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IMPLICATIONS OF CHERNOBYL FOR SEABROOK

by

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The views presented in this paper are the responsibility of the author, and do not necessarily reflect those of the Nuclear Engineering Department, nor of the Massachusetts Institute of Technology. The author wrote the paper for Professor Albert Carnesale of the Kennedy School of Government of Harvard University in connection with his study of the subject (the implications of Chernobyl for Seabrook) for Governor Dukakis.

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Abstract

Chernobyl Unit 4 was one of the newest plants of the RMBK graphite-moderated, boiling water reactors which supply 14,700 MWe of Soviet electric power. It had incorporated a number of safety features which were not included in earlier RMBK's, notably a pressure suppression system which had some, but not all, functions of U.S. reactor containments.

The RMBK reactor core includes more than four times as much zirconium as a U.S. PWR of the same capacity. This material provides a large source of hydrogen which could react with steam following a loss-of-coolant and core damage accident. The graphite moderator blocks, of about 2,000 metric tons mass, burn in air at high temperatures and also produce hydrogen and carbon monoxide in a reaction with steam, both of which can complicate core damage accidents. The core also has a positive reactivity coefficient in the presence of steam voids in the pressure tube channels. This represents a control difficulty and an accident risk.

The accident itself began as a power excursion during an experiment involving the turbine, in which human error played a part. The operators lost control of the course of the accident, which was the world's most serious nuclear accident to date, involving release of a significant fraction of the radioactive inventory of the core. The threat of propogation of the accident to three neighboring reactors was averted by actions of the operating crews.

From the limited available information, the important accident events are hypothesized. Some of them could apply to the safety of U.S. Pressurized Water Reactors, such as Seabrook, and some, because of differences in principle and design, cannot. The latter are identified. Those that could apply are discussed in the context of the safety reviews conducted by the NRC and the documentation of the Final Safety Analysis Report (FSAR). It appears now that the events at Chernobyl do not pose new and unreviewed safety questions beyond those considered in the (Seabrook) FSAR. Finally, the Chernobyl accident emphasizes the importance of reactor containment structures and systems at Seabrook and in general.

Table of Contents

		Page Number
	ABSTRACT	i
	Table of Contents	ii
1.	Purpose of Paper	1
2.	Brief Description of Chernobyl . . .	2
2.1	Safety Features	4
3.	The Chernobyl Accident	12
4.	Applicability of Chernobyl Findings	27

IMPLICATIONS OF CHERNOBYL FOR SEABROOK

1. Purpose. The purpose of this paper is to attempt to assess the implications of Chernobyl for Seabrook from the point of view of nuclear science and engineering. At best, this can only be a tentative assessment because detailed information on the cause and course of the Chernobyl accident is not available as of now. The Soviet authorities have scheduled a technical briefing on their investigation during the last week of August, which may shed light on these matters.

The organization of the paper is along the following line: first, a brief description of the Chernobyl nuclear plant is presented, including some of its safety features and concerns. Second, the factual information reported in the newspapers and various sources is reviewed; along with this I make some assumptions about what might have happened to develop a more complete picture, which is presented in the form of a list of accident events. Because of fundamental differences between Chernobyl and Seabrook, some of these events do not apply to Seabrook, and these are identified. The events that remain are the ones that could apply. The latter are discussed against the background of the Seabrook licensing process, in order to establish whether any of these events are new and unreviewed safety questions.

2. <u>Brief Description of Chernobyl</u>.[1] Chernobyl Unit 4 was a 1,000 MWe (gross) nuclear station, a twin of Unit 3 and adjacent to it. The reactor is graphite moderated and cooled by boiling water, of a type denoted by "RMBK" in the Soviet Union, of which there are 27 units with a capacity of about 14,700 MWe. Chernobyl Unit 4 was one of the newest plants of the 1,000 MWe class, with additional safety features which are not present in the original plants of this size near Leningrad. The additional safety features will be reviewed later. Two larger units of 1,500 MWe have apparently been in service for less than a year.

The reactor core is 7 meters in height, with a diameter of 12 meters, and is made up of graphite blocks, through which pass pressure tubes which contain the fuel assemblies. There are 1,693 such pressure tubes which are connected to headers at the reactor inlet and outlet. The fuel assemblies in the pressure tubes are cooled by boiling water, and the steam and water mixture flows from the tubes to the outlet header, where steam and water are separated, and the steam dried before it flows to the twin steam turbines. Saturated water from the outlet header and feedwater from

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[1] B. A. Semenov, "Nuclear Power in the Soviet Union," IAEA Bulletin, Vol. 25, No. 2, June 1983, and Directory of the Nuclear Power Plants in the World, 1985, Japan Nuclear Energy Information Center.

the turbine condensers are mixed and then pumped to the header at the reactor inlet, completing the cycle.

The stack of graphite blocks weighs about 2,000 tons. The graphite is normally isolated from the steam-water mixture by the pressure tubes. The graphite blocks are also isolated from air by a tank which surrounds them, and which contains inert gas (nitrogen and helium). The pressure tube material is an alloy of zirconium, as are the fuel rods which contain the fuel in the form of uranium dioxide. The fuel loading is equivalent to about 180 tons of uranium metal. The initial core enrichment was 1.7% U-235; replacement fuel enrichment is 2% U-235. The reactor utilizes on-line refueling, i.e., the plant does not shut down for refueling, but a continuing replacement of fuel takes place, one assembly at a time, while the reactor is in operation, though it may be at less than full power during that operation. (On-line refueling in this type of reactor may be associated with production of special nuclear materials for weapons. However, the IAEA has reason to believe that Chernobyl Unit 4 was not being used for this purpose.) The reported fuel discharge burnup is 18,500 MWD/T (megawatt-days per metric ton of heavy metal). The fission product inventory of the RMBK is approximately the same as a light water reactor of the same capacity.

2.1 Safety Features

Some new safety features in Chernobyl 4 are described in a New York Times lead article by S. Diamond on 5/19/86, which describes "a large structure of steel and concrete," which surrounds the reactor. This structure appears to comprise a pressure suppression system with a function similar to that used in boiling water reactors in use in the U.S., Japan, and Europe. The idea of pressure suppression is to enclose the reactor and associated coolant piping in a secondary pressure vessel or boundary which has ducts leading to a pool of water. If a pipe break occurs during operation, the escaping water and steam increases pressure in this secondary space. In turn, this pressure causes the hot water and steam to flow through exit ducts from the secondary space into a pool of water. The water pool absorbs the heat in the hot water and steam which have escaped from the reactor coolant system through the pipe break. The result is a reduced pressure rise in comparison to that which would occur in the absence of a pressure suppression system. The general significance of this feature is to reduce the structural requirements for the containment or confinement building. In the Chernobyl design, the pool of water resides in the lowest part of the building, under the reactor.

One of the most important questions in the aftermath of the accident is whether Chernobyl Unit 4 did or did not have a true containment building for the purpose of containing the radioactive release from an accident with severe core damage. I. Yemelyanov, a Soviet engineer with reactor design responsibilities, answered this question in an Associated Press interview. He said that the reactor did not have a containment structure like those used for Western reactors.

The Soviets have not as yet revealed what the design basis of the structure at Chernobyl was. Presumably the design basis was related to the loss-of-coolant accident and emergency core cooling system design basis. That is to say, a loss-of-coolant accident for sizes up to the pressure tube header rupture would be accommodated by the pressure suppression structure, ducting, and water pool so that the civil works structures surrounding the reactor systems would withstand the pressure of escaping hot water and steam, and so that there would be no leakage, or negligible leakage of the contents of the reactor spaces, including radioactivity, outside of these spaces. The function, in effect, would be that of containment.

There are at least two aspects of the design which deserve comment in the context of this study. The first is a feature at Chernobyl which complicates the pressure suppression system design. In order for pressure suppression to function, the pressure boundary around the reactor spaces must stand intact without leakage during and after an accident. A part of this boundary is the structure between the top of the reactor and the refueling space floor. The refueling equipment and its access to the individual pressure tubes passes through this part of the boundary. Here the complication arises: if an accident involving this equipment or an accident at this part of the pressure boundary occurs, the boundary may lose its integrity. In such an event, the pressure suppression system would not function properly because of the escape path to the space above the refueling floor. The pressure rise in the reactor space would vent much of the steam, hot air, and radioactivity to the space instead of to the water suppression pool. From this refueling space, radioactivity would readily escape to the environment. In other words, the containment function of the Chernobyl pressure suppression system would fail.

The second aspect concerns the shape of the pressure boundary: it appears to consist of plane floors, ceilings, and walls joined at right angles. Such a configuration for a pressure vessel leads to problems in withstanding the forces which result from loadings in the pressurized condition. Pressure vessels typically have cylindrical or spherical walls, or combinations of the two, to distribute stresses under loaded conditions. Plane walls and rectangular joints, as are shown in the Chernobyl building sketch, are not suitable for high pressure differences across the walls unless they have strong backs and external support. The plane walls, and particularly the boundary above the reactor, which separates it from the refueling room, appear to have a limited capability to withstand pressure, i.e., a small margin to accommodate uncertainties in an accident.

Other safety features included duplicate and protected power cables (it is not clear whether they were also separated); modern control equipment of the same type used in Western reactors; and valves and seals for the purpose of isolating problem areas within the plant.

To provide for the control of serious reactor accidents, it is also necessary to install cooling systems of several kinds with redundancy and backup in case of failure. The first of these is an emergency core cooling system (ECCS), which serves to pump water into the reactor coolant system after the pipe break in order to maintain cooling of fuel assemblies and prevent fuel damage. Our understanding of the Chernobyl ECCS system is that it was designed with the capacity to accommodate the rupture of a header for the reactor pressure tubes. These headers have a diameter of 0.9 meter. The ECCS system must transport and transfer the reactor shutdown heat to the environment outside of the reactor building. To prevent escape of radioactivity, the heat must be transported by an isolated system on the reactor side, across heat exchangers to a "clean" heat removal system on the outside.

In addition to the ECCS, there should also be a heat removal system to remove heat from the pressure suppression pool, acting on a longer time scale.

It should be noted that automatic and reliable detection of such an accident, as well as any unsafe condition, and automatic shutdown of the reactor without delay is essential. The effect of reactor shutdown is to reduce the heat generation to levels substantially less than full power. For example, reactor shutdown from 100% of full power reduces the output to about 7% of full power just after shutdown; power decays by a factor of 10 in 10 hours, and by another factor of 10 over a period of about five weeks. These quantities are part of the design basis of the reactor and emergency cooling system.

In the event of a loss-of-coolant accident and a failure of the ECCS, the reactor fuel elements will not be cooled, and will heat up due to decay heat. The sequence of events expected would be at first a failure of fuel rod integrity and the escape of some gaseous fission products. As the temperature of the zirconium clad rises above 800°C, it will react chemically with steam that is present, producing additional heat and free hydrogen. Temperature would increase even further. Fuel rods would disintegrate, and melting of the uranium dioxide fuel pellets would occur. The hydrogen from the zirconium-steam reaction adds to the problem of controlling and containing the accident, because it can react with oxygen in the atmosphere in the reactor building, either by burning, or, if the hydrogen concentration gets high enough, by exploding. The hydrogen concentrations in air for these outcomes are approximately 4% and 10% by volume, respectively.

The approximate amounts of zirconium in the RMBk core are 85 metric tons for the pressure tubes, and 50 metric tons for the fuel clad. Pressure tube material as well as fuel clad would be available for metal-water reaction during a loss-of-coolant accident. The total amount of zirconium in the RMBK core is more than 4 times the amount in a PWR of the size of Seabrook.

The presence of the graphite blocks in the RMBK reactors adds to the complexity of the situation described in the preceding paragraph. Graphite reacts with oxygen, producing heat, carbon monoxide, and carbon dioxide. This reaction takes place at high temperature (in excess of 1,000^{o}C). Thus, if air could find its way to the graphite, and if the graphite temperature could increase from its normal value during reactor operation (about 700°C), a graphite fire, including the combustion of the carbon monoxide with the oxygen in air, could get underway. For air to find its way to the graphite, failure of the reactor pressure tubes, or of the steel tank surrounding the graphite would be necessary. Pressure tube failure could occur as a result of fuel melting, or also as a result of excessive pressure inside the pressure tubes.

Graphite will also react with water or steam, at high temperature (in excess of 1000°C). In this case, the reaction <u>absorbs</u> heat, tending to cool the graphite, but producing hydrogen and carbon monoxide. The latter products, as in the case of graphite combustion, can burn or explode. The conditions for steam finding its way to the graphite are the same as those for air.

There are three aspects of the control of reactor reactivity in the RMBK which are important, because they make control difficult. One of these is the fact that a steam void in the pressure tubes increases reactivity. This is a result of the property of the water in the pressure tubes to absorb neutrons. When neutrons are absorbed by water, they become unavailable for causing fission in the uranium fuel. A steam void in the pressure tubes can come about in two ways: first, by a pressure reduction (as is the case in a loss-of-coolant accident) when water flashes to steam, thereby displacing water from the pressure tube; second, by a power increase which increases boiling, and also displaces water. When water is displaced from the pressure tube, the neutrons that were going to be absorbed by water are not so absorbed, and they proceed to increase the fission rate in the fuel: power thereby increases. This effect is known as a positive steam void reactivity coefficient or a positive power coefficient. It does not apply to LWR power reactors.

The second aspect of the RMBK design is the time delay of control rod insertion. The control rods are connected to a system of cables which are driven by weights. When the trip signal is given, weights are free to fall, and they drive the control rods upward from underneath the reactor into tubes which penetrate the graphite blocks. When in place in the graphite blocks, the control rods strongly absorb neutrons, and shut the reactor down. From the trip signal (personal communication from H. Kouts), it takes 20 seconds for the control rods to complete their journey into the reactor. This is a very long time, when we consider that the Soviets have stated that the RMBK reactor can go into a reactor excursion period of 4 seconds (this, in short, means that power level will increase by a factor of 2.72 in 4 seconds). It is clear that such a long delay in reactor shutdown means that reactor power can increase greatly after it is detected, after corrective action to trip the control rods is taken, and before the reactor does shut down.

The third aspect of the control of RMBK's is the large reactor size and the method of controlling the distribution of fuel fission. Because of the strong effect of voids in the pressure tubes described above, each of the 1693 pressure tubes has a variable flow control valve. If fuel fission and power generation is excessive in a particular region, it can be reduced by increasing the content of water in the pressure tubes. Increasing the water flow will do this, and this is accomplished by opening the flow control valve. The opposite effect is accomplished by partially closing the valve. This is an important method of maintaining acceptable power distributions in the reactor. The surprising aspect of this is that it is performed manually, by technicians who, from time to time, enter the space under the reactor while it is in operation to perform manual valve adjustment. This is a potential mechanism for human error.

3. The Chernobyl Accident

The factual information about the accident has been gleaned from the New York Times stories from April 29 through May 30 by Schmeman, Taubman, Tagliabue, Diamond, Sullivan, Gwertzman, Barringa, and others; and quotations of Soviet officials, such as Chairman Gorbachev, Velikoff, Scherbitsky, Ryzhkov, and Ligachev, and statements of the IAEA officials, Blix and Rosen; and presentations by Rosen at Reno (6/16/86) and at MIT (7/15/86).

Just prior to the accident, the reactor was operating at about 7 percent of full power, and an experiment of some sort was underway. The accident began at 1:23 a.m. local time on Saturday, April 26. Although a number of stories have been reported about the initiation, the official Soviet position is that the reactor power increased in a time interval of 10 seconds from 7% to 50% of full-rated power (equivalent to a reactor excursion period of 5 seconds); an explosion of hydrogen above the reactor set off a fire in the refueling area; a combustible paint used for decontamination was ignited, as was an asphalt material used on the walls of the refueling building. Subsequent to this fire, and presumably related to the explosion and fire, the refueling machine weighing about 300 tons fell down on the top of the reactor, and broke some number of pressure tubes and piping.

It appears that a primary pipe break and loss-of-coolant accident occurred at the initiation of the accident, because one of the first reactor technicians killed was scalded by steam (the other was struck by a falling object). The subsequent pipe breaks undoubtedly increased the size and severity of the loss-of-coolant accident.

The Soviets have said that the control room instrument recordings have been recovered, and that these do not indicate problems prior to the accident initiation itself.

A recent statement by the Politburo (New York Times 7/20/86) says that the cause of the accident was "unauthorized and poorly controlled experiments during scheduled repairs." More explicitly, it states that

> "It was established that the accident had been caused by a series of gross breaches of the reactor operational regulations by workers of the atomic power station," . . .
>
> It added: "Experiments with turbo-generator operation regimes were conducted at the fourth generating unit when it was sidelined for planned repairs at night. The managers and specialists of the atomic power station themselves had not prepared for that experiment, nor approve it with appropriate organizations, although it had been their duty to do so. Finally, proper supervision was not organized when those experiments were carried out, nor proper safety measures taken. The Ministry of Power Engineering and Electrification and the State Atomic Power Inspection were guilty of lack of control over the situation at the Chernobyl plant and did not take sufficient measures to secure compliance with safety regulations and breaches of discipline and operational regulations."

A possible sequence involving the turbine which would lead to a reactor power excursion could be the following: if the turbine throttle valve were opened to admit steam so as to drive the generator and produce some, or more, electricity, the steam pressure in the reactor pressure tubes would fall; the steam voids in the reactor would increase; and as indicated above, the reactor power would increase. Depending on the magnitude of the postive void reactivity effect, and on the speed and amount of the turbine admission valve opening, such an experimental sequence could get out of control.

The stories about the accident initiation which appeared in the New York Times during May include the following:

- The accident began with a reactivity excursion, which caused the power level to rise rapidly.
- An explosion occurred, followed by a raging fire with flames 90-100 feet high.
- The explosion resulted from a chemical reaction.
- The accident developed in "an unusual way, not as scientific knowledge would have predicted" (President of Ukranian Republic); first there was a small explosion and a small radioactive emission.
- There was no explosion at first (Intourist guide); heat cracked the wall between the turbine generator hall and the reactor 60 yards away.
- There was an explosion involving the engine room, presumably the turbine generator hall.
- There were several explosions.
- There was a primary coolant system rupture with the sound of escaping steam, followed by an explosion.

Some of these stories are consistent with the official version, and some are not. It could be that they were derived from accounts of witnesses who saw consequences at different locations in the plant, i.e., people at different locations saw or interpreted events differently.

The Soviet press photographs of the plant show severe damage to the reactor building external walls, and the roof above the reactor had been blown away. This space originally housed a bridge and crane for maintenance and refueling operations, which in addition to the refueling machine may have fallen down on top of the reactor. The damage portrayed was the result of fire and probably from a big explosion. A non-explosive pressure increase inside the reactor building could have caused structural damage from failure of walls, but such an event would more likely have blown out a weak section and relieved the pressure, with less severe damage than is evident in the pictures.

The sequence described above poses some unanswered questions, such as:

- The source and mechanism of hydrogen generation that caused the initial explosion. The metal-water reaction of the zirconium fuel clad is the most likely source of hydrogen, but it is unlikely that a sufficient amount could be generated during the 10-second power excursion to cause the explosion. Hydrogen generation over a longer time from a fault in the reactor which predated the indicated accident initiation would appear more plausible.

- The source of oxygen to combine explosively with hydrogen. Oxygen would not be present in sufficient quantity in the pressure tubes, unless it had been introduced by some error in a refueling operation.
- Did the reactor shut itself down, through automatic trip on excessive power level, or did the operator shut it down somewhat later? Had the reactor not been shut down, the fire fighters combatting the blaze might have been exposed to neutrons from the reactor, but the reported doses to the plant personnel were gamma radiation and not neutron radiation. This suggests that the nuclear reaction was shutdown early in the accident.

There are other questions. We do not know whether the pressure suppression system began to function, or was negated at the accident initiation by rupture of the pressure boundary above the reactor. If not initially ruptured, it appears likely that it would have been ruptured by the falling refueling machine. In any case, whenever the severe explosion and structural damage occurred, it is clear that pressure suppression could no longer function because of the direct leakage path path to the environment outside the reactor building.

We do not have information about the performance of the ECCS system, except a report that the fire in the auxiliary building between Units No. 3 and No. 4 took out the emergency electrical supply for Unit No. 4. If this was the cause of failure of ECCS, it would have occurred at some time after the accident initiation, from 10 minutes to several hours, to allow time for the fire to take its toll. This missing information is important because large amounts of hydrogen generation from the reaction of zirconium and water discussed above would be expected after the failure of ECCS. This consideration suggests the scenario of a second, and larger, explosion which destroyed the roof and walls, subsequent to the accident initiation.

The Soviet reports indicate that human error was involved in the accident: statements to that effect were made by Yeltsin and Chairman Gorbachev. The chairman of the Investigating Committee, Deputy Prime Minister Scherbina, also said that "the accident was the result of coincidences of several highly improbable and therefore unforeseen failures." Human error and loss-of-coolant could coincide if a refueling operation were underway, and improper procedures were used in such a way that operators failed to close off the reactor pressure tube while removing or replacing the fuel element.

When the explosion and fire occurred, electric power cables were damaged. Control of some safety and auxiliary systems may have been lost. This would have had serious consequences for Unit 4, but if the fire had not been checked, it could have spread to affect systems of Unit 3, an adjacent reactor having a common auxiliary building with Unit 4. The fact that Unit 3 was safely shut down with no further involvement in the accident, suggests that the fire-fighting measures taken were probably successful, and also crucial to confining the consequences to Unit 4. Considering the consequences of an even greater accident than that which actually occurred, the fire fighters, some of whom have died of radiation exposure, are heroes in any book.

At the time of the accident, the graphite moderator blocks would have been at temperatures below the ignition point with air, and also for the graphite water reaction. Graphite temperatures would have to increase from about 700°C to 1000°C for these reactions to begin. Involvement of graphite in the accident would happen when the zirconium alloy pressure tubes failed, and when graphite became hot from the heat of zirconium-water reaction, or possibly from heat transfer from very hot or melting fuel. This would take a long time because of the heat capacity and high thermal conductivity of graphite. Thus, a graphite fire would take many hours to several days to develop. Once underway, however, it would be very difficult to control. The graphite fire apparently came to dominate the accident for many days, and major attention was devoted to ending it. That was accomplished by dropping wet sand, boron, and lead on the reactor by helicopters, in all, 4,000 tons. In effect, the fire was put out by preventing the ingress of air. This was apparently taking place for several days, beginning April 29. The reactor was still smoking on May 7, according to the report of the IAEA observers on May 8. Wet sand would help to collect or scrub out fission products, as well as prevent air from entering the reactor. Presumably the boron was dropped on the reactor in the expectation that it would make its way down into the reactor and help to keep the reactor subcritical by absorbing neutrons. The Soviets received advice on putting the fire out from the F.R.G., and the U.K.

At this time, there are many questions to be answered about the graphite fire, and the part that it played in the accident. A large graphite fire would have the the potential for considerably increasing the accident source term or radioactivity discharged to the environment, by comparison with the assumptions of the U.S. Reactor Safety Study (WASH-1400). Without a graphite fire, less material would be discharged to the environment. Some observers have expressed doubt that a graphite fire happened, suggesting that the fire could have been consuming zirconium. However, the early reports on the accident referred to a graphite fire, and there has been no statement to the contrary by the Soviets. It is important to establish what in fact occurred.

An analysis of the fire done in Sweden (personal communication) indicated that, at its worst, there were flames 500 meters high, with a towering column of smoke. This had the effect of carrying radioactivity to the 2,000 meter, and higher, levels in the atmosphere, which gave a wide dispersion to the radioactive cloud. This also probably accounts for a lower local fallout than would otherwise be expected.

The problem did not end with putting out the fire. The layer of sand, boron, and lead prevented ingress of air to the reactor, but it also prevented heat removal from the reactor core, which was getting hotter all the time. A second concern was the structural integrity of the reactor, a heavy load to begin with, which had to support the additional 4,000 tons of material dropped on it. This is the reason for the extraordinary measures taken to drain water from the suppression pool and to provide nitrogen gas to cool the smoldering graphite and the melted fuel, in whatever condition it was. The concern was evidently that extremely hot sections of the core would fall into the pool, with the result of a steam explosion. Had this occurred, it could have disrupted the core and sand layer, and considerably increased the release of radioactivity. These activities must have been accomplished at great risk to the people who performed the tasks, such as entering the reactor building to drain it.

Work was begun to enclose the reactor with a new concrete structure and place an additional concrete mat under the existing foundation to prevent radioactivity from entering the water table underneath which would find its way into the lake which supplies Kiev with the water. Work was already underway to build dykes along nearby river banks in order to prevent contaminated ground level water from entering the lake.

The academician Velikoff took charge of the accident several days after it occurred, probably when the Investigating Committee Chairman Scherbina arrived on the scene and discovered how serious the accident was, in contrast to the early reports received in Moscow. Velikoff reported on May 12 "that the turning point had been reached; there was no longer the threat of catastrophe." His conclusion apparently was based on the fact that the water had been drained from the suppression pool, and that reactor temperature measurements must have indicated falling temperatures.

The Swedes were the first to detect the accident outside the Soviet Union, when, on April 29, they discovered high readings on a worker entering their own nuclear station at Forsmark. Subsequent checks showed that the radiation was airborne and did not originate in Sweden. Above-normal radiation levels were discovered throughout Europe in the days after discovery in Sweden and Finland. The Swedes analyzed air samples collected by aircraft at 2,000 meters elevation and identified more than 12 radioactive isotopes including Cesium 137, Neptunium 239, Lanthanum 140, indicating that fuel failure and melting had occurred.

Demands for information from Sweden and Finland led to the Soviet announcement of the accident at Chernobyl. Soviet reports as early as May 7 (Deputy Prime Minster Scherbina) indicated that "the first information we obtained was not the same as what we obtained when we were in the area. Local experts had not made a correct assessment of the accident." So it appears that Moscow was not aware of the seriousness of the situation at Chernobyl during April 26-29.

Reports further indicate that measured radiation levels at the site were not consistent with reported levels. This discrepancy may be a part of the explanation that evacuation of the area surrounding the plant did not begin until 2:00 p.m. local time on April 27, 36 hours after the accident occurred. When evacuation did get underway, it moved rapidly: 40,000 people in and near Pripyat were evacuated in 1,100 buses in less than two and a half hours. They left their homes "with the shirts on their backs." By May 7, 89,000 in total had been evacuated from an area extending 19 miles around Chernobyl. Since that time, numbers of people from radioactive areas in Byelorussia and young children from Kiev have also been evacuated.

By now estimates of the amount of radioactive release from Chernobyl have been made by laboratories in the Soviet Union and the West. Soviet reports are in the 1-3% range, while Western estimates are higher, i.e., 15-40%. Because of the fire, radioactivity was dispersed more widely than has been assumed in most reactor safety studies. As noted above, it could have been more severe if the fire had not been put out.

There were several reports in the New York Times which concerned interviews with Soviet emigre engineers, one in Israel and one in the U.S. These reports indicated problems in the quality of components and of construction at the Chernobyl plants. We do not know what contribution, if any, such defects might have made to the accident.

In summary, the Chernobyl accident is the most severe reactor accident in history. The major factors in the accident appear to be:

- a power excursion, leading to a hydrogen explosion and fire in the refueling area, which led to consequential damage when the refueling machine fell down on the reactor,

- o human error in the initiation of the accident and possibly in some attempts to control it in the first several days,
- o a failure of ECCS, with zirconium-water reaction and generation of an explosive concentration of hydrogen,
- o an apparently big explosion which heavily damaged the reactor building, and a fire which damaged or destroyed redundant power cables and possibly instrumentation for reactor control and other emergency/auxiliary systems,
- o widespread release of a substantial fraction of the radioactive inventory of the reactor core to the environment in the Ukraine, Eastern Russia, and parts of Europe,
- o successful fire fighting measures, which together with other measures taken to safety shut down the adjacent reactor, Chernobyl Unit 3, and two other reactors, all of the same size, effectively prevented the propagation of the Chernobyl Unit 4 accident to the others,
- o a fire, probably involving graphite combustion, which extended the accident duration, and caused wide dispersal of radioactivity

- a successful strategy of controlling the graphite fire by dumping wet sand on it to cut off the supply of air needed for combustion
- heating up of the smothered reactor core due to loss of convective heat transfer: this necessitated removal of water from the suppression pool under the reactor, and the addition of a supply of nitrogen under the reactor to cool the core
- the threat of propagation of the accident to failure of shutdown and control of nearby units, which was averted
- the possibility of poor quality assurance in plant construction and component manufacture, which might be a contributing factor
- failure of management at Chernobyl to make a valid assessment of the seriousness of the situation in the first few days of the accident
- failures in training and safety procedures which might be associated with human error at initiation and during early efforts at accident control
- a lack of effective communications between Chernobyl and appropriate authorities such as the safety authorities , the State Committee for Nuclear Energy, the Electric Power Ministry, and the power plant engineering group in Leningrad.

- a 36-hour delay in undertaking evacuation after indications of a large radioactive release from the plant. Little is known about an evacuation plan for Chernobyl and readiness to put it into effect.
- the mounting of a major accident control and construction activity when the dimensions of the accident were understood by the authorities

4.0 Applicability of Chernobyl Findings

The findings of a thorough investigation of the Chernobyl accident, when completed, will apply directly to identical RMBK units. Such an investigation would move through several levels of design, from the top level of principles, to layout of the plant, to civil works, to systems flow diagrams, and to successively more detailed drawings and specification of nuclear, thermal, mechanical, electrical, and instrumentation and control components.

The same findings, however, may not apply completely to non-identical RMBK reactors. For example, if one of the systems of the non-identical unit performs its function using different principles or operating in a different mode, the findings that involve this system might apply and they might not. An analysis of the differences between the non-identical systems would be needed to establish the point. The same is true of non-identical components, or components of different size and capacity. Even in the case of components of the same size, differences in design methods or fabrication procedures might make it necessary to analyze the differences before applying the findings. The analytical effort required would bear some relationship to the extent of the differences between the two reactors.

The problem of applying the lessons of Chernobyl to Seabrook PWR is much more difficult. In the first place, we do not yet know the lessons. We have attempted to sketch a picture of what may have happened, or what more likely happened, from the limited factual data which has been reported. In the second place, we do not have the detailed knowledge of the engineering methods, the design and the fabrication details of the Chernobyl RMBK. It will be necessary to have both sets of information in order to perform the analysis which can possibly lead to a translation of detailed accident events and lessons from the RMBK framework to the PWR framework.

There is a third factor already mentioned, the fundamental differences between the PWR and the RMBK. In this area, we have much better knowledge, and in it we can make a beginning. Because of our lack of knowledge of engineering detail of the RMBK, we have to work on a more general level, addressing the functions that systems and components per form, rather than the explicit engineering parameters which describe performance.

The starting point for this functional approach to applying the assumed lessons of Chernobyl to Seabrook is to sort through the list of problems during the accident (developed in Section 3), to eliminate the problems that do not apply because of fundamental differences, and then to work with what remains.

The problems that do not apply are those that relate to Chernobyl characteristics which are not present in Seabrook. These are the following:

- the positive void coefficient of reactivity, and the coupling of the reactor and the turbine systems through the direct boiling water reactor cycle (Note that U.S. BWR's avoid the problem because their void coefficients are <u>negative</u>)
- manual control of the pressure tube variable flow control valves
- the trip delay time of the shutdown rods, which is long compared to the reactor period in an excursion
- the partial containment system
- the on-line refueling system
- the graphite moderator blocks

The list that remains is the following:

(a) Power Excursions

Power excursions are possible in the PWR as in any reactor. The important possible causes are ejection of a control rod (resulting from the rupture of a control rod mechanism housing); a control system malfunction and inadvertent control rod withdrawal; or a steam line break with rapid loss of heat from the steam generator and the reactor coolant system, which would cause power to increase. These are all design basis accidents which are analyzed in detail, and for which protection is provided by the Doppler reactivity effect, by a negative void reactivity coefficient, and by a combination of protection system instruments that measure power level and cause rapid reactor shutdown at excessive power level.

(b) Human Error

Since we do not yet know the nature of the human error which was involved at Chernobyl, it is impossible to say anything about implications for Seabrook. We can say that the RMBK is a difficult system to control, and it appears to offer greater opportunity for error than the PWR system. We do know that human error is one of the major contributors to potential reactor accident risks, and in fact occurred at Three Mile Island Unit 2. Very substantial progress has been made since then in the requirements and qualification, training, procedure development and checking, and testing of operator readiness, through the efforts of the nuclear industry, the NRC, and the Institute of Nuclear Power Operations (INPO). That is not to say that nothing else can be done to improve operator performance and to reduce the incidence and consequences of human error.

(c) Loss-of-coolant Accidents

Loss-of-coolant accidents are design basis accidents for all light water reactors, including Seabrook. The Seabrook ECCS system has four subsystems to provide core cooling coverage for the range of pipe breaks that could occur from the smallest pipe to the large reactor coolant pipe (about 0.9 meter in diameter). The motor-driven pump systems are redundant with separate, protected trains, and the alternate power supplies. It is necessary to learn the details of a loss-of-coolant accident at Chernobyl before a judgment can be made on implications, if there are any.

(d) ECCS Failure

U.S. practice at Seabrook and elsewhere provides overlapping systems for different break sizes, protection from consequential accident damage, redundant systems for motor-driven pumping systems, separate trains, and backup power supplies. ECCS design requirements are set forth in detail in Appendix K of 10CFR50. If the failure of ECCS at Chernobyl resulted from a design shortfall in one or more of these areas, there may be no implications for Seabrook. If the system failed to deliver what it was designed to do, it would be advisable to search for analogous weaknesses in the U.S. ECCS systems. This is an important question to pursue.

(e) Hydrogen Explosion

The Seabrook and other U.S. PWR dry containments include hydrogen recombiners to prevent the accumulation of combustible or explosive quantities of hydrogen in the containment.

(f) Radioactive Release Containment

Seabrook has a dry containment structure enclosing the reactor and primary system. It is a pressure vessel designed for an internal pressure of 52 psig. The peak loss-of-coolant accident pressure given in the Final Safety Analysis Report (FSAR) is 46.4 psig for the severest reactor coolant pipe rupture. Other similar dry containment structures, such as Indian Point Unit 2, have been analyzed and found to have ultimate capability of as much as a factor of two times the design pressure. Seabrook may also have substantial additional capability. The issue of containment integrity, including the leak tightness of containment penetrations and of external valves and piping connected to it, is one of the two or three most important lessons of Chernobyl. Continual attention on the part of the nuclear plant managers should be devoted to maintaining containment integrity.

(g) Management Weakness

The quality of management is generally recognized to be a key factor in the safety and effective operation of nuclear power plants. In the U.S., both the NRC and INPO are conducting periodic management audits of all nuclear plants to measure performance. When shortcomings are found, the period between audits is decreased to encourage prompt corrective action. Identifying problems and achieving prompt corrective action are the key points.

(h) Weaknesses in Training and Procedures

The same comment applies as in (g).

(i) Lack of Effective Communications between Plants and the Safety Authority

This weakness was one of the lessons learned from TMI-2. Corrective measures were taken in the U.S., and each plant now has a direct line to the NRC control center in Bethesda, Maryland. Effective communication of information on the accident was clearly lacking at Chernobyl.

(j) Readiness for Evacuation

This is the question outstanding in the case of Seabrook, and is under consideration now.

(k) Quality Assurance

This has been a major problem in a number of U.S. nuclear plant construction projects. My understanding is that there are no major unresolved quality assurance issues at Seabrook.

(l) <u>Fire Protection</u>

Fire protection requirements for U.S. nuclear power plants are set forth in detail in Appendix R of 10CFR50. These are regarded as stringent requirements in the industry, and a great amount of study and investment has gone into the upgrading of nuclear plants which were completed before Appendix R was prepared. Compliance with the requirements of Appendix R on the part of Seabrook is one of the necessary steps in obtaining the NRC license. Many of these requirements were developed after the Brown's Ferry nuclear station fire in 1975. The emphasis is on eliminating fire hazards, and on providing fire protection for all safety-related functions in the plant.

(m) <u>Control Room Access</u>

Although a second unit is not now an issue at Seabrook, it is necessary that access to control equipment be available for purposes of maintaining public safety after an accident at the plant. This is an NRC requirement for U.S. nuclear plants.

(n) <u>Emergency Electrical Power</u>

Electrical power is required for the ECCS, other heat removal and auxiliary systems, and for certain instrumentation and controls following an accident. In the case of Seabrook, the available power sources are described in

Sections 8.2 and 8.3 of the FSAR. These include the off-site sources, consisting of three 345 kV ties to the north-east grid, and two diesel generators on site having a continuous capacity of just over 6 MWe each. The reliability of these sources, taken together, is a matter of NRC licensing review.

We have now a list of problems and functional requirements, gleaned from what we know and what we further assumed went wrong at Chernobyl that could apply in some way to Seabrook. The question is, what does this list signify for Seabrook? More specificlly, is there any aspect of this list which represents a new safety problem for the PWR, having not been reviewed by the NRC in the course of licensing the Seabrook plant?

The answer to this question is that there are no new and unreviewed safety questions in the list that is developed here on the events at Chernobyl that could apply to Seabrook. This is an important conclusion on the level of safety functions and requirements, but it is also limited in the sense that an unfolding of knowledge on the engineering details of the RMBK and the Chernobyl accident may provide lessons at the level of engineering detail. We are not able to say what these might be. If the detailed lessons turn out to have significance for PWRs or LWRs more generally, it is likely that changes would be made to reactors and/or procedures, in a way analogous to the backfits that were developed in the aftermath of Three Mile Island. The fact is that we learned from that accident, and have made improvements, and we can learn from Chernobyl.

A final comment on the contrast of experience at Chernobyl and Three Mile Island is relevant to the consideration of Seabrook. The estimated radioactive release at Chernobyl ranges from a low of about 3×10^6 Curies (Soviet) to a high of about 40×10^6 Curies. The containment building held at Three Mile Island, and the total release was about 15 Curies. From the point of view of public safety, this is the most dramatic contrast between the two accidents. It demonstrates something of importance about the purpose and performance of containment. A strong containment structure enclosing the reactor primary system, with leaktight penetrations and reliable cooling systens, provides a barrier to prevent radioactive release of very large significance to public safety.