of Nuclear Safety of the Academy of Sciences of the USSR: Moscow, 1991.

Begichev, S. N., A. A. Borovoi, E. V. Burlakov, A. Ju. Gagarinsky, V. F. Demin, I. L. Khodakovsky, and A. A. Khrulev. "Radioactive Releases Due to the Chernobyl Accident" (preprint). Presented at the International Seminar *Fission Product Transport Processes In Reactor Accidents*, Dubrovnik, Yugoslavia, May 22–26, 1989. Moscow, Russia: I.V. Kurchatov Institute of Atomic Energy, 1989.

Belyayev, Spartak T. and Alexandr A. Borovoi. "Radioactive Releases from Chernobyl Nuclear Power Station Unit-4," in *Nuclear Accidents and The Future of Energy: Lessons Learned from Chernobyl: Proceedings of the International Conference in Paris, France, April 15–17, 1991*, by the European Nuclear Society (ENS). Paris, France: European Nuclear Society, 1991, 151–166.

Belyayev, Spartak T., Alexandr A. Borovoi, and I. P. Bouzouloukov. "Technical Management on the Chernobyl Site. Status and Future of the 'Sarcophagus'," in *Nuclear Accidents and The Future of Energy: Lessons Learned from Chernobyl: Proceedings of the International Conference in Paris, France, April 15–17, 1991*, by the European Nuclear Society (ENS). Paris, France: European Nuclear Society, 1991, 26–46.

Belayev, S. T., A. A. Borovoi, Yu. P. Buzulukov, A. Yu Gagarinski, Yu. L. Dobrinin, N. N. Dolinin, Yu. I. Sulgin, A. D. Shramchenko. "Some Aspects of Post-Accident Activity in Control Zone of Chernobyl NPP." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 134–146. Moscow, Russia: Nauka.

Borovoi, Alexandr Alexandrovich. "Fission Product and Transuranic Element Release During Chernobyl Accident" (preprint). Presented at *The International Conference "The Fission of Nuclei — 50 Years," Leningrad, USSR, October 16–20, 1989*. Chornobyl, Ukraine: The Chornobyl Complex Expedition of the I. V. Kurchatov Institute of Atomic Energy, 1990.

Borovoi, A. A. "Post-Accident Management of Destroyed Fuel From Chernobyl: Technologies Used and Lessons Learned." Chornobyl, Ukraine and Moscow, Russia: International Atomic Energy Agency, 1990.

Ilyin, L. A. M. I. Balonov, L. A. Buldakov, V. N Bur'yak, K. I. Gordeev, S. I. Dement'ev, I. G. Zhakov, G. A. Zubovsky, A. I. Kondrusev, Y. O. Konstantinov, I. I. Linge, I. A. Likhtarev, A. M. Lyaginskaya, V. A. Matyuhin, O. A. Pavlovsly, A. I. Potapov, A. E. Prysyazhnyuk, P. V. Ramsaev, A. E. Romanenko, M. N. Savkin, N. T. Starkova, N. D. Tron'ko, A. F. Tsyb. "Radiocontamination Patterns and Possible Health Consequences of the Accident at the Chornobyl Nuclear Power Station." *Journal of Radiological Protection*, Vol. 10, No. 1 (1990): 3 – 29.

Krayushkin, A. B., A. V. Kubarev, V. F. Tokarenko, V. V. Shalya, A. M. Fedosov, D. I. Yanushevich. "Simulation of the Initial Phase of the Accident at the Chernobyl NPP 4th Power Unit." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 41–49. Moscow, Russia: Nauka.

Ponomarev-Stepnoy, Nikolay N. "Prospects of Nuclear Power in the USSR After the Chernobyl Accident," in *Nuclear Accidents and The Future of Energy: Lessons Learned from Chernobyl: Proceedings of the International Conference in Paris, France, April 15–17, 1991*, by the European Nuclear Society (ENS). Paris, France: European Nuclear Society, 1991, 128–138.

Sedunov, Yu. S., V. A. Borzilov, N. V. Klepikova, N. I Troyanova, E. V. Chernokozhin. "A Set of Models for Radionuclide Transport and its Application for Estimating Source Parameters and Describing Contamination After the Chernobyl Accident." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 125–134. Moscow, Russia: Nauka.

U.S.S.R. State Committee on the Utilization of Atomic Energy (comp.), *The Accident at the Chernobyl Nuclear Power Plant and Its Consequences; Part I: General Material*, report presented at the International Atomic Energy Agency Expert's Meeting, August 25–29, 1986, Vienna.

Velikhov, Evgeni P. et al. "The Chernobyl Accident: Current Vision of its Causes and Development," in *Nuclear Accidents and The Future of Energy: Lessons Learned from Chernobyl: Proceedings of the International Conference in Paris, France, April 15–17, 1991*, by the European Nuclear Society (ENS). Paris, France: European Nuclear Society, 1991, 3–25.

West, John W. "Lessons From Chernobyl As Viewed Before Workshop." In *Proceedings of the First International Workshop on Past Severe Accidents and Their Consequences, October 30 – November 3, 1989*, edited by E. P. Velikhov and L. A. Bolshov, 33–40. Moscow, Russia: Nauka.

IV. Soviet Popular Press Press (in Belarusian, Russian, and Ukrainian)

Абагян, А. А., Н. К. Гасников, А. А. Дубинин, В. И. Журавлёв, И. Н. Качанов, В. А. Климанов, В. П. Машкович, А. А. Строганов. *Вторичное гамма-излучение в радиационной защите*. Под редакции А. А. Дубинина. Москва: Энергоатомиздат, 1984.

Арутюнян, Р. В., Л. А. Большов, В. Н. Головизнин, В. П. Киселев, И. Е. Краюшкин, А. Г. Попков, В. В. Чуданов. "Моделирование проплавления корпуса реактора в бетоне при тяжелых авариях на АЭС С ВВЭР с помощью комплекса программ «РАСПЛАВ»" Припринт ИАЭ-4778/3. Москва, Россия: Центральный научно-исследовательский институт информации и технико-экономических исследований по атомной науке и технике (ЦНИИатоминформ), 1989.

Байбаков, В. Д., Л. П. Кабанов, Т. Х. Маргулова, и В. И. Плютинский. *Атомная энергетика сегодня и завтра*. Москва, Россия: Высшая школа, 1989.

Броука, П. У. (галоуны рэдактор). *Беларуская Савецкая Энцыклапедыя.* Акадэмія Навук БССР: Мінск, Беларусь, 1971.

Герасимов, А. С., Т. С. Зарицкая, А. П. Рудик. *Справочник по образованию нуклидов в ядерных реакторах.* Москва: Энергоатомиздат, 1989.

Григорьев, В. А. и В. М. Зорин, общие редакроры. *Тепловые и атомные электрические станции – книга 3*, в серии *Теплоэнергетика и теплотехника.* Москва, Россия: Энергоатомездат, 1989.

Гричорьева, В. А. и В. М. Зорина общие редакторки. *Тепловые и атомные электрические станции* (2-е издание, переработонное). Справочник в серии *Теплоэнергетика и теплотехника*, Москва: Энергоатомиздат, 1989.

Дементьев, Б. А. *Ядерные энергетические реакторы: Учебник для вузов.* Москва: Энергоатомиздат (1990).

Доллежаль, Н. А., И. Я. Емельянов. *Канальный ядерный энергетический реактор.* Москва: Атомиздат, 1980.

Израэль, Ю. А., редактор. *Чернобыль: радиоактивное загрязнение природных сред.* Ленинград, Россия: Гидрометеоиздат, 1990.

Карасюк, А. А. и А. И. Сидоренко. *Вокруг Чернобыля: диалоги с учеными.* Москва: ИздАТ, 1991.

Львов, Г. "Чернобыль: Анатомия Взрыва." *Наука и Жизнь.* Издательство «Правда»: Москва, Россия, (12) 1989.

Малкин, Г., составитель. *Ядерный след.* Москва: Энергоатомиздат, 1990.

Матуковский, Н. «Катастрофа: Чему учат уроки Чернобля?» *Известия* № 86 (22989), (26-го марта 1990): 3.

Маценко, Г. О., *Україна в цікавих фактах: Книга рекордів України*, Львів: Слово (1992).

Рудич, Ф. М. (голова редколегії). *Історія Міст і Сіл Української РСР.* Інститут Історії Академії Наук УРСР: Київ, Україна, 1971.

Сивинцева, Ю. В., В. А. Качалова общие редакторы. *Чернобыль: Пять трудных лет.* Сборник материалов о работах по ликвидации последствий аварии на Чернобыльской АЭС в 1986–1990 гг. Москва: ИЗДАТ (1992).

Українська Радянська Соціалістична Республіка – Енциклопедичний Довідник. Київ: Українська Радянська Енциклопедія (1986).

Яков, Валерий. «Чернобыль: Шесть лет спустя.» *Известия* № 99 (23673), (25-го апреля 1992): 1.

Ярошинская, Алла. «Сорок секретных протоколов кремлевских мудрецов: Ложь о Чернобыле так же страшна, как и сама катастрофа.» *Известия,* № 98 (23672), (24-го апреля 1992): 3.

V. Soviet Internal Scientific Reports and Preprints

Абагян, А. А., Н. К. Гасников, А. А. Дубинин, В. И. Журавлёв, И. Н. Качанов, В. А. Климанов, В. П. Машкович, А. А. Строганов. *Вторичное гамма-излучение в радиационной защите.* Под редкцей А. А. Дубинина. Москва: Энергоатомиздат (1984).

Абалин, С. С., С. Т. Белаев, А. А. Боровой, А. А. Васильёв, В. Г. Волков, А. Ю. Гагаринский, И. Н. Камбулов, В. И. Морозов, Н. Е. Кихаркин, С. С. Огородник. "Диагностические исследования аварийного реактора Чернобыльской АЭС." *Атомная Энергия*, том 68, выпуск 5 (Май 1990).

Бегичев, С. Н., А. А. Боровой, Е. В. Бурлаков, С. Л. Гаврилов, А. А. Довбенко, Л. А. Левина, В. М. Маркушев, А. Е. Марченко, А. А. Строганов, А. Л. Татуров. "Топливо Реактора 4–го Блока ЧАЭС." Припринт ИАЭ-5268/3. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990.

Безбатченко, Н. И., Г. А. Котельников, Л. Н. Нефедова, А. Г. Мотлич, К. П. Чечеров. *Моделирование аварии на ЧАЭС: Обзор по материалам зарубежной печати.* Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990.

Техническое Обоснование Ядерной Безопасности Объекта "Укрытие". Под редакцей группы в составе: С. Т. Беляев, А. А. Боровой, Ж. Г. Волков, А. Ю. Гагаринский, Н. Е. Кухаров, Г. А. Шароваров, В. Ф. Шикалов. Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, 1990.

Богатов, Сергей Алексангрович. "Ядено-физические исследования форм топливного выброса при запроектной аварии ядерного реактора." Диссертация на соискание учёной степени кандидата физикоматематических наук, Институт атомной энергии им. И. В. Курчатова: Москва, Россия, 1989.

Богатов, С. А., А. А. Боровой. "О некоторых свойствах топливосодержащих частиц, образовавшихся при аварии на Чернобыльской АЭС, и особенностях формирования топливного выброса." Припринт ИАЭ-5344/3. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1991.

Богатов, С. А., А. А. Боровой, А. С. Евстратенко, А. П. Криницын, Э. А. Пазухин, А. И. Сурин. *Лавообразные топливо-содержащие массы объекта «Укрытие».* отчёт Межотраслевой научно-технический центр «Укрытие» АН Украины, Отделение ядерной и радиационной безопасности. Чернобыль, Украина (февраль 1993).

Богатов, С. А., А. А. Боровой, А. Н. Киселёв, Л. А. Обухова, К. П. Чечеров. "Оценка скорости эрозии топливосодержащих масс внутри «Саркофага» и характеристики образующихся частиц." Припринт ИАЭ-5434/3. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1991.

Бродкин, Э. Б., А. В. Хрусталев. "Нейтронно-Физические Характеристики ЛТСМ Объекта «Укрытие»." Припринт ИАЭ-5270/4. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990.

Боровой, А. А. "Внутри и Вне «Саркофага»." Припринт. Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, 1990.

Боровой, А. А., Г. Д. Ибраимов, С. С. Огородник, В. Д. Попов, К. П. Чечеров. "Состояние IV Блока ЧАЭС и Ядерного Топлива, Находящегося в Нём (По Результатам Исследований 1988 – 1989 гг)." Припринт. Чернобыль, Украина: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, 1990.

Векслер, Л. М., В. К. Попов. "Авария на Чернобыльской АЭС и её уроки (1986 – 1990)." Припринт. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990.

Гострой СССР. Чертежи ВНИКИЭТа. Москва. Ноябрь 1976, Октябрь 1979.

Государственная комиссия по чрезвычайным ситуациям, Кабинета Министров СССР – Комитет по ликвидации последствий аварии на Чернобыльской АЭС. *Чернобыль: Информационный бюллетень.* Москва: Энергоатомиздат и Цчииатоминформ (6/1992).

Государственный комитет по использованию атомной енергии СССР. *Авария на Чернобыльской АЭС и её последствия, Часть II: Приложення, Информация подготовленная для совещания экспертов МАГАТЭ, 25 – 29 августа 1986, Вена.* Москва, арвгуст 1986.

Государственный Комитет СССР по надзору за безопасным ведением работ в промышленности и атомной энергетике, *О Причинах и обстоятельствах аварии на 4 блоке чернобыльской АЭС Апреля 1986 г.,* Доклад Комиссии Госпроматомнадзора СССР, Москва (1991): 6–7.

Евстратенко, А. С. Справка – *Анализ влияния пожара в пом. 805 объекта «Укрытие» на окружающую среду (по данным штатных систем контроля).* Чернобыль, Украина. (1993).

Евстратенко, А. С. Справка – *Анализ работы систем вентиляции за период 1986-92 г.г. и воздухообмена 4-го блока.* Чернобыль, Украина. (1993).

Израэль, Ю. А., С. М. Вакуловский, В. А. Ветров, В. Н. Петров, Ф. Я. Ровинский, и Е. Д. Стукин. *Радиоактивное загрязнение природных сред,* под редакцией Ю. А. Израэля. Ленинград: Гидрометеоиздат, 1990.

Киселёв, А. Н., А. Ю. Ненаглядов, А. И. Сурин, К. П. Чечеров. "Экспериментальные исследования лавообразных топливосодержащих масс (ТСМ) на 4-м блоке ЧАЭС (по результатам исследований 1986 – 1991 годах." Припринт ИАЭ-5533/3. Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1992.

Котельников, Г. А., Н. Е. Завойская, Г. А. Котельников, В. Н. Кошелев. Аннотационный Отчёт Инв. № 006-09/49. "Анализ зарубежных научно-техничехких публикаций, связанных с аварией на ЧАЭС." Москва, Россия: Институт атомной энергии им. И. В. Курчатова, 1990.

Крышев, И. И. *Радиоэкологические последствия чернобыльской аварии.* Серия "Радиоэкологические аспекты ядерной энергетики." Москва: Ядерное Общество СССР, 1991.

МНТЦ «Укрытие». *Подготовка и экспертная оценка исходных материалов для новой редакции ТОРБ Объекта «Укрытие».* Чернобыль, Украина. (1992).

Международный консультативный комитет МАГАТЭ. *Международный Чернобыльский Проект: Технический Доклад.* Оценка радиологических последствий и защитных мер. Вена: МАГАТЭ (1992).

Министерство энергетики и электрификации СССР – ЦДУ ЕЭС СССР, Объединенное диспетчерское управление Южными энергосистемами, *Годовой Отчёт Технический,* Киев, (1966–1992).

Минчернобыль Украины и Академия Наук Украины. Описание объекта «Укрытие» и требования к его преобразованию. Киев: Наукова Думка, 1992.

Паниткоя, Ю. С., И. А. Банель, А. М. Бернадская, В. П. Бескоровайный, Н. В. Горбачева, Н. М. Груша, В. В. Котович, Л. Н. Козловская, В. Г. Молодых, Н. К. Мышкина, Н. В. Нитей, В. В. Ничипор, Т. А. Павлина, В. В. Скурат, Л. А. Станкевич, Э. М. Тащилова. *Отчёт о научно-исследовательской работе: Восстановление динамики разрушения 4-го блока ЧАЭС на основе физического и математического моделирования: Разработка физической модели чернобыльской катастрофы.* Минск, Беларусь: Академия Наук Беларуси, 1991.

Плескачевский, Л. А., et. al. Отчёт о научно-исследовательской работе: "Бассейн-барботер IV Блока ЧАЭС: Радиационная обстановка, физико-химические характеристики топливных масс, оценка количества топлива." Научно-производственное объединение "Радиевый институт имени В. Г. Хлопина": Ленинград, Россия, 1990.

Херувимов, А. Н. 2. "Разработка методики радиохимического определения ультрамалых количеств плутония в пробах почвы." Отчёт – *Разработка новых методов анализа топливо-содержащих масс объекта «Укрытие.»* Чернобыль, Украина. (1992).

Херувимов, А. Н. и Евстратенко, А. С. *Радиозольная загрязненость воздушной среды вокруг объекта «Укрытие.»* Чернобыль, Украина. (1992).

Шароваров, Г. А., et al. Характеристика объекта «Укрытие», его физическая и математическая модель. Отчёт о научно-исследовательской работе: Обоснование ядерной безопасности объекта «Укрытие» на основе исследования динамики аварийных процессов. Инв. 1448, Минск, Белорусь: Институт ядерной энергетики, 28.II.1990.

"Информация об аварии на Чернобыльской АЭС и её последствиях, подготовленная для МАГАТЭ." *Атомная Энергия*, том 61, выпуск 5 (Ноябрь 1990).

Метод сравнительной оценки биологической опасности ингаляции "горячих частиц" чернобылькой аварии. Чернобыль, Украина. (1992).

Оценка влияния разрушенного 4-го блока ЧАЭС на окружающую среду. Чернобыль, Украина. (1992).

Подготовка и совершенствование ТОРБ объекта «Укрытие» на основе оцененных баз данных по объекту и его влиянию на окружающую среду. Чернобыль, Украина: Академия Наук Украины – Межотраслевой научно-технический центр «Укрытие», 23.XII.1993.

Техническое описание конструкции реакторе РБМК-1000.

Техническое Обоснование Радиационной Безопасности Объекта «Укрытие». Чернобыль, Украина; Минск, Беларусь: Комплексная экспедиция при Институте атомной энергии им. И. В. Курчатова, Институт радиоэкологических проблем при АН Беларусь, 1992.