MCNP4B MODELING OF PEBBLE-BED REACTORS

By

Julian Robert Lebenhaft

B.Sc. (Chemistry with Physics) 1977
M.Sc. (Chemical Physics) 1978
Ph.D. (Chemical Physics) 1982
University of Toronto

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Signature of Author: _____
Department of Nuclear Engineering
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Certified by: _____
Michael J. Driscoll
Professor Emeritus of Nuclear Engineering
Thesis Supervisor

Certified by: _____
Pavel Hejzlar
Program Director, Center for Advanced Nuclear Energy Systems
Reader

Accepted by: _____
Jeffrey A. Coderre
Assistant Professor of Nuclear Engineering
Chairman, Department Committee on Graduate Students

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ABSTRACT

The applicability of the Monte Carlo code MCNP4B to the neutronic modeling of pebble-bed reactors was investigated. A modeling methodology was developed based on an analysis of critical experiments carried out at the HTR-PROTEUS and ASTRA facilities, and the critical loading of the HTR-10 reactor. A body-centred cubic lattice of spheres with a specified packing fraction approximates the pebble bed, and exclusion zones offset the contribution of partial spheres generated by the geometry routines in MCNP4B at the core boundaries. The coated fuel particles are modeled in detail and are distributed over the fuelled region of the fuel sphere using a simple cubic lattice. This method predicted the critical core loading accurately in all cases. The calculation of control-rod worths in the more decoupled tall annular ASTRA core gave results within 10% compared to the reported experiments.

An approximate method was also developed for the MCNP4B modeling of pebble-bed reactors with burnup. The nuclide densities of homogenized layers in the VSOP94 reactor model are transferred to the corresponding MCNP4B model with the lattice of spheres represented explicitly. The method was demonstrated on the PBMR equilibrium core, and used for a parallel study of burnup k_∞ and isotopics on a single pebble.

Finally, a study was carried out of the proliferation potential of a modular pebble-bed reactor for both normal and off-normal operation. VSOP94 analysis showed that spent fuel from pebble-bed reactors is proliferation resistant at high discharge burnup, because of its unfavourable plutonium isotopic composition and the need to divert ~157,000 pebbles to accumulate sufficient ^{239}Pu for a nuclear weapon. The isotopics of first-pass fuel pebbles are more favourable, but even more pebbles (~258,000) would be needed. However, a supercell MOCUP model was used to demonstrate that ~20,000 pebbles would be needed if loaded with depleted uranium. But the associated reactivity loss would necessitate a compensatory increase in core height of approximately 50 cm. Such a change in core loading, as well as the properties of the special pebbles, would be noticed in a safeguarded facility.

Thesis Supervisor: Michael J. Driscoll

Title: Professor Emeritus of Nuclear Engineering

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1. INTRODUCTION

Although high-temperature gas-cooled reactors (HTGRs) exist today only as pilot-scale facilities, the growing recognition of their unique characteristics makes them leading candidates for the future electricity generating market. These characteristics include inherent safety, simplicity of design and expected low capital cost, fuel-cycle flexibility and high thermal efficiency. HTGRs are graphite-moderated and –reflected reactors, which are loaded with a unique type of fuel and are cooled by helium gas. Two types of HTGRs exist, which differ in the shape of their fuel elements—prismatic and spherical. The focus of this thesis is on the physics aspects of the latter type of reactor, the pebble-bed reactor.

After a statement of the thesis scope and objectives, this chapter will provide a historical overview of HTGR development, and a summary of the research reported here.

1.1 Scope and Objectives

From the 1960s until the present, the neutronic design of pebble-bed reactors has been carried out using diffusion-theory codes. These include the German VSOP[1] suite of codes [1-1], the modern Dutch code PANTHERMIX [1-2, 1-3], and PEBBED that is currently under development at the INEEL [1-4]. The VSOP code, as well as the unique features of pebble-bed reactor physics, will be described briefly below. However, the subject of this thesis is the neutronic modeling of pebble-bed cores using the Monte-Carlo code MCNP4B [1-5]. Prior to the research reported here, MCNP (Versions 4A and 4B) modeling of pebble-bed cores has been limited to the analysis of HTR-PROTEUS critical

[1] Very Special Old Programs.

experiments involving regular lattices [1-6]. Randomly packed cores had only been investigated using MCNP-BALL, which is a version of MCNP3B that was modified to include a stochastic geometry feature [1-7]. The goal of the research undertaken at MIT was to determine whether randomly packed cores could be described with sufficient accuracy by regular lattices, an approximation that is imposed by the use the repeated-geometry feature in MCNP4B. Such a methodology was developed and validated against several critical experiments, including the stochastic HTR-PROTEUS cores, the HTR-10 start-up core and the ASTRA criticals.

1.2 Gas Cooled Reactors

The history of gas-cooled reactors dates back to the plutonium-production piles built in the US at Hanford in the 1940s, and in the UK at Windscale in the 1950s. In the US, gas cooling of nuclear reactors was subsequently rejected in part because of anticipated difficulties with the procurement of blowers and pressure vessels. However, a different route was followed in the UK, where the first power reactors were natural-uranium fueled, graphite-moderated and utilized atmospheric air-cooling. This choice of reactor was initially dictated by the availability of nuclear materials, but the inherent safety features of gas-cooled reactors were soon recognized.

The early gas-cooled reactors were the British Magnox reactors, which were CO_2 cooled, graphite moderated, and used metallic natural uranium clad with a magnesium-aluminium alloy. Because the operating temperature of this reactor is limited to 500°C to prevent CO_2 oxidation of the cladding, the maximum coolant temperature achieved is 365°C. The power density is very low (approximately 0.5 MW/m^3) and, even with on-

line refueling, the discharge burnup of fuel in Magnox reactors is about 6 MWd/kgU. The first Magnox reactor began operating at Calder Hall in 1956, and the last of these first-generation reactors will be shut down by 2010. Typical parameters of the British Magnox reactors are given in Table 1-1.

Table 1-1
Typical Parameters of British Magnox Reactors [1-8]

Item	*Calder Hall*	*Hinkley Point A*	*Oldbury*	*Wylfa*
First power	1956	1965	1968	1971
Net power [MW(e)]	35	250	300	590
Net design efficiency (%)	19	25	33.6	31.5
Active core:				
Length (m)	6.4	7.6	9.6	9.15
Diameter (m)	9.45	14.9	13	17.35
Power density (MW/m^3)	0.5	0.74	0.65	0.87
Specific power ($kW/kg\ ^{235}U$)	190	360	400	450
Maximum burnup (MWd/kgU)	2.7	≥ 3	4.5	≥ 3
Number of fuel channels	1696	4500	3308	6150
Fuel channel diameter (mm)	54	96	97	96.5
Elements per channel	6	8	8	8
Fuel element:				
Diameter (mm)	29	28.5	28	28
Length (mm)	1015	900	960	1050
Max cladding temperature (°C)	418	430	472	451
Coolant:				
Pressure (MPa)	0.8	1.36	2.55	2.7
Temperature (°C)	140-336	180-375	245-410	247-414
Power per circulator (MW)	1.4	5.5	5.2	14
Steam (Inlet/Outlet):				
Pressures (MPa)	1.5/0.4	4.7/1.3	10/5	4.8
Temperatures (°C)	314/182	363/350	400/393	396
Pressure vessel type	Steel	Steel	PCRV	PCRV
Thickness (mm)	50.8	75	4600-6700	3350
Length (m)	21.65	20	18.3	29.3
Diameter (m)	11.25	20	23.6	29.3

The Advanced Gas Reactor (AGR) represents an evolutionary improvement over the Magnox reactor. The use of 2.5% enriched uranium oxide fuel and stainless steel cladding permits a higher gas temperature (560°C), increases fuel discharge burnup to

Table 1-2
Typical Parameters of AGRs [1-8]

Item	*WAGR*	*Hinkley Point B*	*Dungeness B*	*Heysham 2*
First power	1963	1976	1982	1987
Net power [MW(e)]	28-33	625	600	620
Net design efficiency (%)	28-31	41.5	41.5	40
Active core:				
Length (m)	4.2	8.3	8.2	8.3
Diameter (m)	4.5	9.5	9.4	9.45
Power density (MW/m^3)	1.43	2.55	2.5	2.65
Specific power ($kW/kg\ ^{235}U$)	350	~600	~500	~600
Maximum burnup (MWd/kgU)	10-20	~20	18-20	18
Fuel enrichment ($\%^{235}U$)	2.5	1.4-2.6	1.5-2.5	2.11-2.77
Number of fuel channels	210	310	410	332
Graphite sleeve ID (mm)	130	190	178	190
Elements per channel	8	8	8	8
Fuel element:				
Number of rods	21	36	36	36
Rod diameter (mm)	10.2	14.5	14.5	14.5
Rod length (mm)	510	1040	1040	1040
Max cladding temperature (°C)	650-750	825	835	—
Coolant:				
Pressure (MPa)	1.9	4.2	3.45	4.35
Temperature (°C)	250-560	290-670	320-675	335-635
Power per circulator (MW)	1.4	4.3	10.9	5.3
Circulator pressure rise (MPa)	0.1	0.24	0.32	0.29
Steam:				
Pressures (MPa)	4.6	16.3	16.3	16
Temperatures (°C)	454	538	565	538
Reheat (MPa/°C)	None	4.4/538	3.9/565	3.9/538
Pressure vessel type	Steel	PCRV	PCRV	PCRV
Thickness (mm)	44.5-111.1	4900-7300	3800-6400	5800
Length (m)	16	19.4	17.7	21.9
Diameter (m)	6.3	18.9	20	20.2

20 MWd/kgU, and decreases the size of the core. The first AGR began operation at Windscale in 1963 and fourteen such reactors were subsequently built and operated. Typical parameters of the British Magnox reactors are given in Table 1-2.

The design of the high temperature gas-cooled reactor (HTGR) was initiated in the UK at the same time as the AGR. The goal of this program was an all-ceramic, helium-cooled and graphite moderated reactor utilizing the thorium fuel cycle. The first such reactor, the 20 MW(t) DRAGON High Temperature Reactor, achieved criticality at Winfrith in August 1964, and was soon followed by two other prototypes: the 40 MW(e) Peach Bottom Unit 1 in March 1966 in the US, and the 15 MW(e) AVR in August 1967 in West Germany.

Both DRAGON and Peach Bottom utilized fuel assemblies that contained coated fuel particles uniformly dispersed throughout annular graphite compacts. The original fuel particles were composed of 93% enriched uranium and thorium carbide surrounded by a single pyrolytic carbon coating. This primitive coating proved inadequate, and BISO fuel particles were introduced that were coated with a double layer of pyrolytic carbon. BISO fuel was used successfully in Peach Bottom, where very low activity levels were subsequently experienced in the primary cooling system. Fuel was irradiated successfully in DRAGON to burnups exceeding 100 MWd/kgU. The main characteristics of HTGRs are given in Table 1-3.

A key feature of the HTGR is the use of coated fuel particles that are dispersed in a graphite matrix. The purpose of this design is to avoid corrosion to the fuel element and to enhance the retention of fission products with the graphite. However, this basic

concept can be satisfied by several fuel geometries. The British and US reactors relied on the traditional rod geometry, either hexagonal (DRAGON) or cylindrical (Peach Bottom). A completely different approach was followed in Germany, where the development of spherical fuel elements led to the design of the pebble-bed reactor. The fuel spheres are loaded from the top and discharged from the bottom of the reactor core. This is a particularly attractive concept because of its apparent simplicity and flexibility.

Table 1-3
Main Characteristics of HTGR Prototypes [1-8]

Item	*Dragon*	*Peach Bottom*	*AVR*
Country	UK	USA	Germany
Thermal power (MW)	20	115	49
Net electrical power (MW)	—	40	15
First power operation	1965	1967	1968
Helium pressure (MPa)	2	2.25	2.25
Helium temperatures†	350/750	345/725	200/850
Active core:			
Diameter (m)	1.07	2.8	3.0
Height (m)	1.6	2.3	3.5
Core power density (MW/m^3)	14	8.3	2.3
Fuel element:			
Design	Hex rods	Cylinders	Spheres
Number	37×7	804	100,000
Diameter (mm)	72	89	60
Length (mm)	2540	3660	—
Max fuel burnup (MWd/kgU)	≥ 100	~75	160
Steam conditions (MPa/°C)†	—	10/538	7.2/504
Net cycle efficiency (%)	—	35	30

† Inlet/Outlet

The first prototype pebble-bed reactor was the Arbeitsgemeinschaft Versuchsreaktor (AVR), which was started up at Jülich, West Germany, in August 1967. The AVR was a helium-cooled, graphite-moderated, high-temperature reactor with a thermal power rating of 46 MW and an electric power output of 15 MW. The core, the steam generator and the two helium circulators were contained in a double-walled pressure vessel. With the

exception of a water ingress accident from a leak in the steam generator in 1978, the AVR operated successfully for 21 years. During these years, the AVR was used to test a variety of fuels and to demonstrate the inherent safety of the pebble-bed reactor.

These prototype HTGRs were followed in 1974 by the following third-generation gas-cooled reactors: the General Atomics 330 MW(e) nuclear power station at Fort St. Vrain, USA, which utilized hexagonal graphite fuel elements with TRISO coated fuel particles; and the Thorium High Temperature Reactor (THTR), a 300 MW(e) pebble-bed reactor that was built in Schmehausen, West Germany, between 1971 and 1983. Both reactors used a PCRV to enclose the core and primary cooling system. The Fort St. Vrain reactor was shut down prematurely because of numerous mechanical problems, while the THTR was shutdown because of both mechanical problems and an unfavourable political climate in Germany after the Chernobyl accident.

Interest is being expressed once again in HTGRs because of their inherent safety, simplicity and potential for competing economically with other forms of electricity generation. Several countries are actively pursuing the development of HTGRs for a variety of applications. These include two prismatic reactors: the 30 MW(t) High Temperature Engineering Test Reactor (HTTR), which is currently undergoing commissioning tests at the Oarai Research Establishment in Japan, and the General Atomics GT-MHR intended for the disposition of excess weapons-grade plutonium. A small pebble-bed reactor, the HTR-10, was recently constructed in China, and the Pebble Bed Modular Reactor (PBMR) project is at an advanced design stage in South Africa. Details of the HTR-10 and PBMR appear elsewhere in this report. Table 1-4 summarizes

the main characteristics of the fourth-generation modular HTGRs. Numerous paper studies are underway elsewhere, including the Dutch conceptual design of a small (40 MWt) pebble-bed type HTGR [1-9, 1-10].

Table 1-4
Main Characteristics of MHTGRs

Item	*HTTR*	*HTR-10*	*GT-MHR*	*PBMR*
Country	Japan	China	USA/ Russia	South Africa
Thermal power (MW)	30	10	600	268
Net electrical power (MW)		–	284	110
Helium pressure (MPa)	4	3	7	7
Helium temperatures	395/950	250/700	490/850	491/850
Active core:				
Diameter (m)	2.3	1.8		3.5
Height (m)	2.9	1.97		8.5
Core power density (MW/m^3)	2.5	2.0		3.27
Fuel element:	UO_2	UO_2	PuO_2	UO_2
Design	Prismatic	Spherical	Prismatic	Spherical
Enrichment (% ^{235}U)	3-10	17		8
Number	150	27,000	1020	285,000
Diameter (mm)	360[†]	60	360	60
Length (mm)	580	–	800	
Max fuel burnup (MWd/kgHM)		80,000		80,000

[†] Flat-to-flat distance.

The work described in this report is part of a larger effort at MIT on the development of an advanced modular pebble-bed reactor [1-11]. The objective of this project is to develop a conceptual design for a 110 MWe helium-cooled, gas turbine powered nuclear power plant that will be competitive with natural gas. Funded by the Idaho National Engineering and Environmental Laboratory (INEEL), the project has focused on fuel performance modeling, reactor physics, safety analysis, balance of plant design, and the application of modularity to the construction of the plant. The design features an

intermediate heat exchanger that decouples the gas turbine from the primary cooling system.

1.3 Overview of Research

The remainder of this thesis is organized as follows. Chapter 2 covers pebble-bed reactor physics, treating in detail the unique features associated with neutron transport in such reactors and the computer codes used to perform this research (VSOP94 and MCNP4B). The discussion includes both diffusion theory and Monte Carlo methods.

The application of diffusion theory to core physics calculations requires the preparation of few-group cross sections and diffusion coefficients [1-12]. These parameters are obtained by the homogenization of fine-group cross sections, which are generated from detailed calculations in a large number of energy groups with a coarser spatial dependence. An important part of this spectrum calculation is the accurate determination of resonance absorption of neutrons in ^{238}U. The collision probability form of the transport equation is used for this calculation, which requires the determination of the Dancoff factor appearing in the expression for the probability that a neutron experiences its next collision in the moderator. The Dancoff factor is the moderator escape probability [1-12]. Use of coated fuel particles creates a double heterogeneity on both the microscopic and macroscopic levels (the coated particle and the pebble) that complicates the calculation of the Dancoff factor. An additional peculiarity of pebble-bed reactor physics is the need to introduce a streaming correction to the calculation of the diffusion coefficient because of the effect of voids between pebbles on neutron leakage.

Use of the Monte Carlo method in conjunction with a point-wise cross-section library eliminates the need to prepare few-group parameters or to calculate the Dancoff and diffusion streaming corrections. The Monte Carlo method is an effective numerical tool for solving the Boltzmann transport equation [1-13], and its implementation in codes such as MCNP is becoming increasingly the method of choice for the analysis of light water and liquid metal reactors. Its application to HTGRs has been limited until recently to the analysis of homogenized cores [1-14], the HTR-PROTEUS critical experiments involving regularly packed pebble beds [1-6, 1-15, 1-16], and the prismatic Very High Temperature Reactor Critical assembly in Japan [1-17]. Significant progress was made last decade in Japan, where a new sampling method was developed for irregularly distributed fuel elements [1-7]. In this approach, the location of the modeled fuel element is generated probabilistically along the flight path of the neutron by sampling from nearest-neighbour distribution functions for the fuel spheres and the coated fuel particles.

The MCNP4B modeling methodology is described in Chapter 3. In common with all full-core MCNP4B models, the pebble-bed reactor structure can be modeled in detail. The challenge lies in the representation of the randomly packed core, which must be approximated by a regular lattice of spheres. Of several possible types of packing, the body-centred cubic (or body-centred tetragonal) was found to be accurate and convenient. The large number of fuel and moderator spheres in such reactors precludes the explicit specification of the core geometry, and regular lattices of spheres are used instead. Analysis of several critical experiments showed that MCNP4B can be used for accurate criticality calculations of pebble-bed cores using appropriately modeled regular lattices to approximate the random loading [1-18].

Analyzing three sets of critical experiments validated this modeling methodology. The HTR-PROTEUS experiments [1-19] are discussed in Chapter 4. MCNP4B analysis of three stochastic cores showed the need for a peripheral buffer zone to compensate for partial fuel spheres at the reflector interface. These partial spheres, which are introduced into the model by the repeated-structure feature of code, have the effect of adding extra fuel into the core. The same approach was then applied successfully to the prediction of the initial critical loading of the HTR-10 reactor (a total sphere loading of 16,830 calculated *versus* 16,890 measured). This analysis was part of a larger IAEA physics benchmark problem [1-20], which is the subject of Chapter 5. A single zone and two types of spheres (fuel and moderator) characterize both the HTR-PROTEUS and the HTR-10 cores. A considerably more complicated pebble-bed core geometry was assembled for the ASTRA experiments [1-21]. This configuration constituted a scaled mock-up of the PBMR annular core, with an inner reflector zone, an outer fuel zone and an intermediate mixing zone. Moreover, a small number of absorber spheres were added to the fuelled zones. The polygonal shape of the ASTRA core vessel precluded the use of an explicit exclusion zone, because a distribution of partial spheres of all sizes does not occur in this case. However, the equivalent reduction in the amount of fuel was achieved by using a reduced packing fraction. The presence of an absorber and the more neutronically decoupled core resulted in poorer agreement with experiments. The MCNP4B modeling of the ASTRA experiments is discussed in Chapter 6.

The ultimate goal of the MCNP4B methodology described here is the modeling of a large pebble-bed core such as that of the Pebble Bed Modular Reactor [1-22]. Although not

investigated in this report, the approach used to model the ASTRA criticals is directly applicable to the PBMR start-up core. More important is the ability to analyze a pebble-bed reactor with a representative equilibrium burnup distribution. The composition of depleted fuel can be readily determined in a static core, but a key feature of pebble-bed reactors is the continuous recycling of fuel spheres [1-23]. In theory, the stochastic nature of such cores lends itself to direct Monte Carlo simulation. However, the large number of pebbles found in a typical core (for example, there are approximately 370,000 pebbles in the PBMR) renders the direct simulation of three-dimensional pebble flow impractical at this time. An alternative procedure is to perform the fuel management study using a diffusion theory-burnup code and to transfer the equilibrium fuel compositions to the detailed MCNP4B model. Chapter 7 describes one such approach, which involves a semi-automated link between VSOP94 and MCNP4B. The method is demonstrated in principle on the PBMR equilibrium core using the reference VSOP model of the reactor and an equivalent MCNP4B model.

The final topic covered in Chapter 8 is a preliminary investigation of the proliferation potential of the reference PBMR fuel cycle performed in collaboration with the INEEL. Four physics codes were used to estimate the production of plutonium in the reactor, including VSOP94, MCNP4B, ORIGEN2 [1-24] and MOCUP [1-25]. The Monte Carlo analysis was carried out at the INEEL using a simple-cell model representing an infinite lattice of pebbles [1-26], and at MIT using a supercell model consisting of a single production pebble in the center of a driver core representative of the PBMR. The ^{239}Pu production was estimated from a tally of the $^{238}U(n,\gamma)^{239}U$ reaction rate for an MCNP4B snapshot simulation, and by tracking the isotopic composition of the production pebble in

a MOCUP depletion calculation. The results were compared with VSOP94 predictions for the composition of discharged fuel. The analysis confirmed that spent fuel from pebble-bed reactors is proliferation resistant at high discharge burnups ($\geq$ 80 MWd/kgU), because of its unfavourable plutonium isotopic composition and the large number of pebbles that would have to be diverted—about half a core load. The isotopics of first-pass fuel pebbles are more favourable, but an even larger number would be needed to accumulate 6 kg of ^{239}Pu. However, the analysis also showed that it is possible to produce a significant quantity of plutonium in a pebble-bed reactor by inserting special pebbles with a high loading of depleted uranium. Only 20,000 pebbles would have to be diverted over a minimum period of 1.5 years, in the unlikely event that the associated loss in reactivity can be compensated undetected by raising the core height or other means.

The thesis concludes with a discussion of the results and recommendations for future research in Chapter 9. All models and computer programs developed during the course of this thesis research are documented in the Appendices.

2. PEBBLE BED REACTOR PHYSICS

The physics analysis of pebble-bed reactors shares much in common with other thermal reactors. With the exception of early KENO analysis of homogenized cores [2-1], the neutronic design of pebble-bed reactors has been carried out exclusively using S_N and diffusion-theory codes, whose few-group parameters are generated by averaging fine-group cross sections [2-2, 2-3]. The fine-group parameters are obtained from a detailed spectrum calculation using a large number of energy groups with a coarse spatial dependence. However, the calculations are complicated by some features of pebble-bed reactors, including the use of spherical fuel elements, the double heterogeneity associated with the embedded coated fuel particles, and the irregular packing of fuel spheres in the core. Of particular interest are resonance absorptions and neutron streaming in pebble beds. These special features are discussed in this chapter both because of their general importance and as motivation for the use of Monte Carlo methods, which offer an alternative and often-simpler route for pebble-bed reactor physics calculations.

2.1 **Diffusion Theory** [2-2, 2-3]

In common with all HTGRs, pebble-bed reactors are graphite-moderated and -reflected. While graphite has a relatively high atomic weight for a moderator, its very low absorption cross-section makes it inferior only to heavy water and beryllium as a moderator. The nature of this moderator dictates the slowing down process and the choice of energy structure for few-group reactor calculations. The upper bound of the thermal group is chosen such that the probability for a neutron gaining energy in a collision becomes negligible. For HTGRs, this occurs at approximately 2 eV, and the range above

the thermal group is usually subdivided into three energy groups that contain the resolved resonances, the unresolved resonances, and higher energies where the resonance structure of the heavy metal cross-sections is unimportant. The group boundaries used in the VSOP94 model of the PBMR are 1.86 eV, 29 eV and 100 keV.

2.1.1 Resonance Absorption

Fission neutrons are born with an average energy of approximately 2 MeV, and are rapidly slowed down through collisions with carbon atoms. In order to sustain the chain reaction, a sufficient number of neutrons must be thermalized without being absorbed in the large resonances of ^{238}U. Moreover, as burnup proceeds, the ^{240}Pu isotope also becomes an important resonance absorber. These resonance absorptions have a significant effect on the physics of HTGRs, especially on core reactivity, plutonium breeding and burnup. Because of the heterogeneous fuel geometry and the large changes in cross section exhibited by resonance materials, resonance absorptions are often treated using collision probability methods for solving the integral Boltzmann equation. The resonances of ^{238}U are distinct (resolved) up to about 1-4 keV. Above this energy, the resonance cross-sections are calculated using statistical distribution laws for the widths and separations of the unresolved resonances.

The spherical fuel element used in pebble-bed reactors is a 6 cm-diameter graphite ball with a (nominal) 5 cm-diameter inner-fuelled zone. The fuel typically is contained in coated particles that are randomly embedded in the graphite matrix. The TRISO coated fuel particle consists of a 500 μm-diameter UO_2 kernel surrounded by an inner low-density carbon buffer layer (9 μm thick), an inner high-density pyrolytic carbon layer (7

μm), a silicon carbide layer (6 μm) and an outer pyrolytic carbon layer (6 μm). The function of these layers is to retain fission products, while the graphite matrix further protects the fuel against corrosion and moderates neutrons. See Figure 2-1.

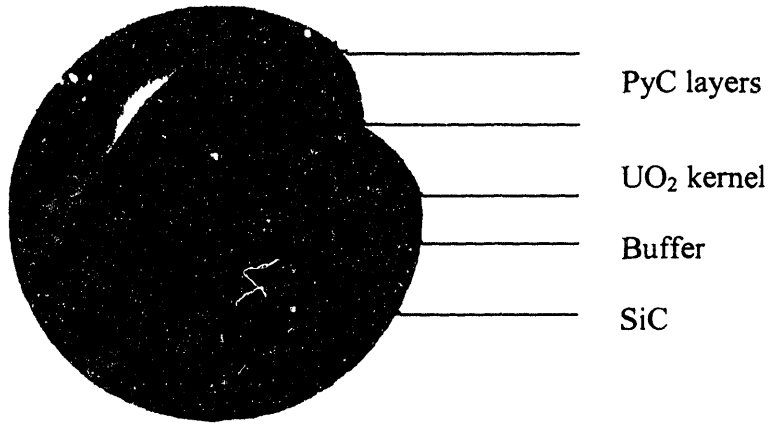


Figure 2-1. TRISO coated fuel particle (General Atomics, San Diego).

The combination of TRISO coated fuel particles and fuel spheres creates a double-heterogeneity on the microscopic and macroscopic levels, which must be factored into the expressions for fuel escape probabilities that appear in the resonance absorption calculations. This is usually achieved via the calculation of the Dancoff correction, γ, defined as the factor by which the fuel escape probability is reduced in a collection of fuel lumps relative to that for an isolated fuel lump [2-4]. Thus, the Nordheim geometric escape probability is given by [2-5]

$$P(E) = \frac{P_0(E) \cdot [1-\gamma]}{1-[1-\bar{l}_0 \Sigma_a(E) P_0(E)]\gamma}, \tag{2-1}$$

where $P_0(E)$ is the probability that a neutron escapes the fuel lump where it is born, $\bar{l}_0$ is the mean penetration chord length and $\Sigma_a(E)$ is the macroscopic absorption cross section.

However, the Nordheim treatment does not apply directly to the double heterogeneity found in pebble-bed reactors, because the small size of the fuel kernel results in $P_0(E) \approx 1$. Teuchert and Breitbarth calculated an alternative escape probability by following the path of a neutron in coated particles and fuel spheres [2-6]. The possible path is subdivided into parts for which the traversing probability can be evaluated numerically, and is expressed in terms of eight collision probabilities as follows:

$$P(E) = W_1 + W_2(W_3 + W_4) + W_2 W_5 \frac{W_6 + W_7}{1 - W_8}, \tag{2-2}$$

where the W_i are the collision probabilities in region I (see Figure 2-2). The first term gives the probability that a neutron born in a fuel kernel undergoes its next collision in the same kernel; the second gives the probability that the neutron leaves the kernel uncollided and suffers its next collision in the graphite matrix of the originating sphere (in either the fuelled zone or shell); while the third gives the probability that the neutron leaves the sphere, penetrates any number of other spheres without collision and suffers its next collision in graphite. This expression was implemented in the VSOP code [2-7].

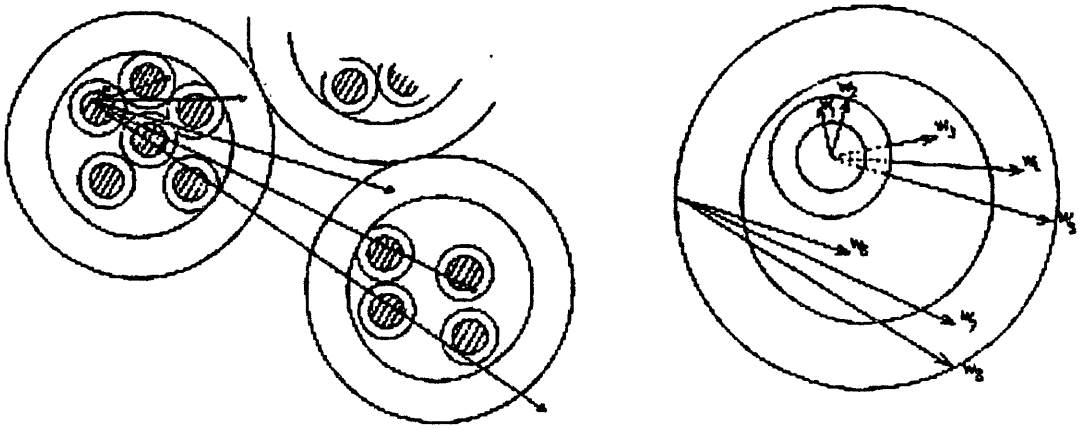


Figure 2-2. Neutron escape probabilities in a pebble-bed core [2-7].

Resonance absorptions are often treated using an equivalence relation, which transforms the complicated heterogeneous calculation into an equivalent one for a homogeneous medium. This is done by defining an energy-independent lattice escape cross section Σ_e, such that [2-4]

$$P_0(E) = \frac{\Sigma_0(E)}{\Sigma_0(E) + \Sigma_e}, \tag{2-3}$$

where $\Sigma_0(E)$ is the macroscopic total cross section for the fuel at energy E. Segev derived the following accurate formula for Σ_e [2-8]:

$$\Sigma_e = \frac{\frac{1}{\bar{l}_0}}{\frac{1}{a} + \frac{1}{\gamma_{eff}} - 1}, \tag{2-4}$$

where $\bar{l}_0$ is the mean penetration chord length in the fuel lump, a is a user selected Bell factor, and γ_{eff} is an effective Dancoff factor for the lattice:

$$\gamma_{eff} = \frac{1}{1 + \left(\frac{1}{\gamma} - 1\right)\beta},$$

and

$$\beta = \left(1 - \bar{l}_c \Sigma_L\right) \frac{1 + \frac{1}{3}\bar{l}_c \Sigma_1 \frac{V_1}{V_c}}{1 + \frac{1}{3} l_c \Sigma_1 \frac{V_1}{V_c} + \frac{\Sigma_L}{\Sigma_1}\frac{V_c}{V_1}}. \tag{2-5}$$

Here, $\bar{l}_c$ is the mean penetration chord length, Σ_l the moderator cross-section, V_l the volume of the moderator, and V_c is the volume of the nominal cell. The equivalent cross section of the outer (pebble-bed) lattice is given by

$$\Sigma_L = \frac{\frac{1}{L}}{\frac{1}{A}+\frac{1}{\Gamma}-1}, \tag{2-6}$$

where L is the mean penetration chord length, Γ is the Dancoff factor and A is the Bell factor for the outer lattice. Because these equations assume the general form programmed for the escape cross-section in the (two-dimensional) WIMS lattice code [2-9], the above theoretical development defines an alternative calculational route for pebble-bed reactors. An approach of this type is used in the Dutch OCTOPUS reactor physics analysis code system [2-10].

2.1.2 Neutron Streaming

Numerous researchers have investigated the random packing of same-sized spheres in three dimensions since early in the 20th century [2-11]. Scott carried out a series of experiments, which involved the filling of cylindrical tubes with ⅛ in. steel ball bearings [2-12]. The manner of filling the tubes determined the type of packing. When the tubes were filled by pouring and then shaken for several minutes, the resulting packing was termed "dense random packing." The tubes were then tipped horizontally, rotated slowly about the longitudinal axis, and gradually returned to the upright position. The resulting packing was termed "loose random packing." The experiments were carried out in four rigid cylinders with different diameters, and the packing densities in cylinders of infinite

length were determined from extrapolations as in Figure 2-3, plotted against reciprocals of diameters as in Figure 2-4. As $\frac{1}{D} \to 0$, the limiting packing densities are 0.60 for loose random packing and 0.63 for dense random packing.

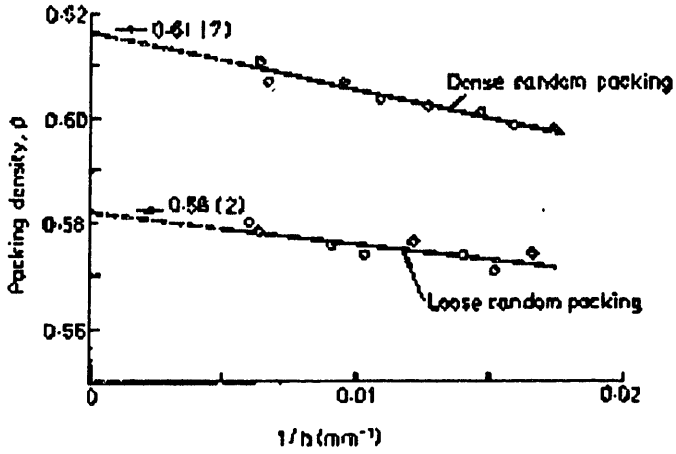


Figure 2-3. Packing density of ⅛" spheres in a 65mm-OD cylinder [2-11]

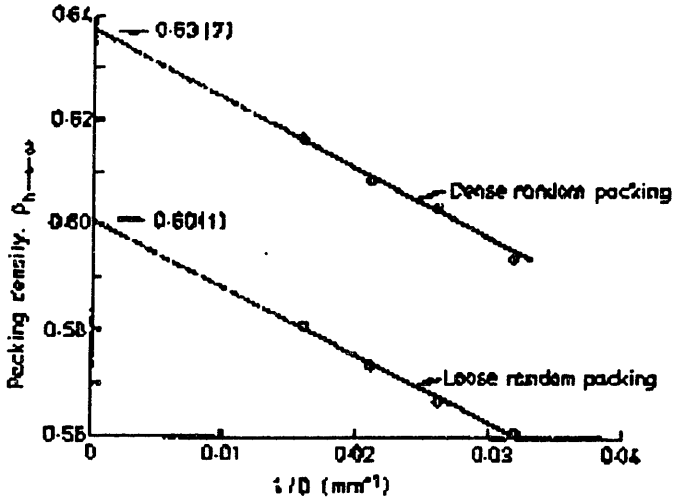


Figure 2-4. Packing density of ⅛" spheres in infinite cylinders of varying diameter [2-11].

The coordination number is defined as the number of spheres in contact with any given sphere. The coordination number can be used as a means for quantifying the arrangement of three-dimensional arrays of spheres. Only even coordination numbers are possible in regularly arranged three-dimensional cubic lattices, although odd coordination numbers are possible in hexagonal and random arrangements of spheres. Wadsworth investigated the distribution of coordination numbers for smooth hard spheres using ¼ in.-diameter steel ball bearings [2-13]. He made three important conclusions:

a) In random packing, the void fraction is only a function of the sphere-to-container diameter ratio and is insensitive to the method of stacking.

b) The random packing in flat-bottomed cylinders tends towards rhombohedral (hexagonal) close packing and the degree of incompleteness is random.

c) A critical diameter exists for forcing complete rhombohedral packing at the flat bottom of a container. This value was estimated to be 20 sphere diameters radially and axially.

The loading of spheres in pebble-bed reactors is usually assumed to be loose random packing with a 0.61 density, with regular configurations appearing only near the walls and on the bottom of the core. Neutron leakage, and hence criticality, is affected by the shape and distribution of cavities in the pebble bed. The core may be homogenized if the cavities are evenly distributed and are small relative to the neutron mean free path. However, this approximation no longer applies for larger cavities. Lieberoth and Stojadinović derived a theoretical expression for the neutron diffusion constant D, which was verified using a Monte Carlo analysis of a system with 3000 spheres [2-14]. Thus,

assuming that no correlation exists between the passage lengths in the cavities and in the spheres,

$$\frac{D}{D_H} = 1 + \frac{\phi^2}{(1+\phi)^2}\left\{\frac{2}{3}\Sigma_{tot}QR + \frac{4}{3}\Sigma_{tot}R, \right. \tag{2-7}$$

$$\left. \times\left[\frac{2\Sigma_{tot}^2 R^2}{2\Sigma_{tot}^2 R^2 - 1 + (1+2\Sigma_{tot}R)\exp(-2\Sigma_{tot}R)} - 1\right] - 1, \right.$$

where

$$Q = \frac{\langle h^2 \rangle}{\langle h \rangle^2}, \tag{2-8}$$

and

$$\phi = \frac{\langle h \rangle}{\langle t \rangle}. \tag{2-9}$$

Here, Σ_{tot} is the total macroscopic cross section in the homogeneous model, R is the radius of a sphere, h is the chord length in a cavity and t is the escape chord length in a sphere (the angular brackets denote an average).

Spectrum and diffusion calculations in heterogeneous reactors are often performed on a homogenized core. In this approach, which is used in the VSOP94 physics code, the cross sections are multiplied by energy dependent self-shielding factors, while the diffusion constant for the homogeneous model is scaled as shown in Equation 2-7.

2.1.3 Thermalization in Graphite

The fission neutrons are slowed down through collisions with the carbon atoms until they equilibrate with the thermal motion of the graphite. The energies of the thermalized

neutrons are distributed about the neutron temperature (which is slightly higher than the moderator temperature because of leakage and absorption hardening) according to the Maxwellian distribution. Thermalized neutrons can gain energy in a collision with a carbon atom. Because the carbon atoms are part of a graphite lattice (see Figure 2.5), the exchange of energy is restricted to the quanta of the crystal vibrational energy (phonons). The interaction between the thermal neutrons and the carbon atoms is given by a double differential cross section, which is commonly expressed in terms of a measured scattering law $S(\alpha,\beta)$, where α and β are dimensionless exchanges of momentum and energy. This scattering law can be related to the frequency distribution of phonons in the graphite, which can be calculated theoretically. The VSOP94 code implements the graphite phonon calculation by Young and Koppel [2-15].

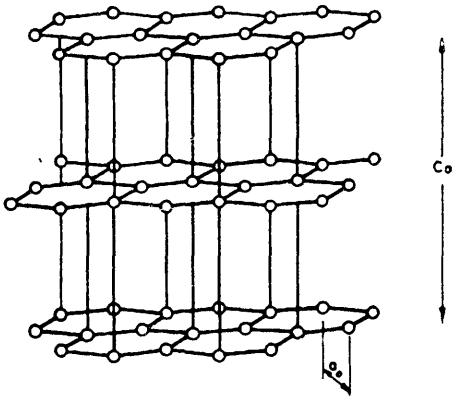


Figure 2-5. The graphite lattice [2-16].

2.1.4 The VSOP94 Code [2-7]

VSOP94 is a computer code system for reactor physics and fuel cycle simulation, which is the main physics code for the neutronic design of pebble-bed reactors. It comprises neutron cross-section libraries and routines for the following neutronic calculations:

nuclear data processing and preparation of temperature-dependent few-group parameters; repeated neutron spectrum evaluation; two- and three- dimensional diffusion calculations based on neutron flux synthesis with fuel depletion and shutdown features; fuel management including pebble recycling; fuel cycle cost analysis; and quasi-static thermal hydraulics. VSOP94 is a general-purpose code, which has also been applied successfully to light- and heavy-water reactors.

The structure of the code is shown in Figure 2-6. The ZUT-DGL code is used to generate the fast spectrum involving resonances in both the resolved and unresolved ranges [2-17]. The corresponding few-group parameters are prepared by the GAM-I code in the P_1 approximation, which accounts for leakage and anisotropic scattering [2-18]. The required fast and epithermal data, which are provided in a GAM library with 68 energy groups ranging from 10 MeV to 0.414 eV, were extracted from the ENDF/B-IV, ENDF/B-V and JEF-I evaluations. In the thermal range, the spectrum calculations are carried out with the THERMOS code, which is based on the integral form of the Boltzmann transport equation [2-19]. The THERMOS library is given in 30 energy groups ranging from 0 to 2.05 eV, and is prepared by the THERMALIZATION code (which is a precursor of the GATHER code [2-20]) from a 96-group library taking into account the specific design of the fuel elements and reactor [2-21]. Both the ZUT-DGL and THERMOS codes have been modified to allow for the double-heterogeneity present in the pebble-bed reactor [2-22]. The graphite scattering matrices are based on the Young phonon spectrum in graphite [2-15].

Several auxiliary codes are used to prepare the geometrical data needed by the main routines. The DATA-2 code prepares the fuel element input data from its geometry specification [2-23]. The auxiliary code BIRGIT prepares a two-dimensional (R-Z) geometric design of the core, which specifies a pebble flow pattern of pebbles in finite

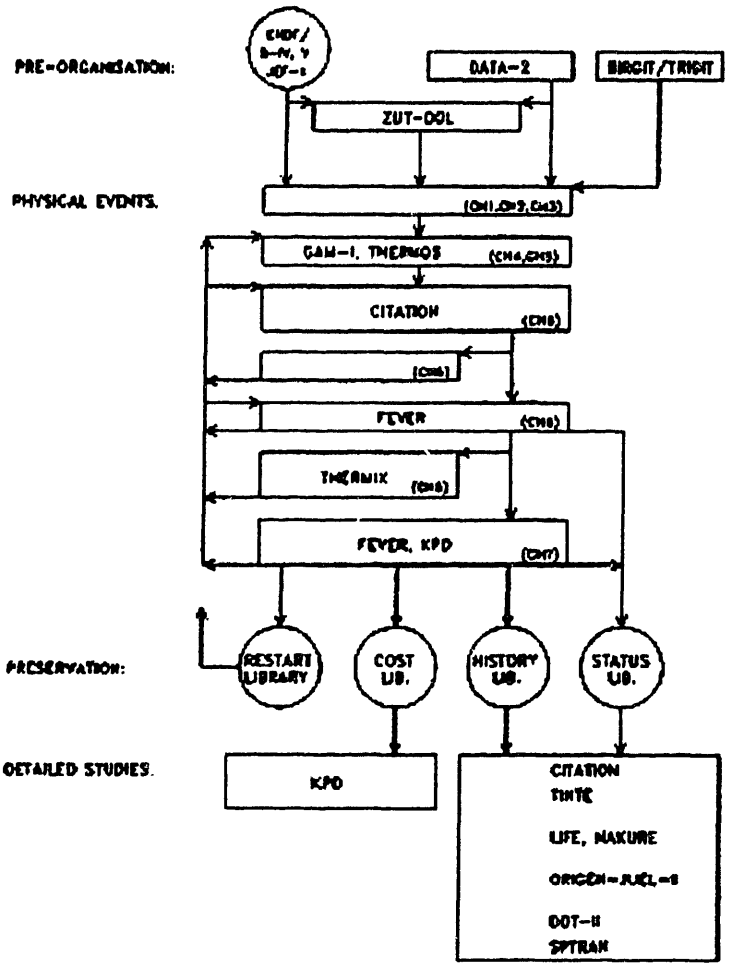
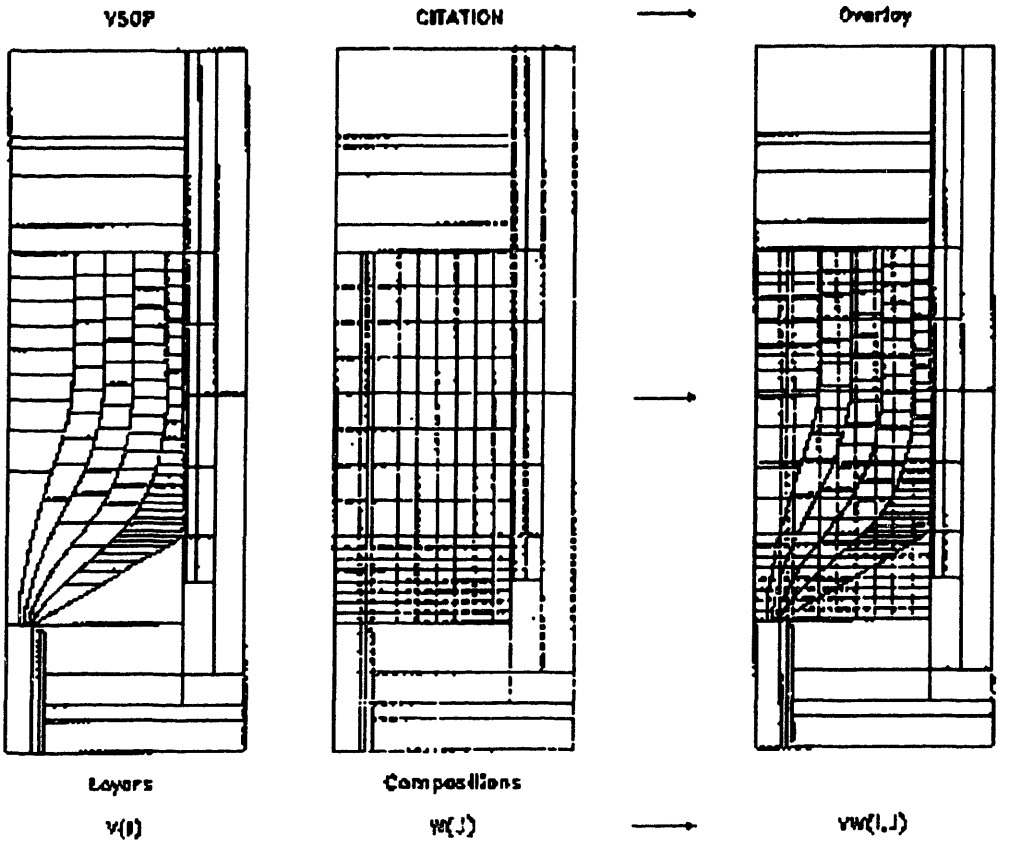


Figure 2-6. Structure of the VSOP94 code [2-7].

batches grouped into layers in different flow channels (see Figure 2-7). The batches are used to represent fuel spheres that have traversed the core a given number of times and hence have a specific burnup. The layers and flow channels allow for axial and radial burnup variations in the core. The material compositions are homogenized within each batch. Burnup is modeled by depleting the fuel in each homogenized batch by the specified time step, then shuffling its contents to the next layer in each channel. Batches at the bottom of the core are either discarded or recycled depending on the burnup.



File 2-7. Overlay of VSOP94 and CITATION meshes [2-7]

A two- or three-dimensional neutron flux map is generated with the CITATION diffusion code in several energy groups (usually four groups are chosen) [2-24]. This is utilized in a burn-up calculation for up to 200 different core regions using a scheme developed from the FEVER code, which follows explicitly the build-up history of 40 fission products in each region [2-25]. The diffusion calculation is repeated for short burn-up intervals, while the neutron spectrum is recalculated at larger time intervals. Because the diffusion calculation is carried out on a regular grid pattern, a matrix transformation (and its inverse) is provided between the VSOP flow pattern and the CITATION mesh for the macroscopic cross sections and neutron fluxes.

The THERMIX code is included in VSOP94 to perform both static and time-dependent thermal hydraulic calculations for pebble-bed reactors [2-26]. The temperatures of the fuel and moderator regions are fed back to the spectrum evaluations for subsequent core neutronic calculations. The fuel management and cost module KPD performs the in-core and out-of-pile fuel shuffling, as well as general evaluations of the reactor and fuel element irradiation history [2-27].

2.2 **The Monte Carlo Method**

The Monte Carlo method consists of simulating a large number of neutron (and/or photon) histories by using a random number generator to sample appropriate probability distribution functions for track lengths between collisions, scattering angles, type of interaction, *etc.* In this fashion, each neutron is followed from birth throughout its life to its removal from the system through absorption or leakage. When a large number of such

histories are followed, the neutron distribution becomes known and quantities of interest such as the neutron flux can be tallied. [2-28, 2-29]

2.2.1 The Boltzmann Equation

The Monte Carlo method is ideally suited for the calculation of integrals. For example, consider the simple integral

$$I = \int_a^b f(x)dx \approx \frac{(b-a)}{N}\sum_{i=1}^{N} f(x_i). \tag{2-10}$$

The x_i are chosen randomly instead of at regular intervals, and the purely statistical error is inversely proportional to $\sqrt{N}$ independently of the dimension of the integral. Because the Boltzmann transport equation can be cast in integral form, it is clear that the Monte Carlo method is ideally suited for simulating neutron and photon transport in nuclear reactors. The following brief description of the Monte Carlo sampling of the Boltzmann equation is based on the discussion in Reference 2-30.

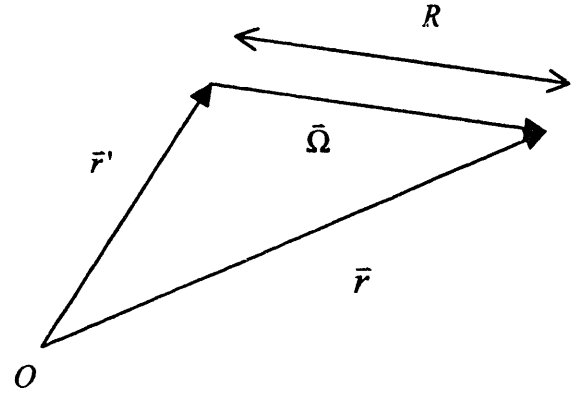


Figure 2-8. Relation between vectors [2-30].

The steady-state Boltzmann equation for the directional flux density $\phi(\vec{r},\vec{\Omega},E)$ is as follows:

$$\vec{\Omega}\cdot\vec{\nabla}\phi(\vec{r},\vec{\Omega},E)+\Sigma_t(\vec{r},\vec{\Omega},E)\phi(\vec{r},\vec{\Omega},E) = \int dE'\Sigma_s(\vec{r},\vec{\Omega}'\rightarrow\vec{\Omega},E'\rightarrow E)\phi(\vec{r},\vec{\Omega},E')+S(\vec{r},\vec{\Omega},E), \quad (2\text{-}11)$$

The first term on the left-hand side of the equation denotes the leakage of neutrons traveling in direction $\vec{\Omega}$, and the second term gives the rate of neutron loss by absorption and scattering. On the right-hand side, $\Sigma_s(\vec{r},\vec{\Omega}'\rightarrow\vec{\Omega},E'\rightarrow E)dE'$ is the differential scattering cross section from energy E' and direction $\vec{\Omega}'$ into the interval $dEd\vec{\Omega}$, and the first term represents the rate at which neutrons appear at position $\vec{r}$ with energy E due to scattering. The term $S(\vec{r},\vec{\Omega},E)$ denotes the rate at which neutrons appear at $\vec{r}$ with energy E and moving in direction $\vec{\Omega}$, with contributions from both fission and extraneous sources.

This integro-differential equation can be converted into the following integral form of the Boltzmann equation:

$$\phi(\vec{r},\vec{\Omega},E)=\int_0^{\infty}dR\cdot\exp\left(-\int_0^{R}\Sigma_t(\vec{r}-R'\vec{\Omega},E)dR'\right) \times\left[\iint d\vec{\Omega}'dE'\Sigma_s(\vec{r},\vec{\Omega}'\rightarrow\vec{\Omega},E'\rightarrow E)\phi(\vec{r},\vec{\Omega},E')+S(\vec{r},\vec{\Omega},E\right], \quad (2\text{-}12)$$

where $\vec{r}'$ is related to $\vec{r}$ and $\vec{\Omega}$ via $\vec{r}'=\vec{r}-R\vec{\Omega}$, and $R=|\vec{\Omega}|$ (see Figure 2-8). This equation is next expressed in operator form as

$$\psi(\vec{r},\vec{\Omega},E)=\int d\vec{r}'\cdot T(\vec{r}',\vec{r}|\vec{\Omega},E)\chi(\vec{r}',\vec{\Omega},E) \quad (2\text{-}13)$$

and

$$\chi(\vec{r},\vec{\Omega},E) = S(\vec{r},\vec{\Omega},E) + \iint d\vec{\Omega}'\,dE'\cdot C(\vec{\Omega}',E',\vec{\Omega},E|\vec{r})\psi(\vec{r},\vec{\Omega}',E'), \tag{2-14}$$

where the collision density ψ is defined as

$$\psi(\vec{r},\vec{\Omega},E) = \int d\vec{r}'\cdot T(\vec{r}',\vec{r}|\vec{\Omega},E) \tag{2-15}$$

and the density χ of collided particles leaving position $\vec{r}$,

$$\chi(\vec{r},\vec{\Omega},E) = \iint d\vec{\Omega}'\,dE'\Sigma_s(\vec{r},\vec{\Omega}'\to\vec{\Omega},E'\to E)\phi(\vec{r},\vec{\Omega},E') + S(\vec{r},\vec{\Omega},E). \tag{2-16}$$

The transport and collision operators are defined respectively as follows:

$$T(\vec{r}',\vec{r}\,|\,\vec{\Omega},E) = \Sigma_t(\vec{r},E)\exp\left(-\int_{\vec{r}'\to\vec{r}}\Sigma_t(\vec{r}'',E)ds\right)\frac{\delta\left(\vec{\Omega}'\cdot\frac{\vec{r}-\vec{r}'}{|\vec{r}-\vec{r}'|}-1\right)}{|\vec{r}-\vec{r}'|^2} \tag{2-17}$$

and

$$C(\vec{\Omega}',E',\vec{\Omega},E\,|\,\vec{r}) = \frac{\Sigma_s(\vec{r},\vec{\Omega}'\to\vec{\Omega},E'\to E)}{\Sigma_t(\vec{r},\vec{\Omega}',E')}. \tag{2-18}$$

The propagation of neutrons is modeled in a recursive manner. Starting with a source term $S(\vec{r}',\vec{\Omega}',E')$,

$$\chi_0(\vec{r}',\vec{\Omega}',E') = S(\vec{r}',\vec{\Omega}',E'), \tag{2-19}$$

$$\psi_0(\vec{r},\vec{\Omega}',E') = \int d\vec{r}'\,T(\vec{r}',\vec{r}\,|\,\vec{\Omega}',E')\chi_0(\vec{r}',\vec{\Omega}',E') \tag{2-20}$$

and

$$\chi_1(\vec{r},\vec{\Omega},E) = \iint d\vec{\Omega}'\,dE'\,C(\vec{\Omega}',E'\to\vec{\Omega},E\,|\,\vec{r})\psi_0(\vec{r},\vec{\Omega}',E'). \tag{2-21}$$

Subsequent steps are given by

$$\psi_n(\vec{r},\vec{\Omega}',E') = \int d\vec{r}\,' T(\vec{r}\,',\vec{r}\,|\,\vec{\Omega}',E')\chi_n(\vec{r}\,',\vec{\Omega}',E') \tag{2-22}$$

and

$$\chi_n(\vec{r},\vec{\Omega},E) = \iint d\vec{\Omega}'\,dE' C(\vec{\Omega}',E'\rightarrow\vec{\Omega},E\,|\,\vec{r})\psi_n(\vec{r},\vec{\Omega}',E')\,. \tag{2-23}$$

The transport operator T propagates the neutron from $\vec{r}\,'$ to $\vec{r}$ by sampling over the interval (0, R) according to Equation 2-22. If $\vec{r}$ is outside the boundaries of the reactor model, the neutron has escaped and the history is terminated; otherwise, an interaction takes place. The collision operator, which describes this interaction via Equation 2-23, may be rewritten as

$$C(\vec{\Omega}',E'\rightarrow\vec{\Omega},E\,|\,\vec{r}) = \frac{\Sigma_s(\vec{r},\vec{\Omega},E)}{\Sigma_t(\vec{r},\vec{\Omega},E)}\cdot\frac{\Sigma_s(\vec{\Omega}',E'\rightarrow\Omega,E\,|\,\vec{r})}{\Sigma_s(\vec{r},\vec{\Omega},E)} \tag{2-24}$$

$$= P_s(\vec{r},\vec{\Omega},E)\cdot C_s((\vec{\Omega}',E'\rightarrow\vec{\Omega},E\,|\,\vec{r})\,,$$

which expresses the collision operator in terms of a scattering kernel multiplied by a correction factor for absorption. The scattering kernel may be further written as follows:

$$C_s(\vec{\Omega}',E'\rightarrow\vec{\Omega},E\,|\,\vec{r}) = \frac{\Sigma_s(\vec{\Omega}',E'\rightarrow\Omega,E\,|\,\vec{r})}{\Sigma_s(\vec{r},\vec{\Omega},E)} \tag{2-25}$$

$$= \left[\frac{N_A(\vec{r})\sum_j \sigma_{Aj}(\vec{\Omega}',E')}{\Sigma_s(\vec{r},\vec{\Omega}',E')}\right]\left[\frac{\sigma_{Aj}(\vec{\Omega}',E')}{\sum_j \sigma_{Aj}(\vec{\Omega}',E')}\right] f_{Aj}(\vec{\Omega}',E'\rightarrow\vec{\Omega},E),$$

where N_A is the atomic number density for nuclide A, and σ_{Aj} is the microscopic cross section for reaction type j. By sampling randomly in the interval (0,1), the bracketed terms are used to determine the interacting nuclide and the type of reaction, and the normalized scattering function f_{Aj} is used to generate the scattering angle, $\mu = \cos\theta$. The particle energy E is determined from $E = E(\mu, E')$ and $\vec{\Omega}$ is calculated so as to satisfy the relation $\mu = \vec{\Omega} \cdot \vec{\Omega}'$. The neutron history is terminated if E is below the energy cutoff, otherwise $\vec{r}'$ and E' are reset to $\vec{r}$ and E.

Monte Carlo codes such as MCNP do not require explicit treatment of the slowing-down process when continuous-energy cross-sections are used, because the values of cross sections can be looked up directly at any energy level. The cross sections for each reaction are given on one energy grid, which is sufficiently dense to permit the reproduction of the evaluated cross sections within a 1% error. For example, for the ENDF/B-V evaluation, the energy grid for ^{1}H contains approximately 250 points, while ^{197}Au uses approximately 22,500. [2-31]

The Monte Carlo method offers further simplifications over the analogous diffusion-theory approach. For example, the ability to specify the exact geometry of the reactor precludes the need for neutron-streaming corrections, which are needed when a homogenized representation of the core is used.

2.2.2 The MCNP Code

MCNP (Monte Carlo N-Particle) is a general-purpose, continuous-energy, generalized-geometry, time-dependent, coupled neutron-photon-electron, Monte-Carlo transport code

system [2-31]. The calculations reported in this thesis were performed with version 4B2 of the code, although a later version (4C) is now available. The generalized geometry capability of MCNP4B, combined with the use of continuous cross-section data, make it possible to model nuclear reactors with great accuracy. The goal of the research reported here was to investigate the applicability of MCNP4B to pebble-bed reactors with randomly packed cores.

MCNP can model an arbitrary three-dimensional configuration of materials arranged in geometric cells, which are bounded by first- and second-degree surfaces and some special fourth-degree surfaces. Point-wise, continuous-energy cross-section libraries are typically used. However, multigroup data may also be used for fixed-source adjoint calculations. The cross-section evaluation accounted for all neutron interactions, and both free gas and $S(\alpha, \beta)$ thermal treatments are used. Fission sources as well as fixed and surface sources are available. For photons, the code takes account of incoherent and coherent scattering with and without electron binding effects, the possibility of fluorescent emission following photoelectric absorption, and absorption in pair production with local emission of annihilation radiation. A very general source and tally structure is available. The tallies have extensive statistical analysis of convergence, and rapid convergence is enabled by a wide variety of variance reduction methods. Normal energy ranges are 0-20 MeV for neutrons and 1 keV - 1 GeV for photons and electrons.

The large number of randomly situated fuel and moderator spheres, and the large number of fuel particles per sphere (approximately 10^4), in pebble-bed reactors precludes the explicit specification of the core geometry, and regular lattices of spheres are used

instead. The repeated-structure feature of MCNP4B permits the definition of an array consisting of hexahedral or hexagonal unit cells. This can be used to approximate the randomly packed pebble-bed core.

2.3 Summary

An overview of pebble-bed reactor physics was presented in this chapter. The double-heterogeneity of the pebble-bed core, which is related to the presence of small fuel grains embedded in graphite spheres, requires the correct treatment of mutual shielding between grains. For diffusion-theory core calculations, the effect of this shielding is embodied in the Dancoff correction for resonance absorptions. Although complicated, this procedure is fully automated in codes like VSOP94. The Monte Carlo code MCNP4B offers an alternative approach by relying on a point-wise representation of nuclear reaction cross sections, in which a large number of energy points are used to describe accurately the resonance curve. Therefore, the effect of mutual shielding between the fuel grains is included automatically. This feature of MCNP4B, as well as its ability to model reactor geometry in detail, is explored in this report.

3. MCNP4B MODELLING OF PEBBLE-BED REACTORS

Constructing an MCNP4B model consists of establishing the geometry of the reactor from engineering drawings, representing each subsystem by a cell whose boundaries are defined mathematically by a logical combination of surfaces, and specifying the density and composition of each such cell [3-1]. In the case of pebble-bed reactors, the structure of the reactor can be modeled as accurately as is required by the application. The challenge lies in modeling the randomly packed pebble-bed core, which must be approximated by a regular lattice of spheres.

3.1 Regular Lattices

Several lattices are available including simple cubic (SC), body-centred cubic (BCC) or tetragonal (BCT), face-centred cubic (FCC), simple hexagonal (SH), and hexagonal close packed (HCP) [3-2]. These lattices differ in the number of spheres present in the unit cell and the maximum packing fraction (see Table 3-1).

Table 3-1
Properties of Regular Lattices

Type of Lattice	*Number of Spheres in Unit Cell*	*Coordination Number*	*Maximum Packing Fraction*
SC	1	6	0.52
BCC or BCT	2	8	0.68
FCC	4	12	0.74
SH	6	5	0.60
HCP	6	12	0.74

The simple cubic and simple (point-on-point) hexagonal lattices can be eliminated for most cores, because of their leakiness and low packing densities. The choice among the

remaining lattices depends on their ability to represent specific sphere combinations, since the packing fraction can be achieved by adjusting the cell size; the size of the unit cell a is related to the radius of the sphere R and the packing fraction f as follows:

$$a = \left(\frac{8\pi}{3f}\right)^{\frac{1}{3}} R . \tag{3-1}$$

For example, a core characterized by a 1:1 fuel-to-moderator sphere ratio is modeled most easily by a BCC or BCT lattice because their unit cell contains two spheres (see Figure 3-1). All spheres contained within the FCC and HCP lattices are positioned along the bounding planes of the unit cell, making it impossible to model more complicated mixtures of spheres (such as the combination of moderator, fuel and absorber spheres encountered in the ASTRA critical experiments) because adjacent spheres overlap incorrectly. Therefore, although the packing of spheres in pebble beds is expected to approximate a rhombohedral lattice (see Section 2.1.2), a loose HCP lattice may not be a proper choice.

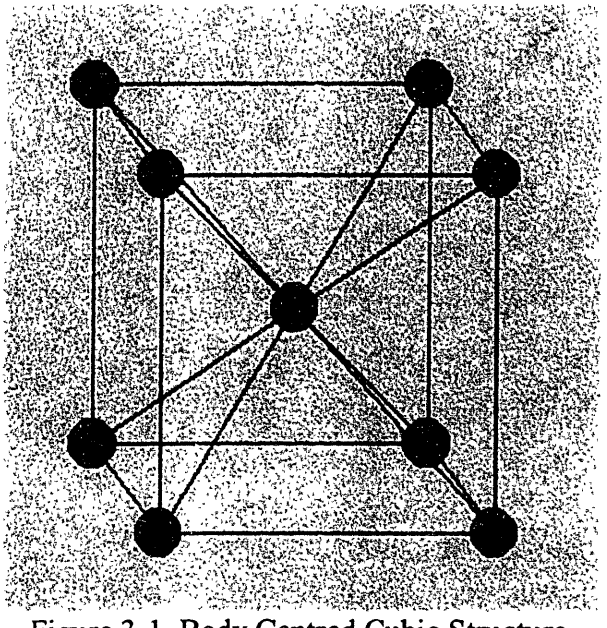


Figure 3-1. Body Centred Cubic Structure

As the subsequent chapters show, the BCC lattice was found to work well for the loose packing typically encountered in pebble-bed reactors.

The effect that the choice of packing arrangement has on neutron streaming was investigated in Reference 3-3. Criticality calculations were performed for both BCT and HCP lattices, using a spherical core (with a radius of 140 cm) packed with spheres; both reflected and unreflected configurations were considered. The results of the analysis showed that the k_{eff} is not very sensitive to the specific sphere arrangement for reflected systems for which leakage effects are less important.

Sphere mixtures other than the 1:1 fuel-to-moderator ratio present a problem. Reducing the size or density of the moderator sphere can approximate a small deviation, such as the 57:43 percent ratio used for the HTR-10 start-up core. Alternatively, a repeating cell may be constructed from several BCC (or BCT) unit cells such that the exact combination of spheres can be defined. For example, ten layers of five BCC unit cells (for a total of 100 spheres) can be used to model the HTR-10 core. More complicated core loadings may also be modeled in this fashion, although the results are sensitive to the (ideally stochastic) manner in which the spheres are distributed throughout the repeating cell.

3.2 Edge Effects in MCNP4B

A side effect associated with the repeated-structure feature in MCNP4B is the appearance of partial spheres at the core boundary (Figure 3-2), because this adds extra fuel to the core. Murata first identified this problem during the development of MCNP-BALL [3-4]. A correction had to be made to the sampling algorithm for spherical fuel spheres in order

to reproduce the specified packing fraction. This was achieved by generating a nearest neighbour distribution function for a slightly higher packing fraction, f':

$$f' = f\frac{V}{V-\Delta V} \le 0.636, \tag{3-1}$$

where f is the actual packing fraction, V is the core volume, and ΔV is the volume of an exclusion zone of thickness R (the radius of a fuel sphere in a one-zone core). Sampled fuel spheres that overlapped the core boundary were rejected.

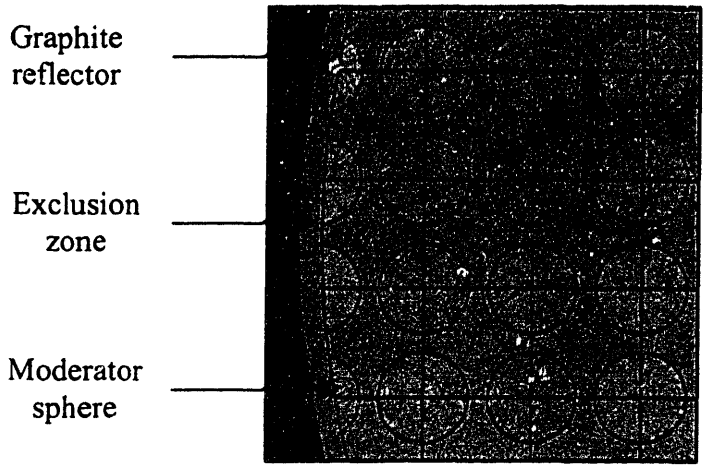


Figure 3-2. Partial spheres generated by MCNP4B

A more direct approach was chosen for the MCNP4B modeling of circular pebble-bed cores in the present work. An exclusion zone was introduced at the boundaries of the core, which effectively reduced the size of the sphere fill volume by ΔV. The size of this exclusion zone was the radius of a sphere, scaled by the ratio of the number of fuel spheres to the total number of spheres in the unit cell. Thus, for the 57:43 percent sphere ratio specified for the HTR-10 reactor, this corresponded to $3\times\frac{57}{57+43}=1.71$ cm.

Because there is a distribution of differently sized partial spheres around the core edge, deleted portions of physically realizable spheres are made up by leftover portions of physically unrealizable spheres (see Figure 3-3). This procedure does not work for the ASTRA facility with its polygonal core, because such a cancellation does not occur on average. Therefore, a reduced packing fraction was used instead in order to eliminate partial spheres.

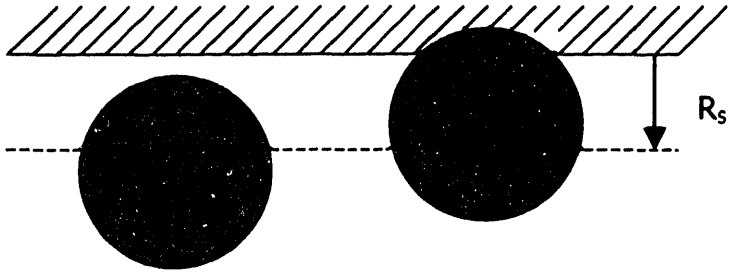


Figure 3-3. The sphere exclusion zone

3.3 **Double Heterogeneity**

For a high-fidelity MCNP model of a pebble-bed reactor, the double heterogeneity of the core must also be reproduced accurately. The coated fuel particles were modeled exactly (Figure 3-4), and the random distribution of these fuel particles in the fuel sphere was approximated using a simple-cubic regular array without an exclusion zone (Figure 3-5). Figure 3-6 shows a slice through the BCC core representation.

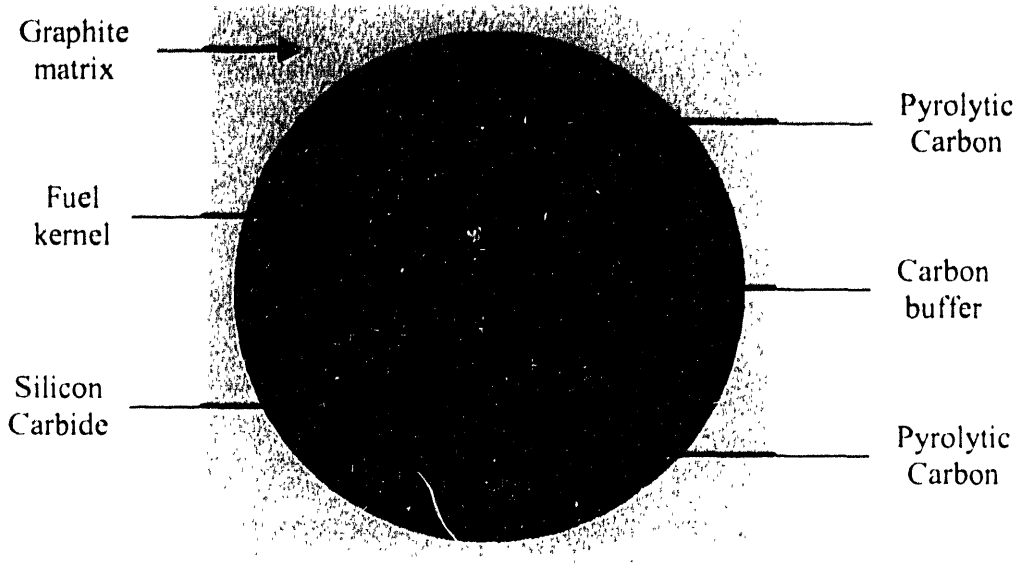


Figure 3-4. MCNP4B Model of a Coated Fuel Particle.

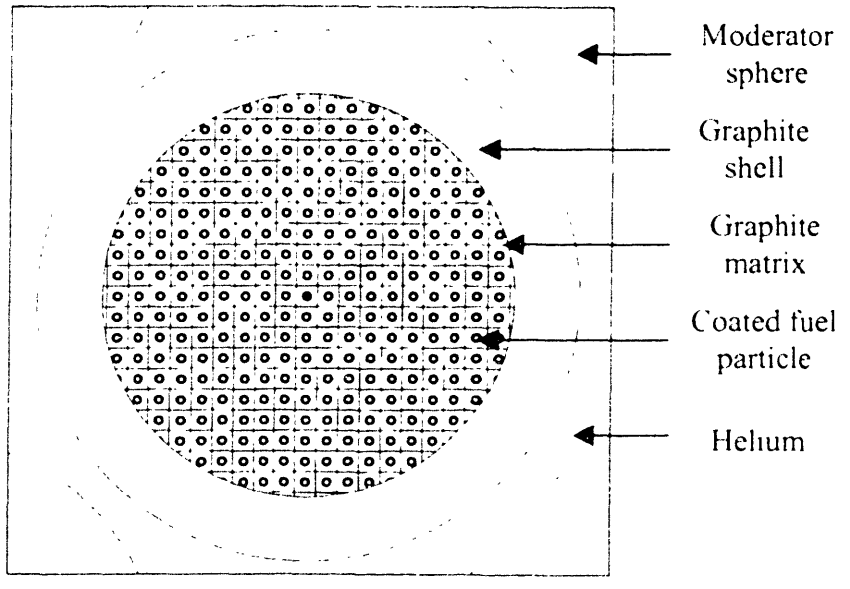


Figure 3-5. MCNP4B Model of a Fuel Pebble

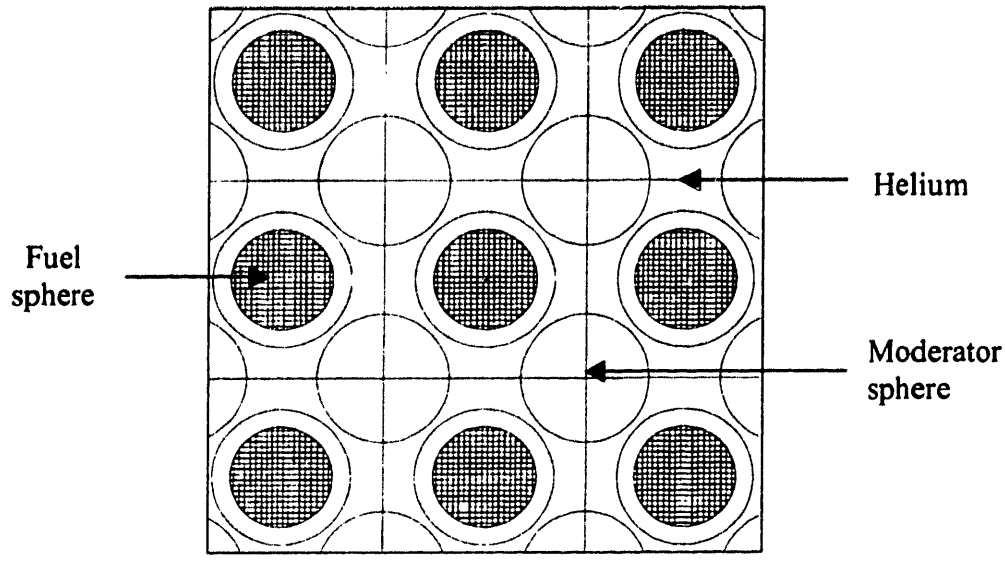


Figure 3-6. MCNP4B Model of a Pebble-Bed Core

3.4 **Conclusions**

The BCC lattice is a convenient, and a neutronically accurate, representation of a randomly packed, reflected pebble-bed core. It is characterized by the size of the cubic unit cell, which is determined from the specified packing fraction and the detailed design of the component spheres. Complicated mixtures of different spheres can be assembled by combining BCC unit cells into larger repeating cells. Use of the repeated-structure feature of MCNP4B generates partial spheres at the core boundaries, whose effect can be minimized by either introducing an exclusion zone or by reducing the packing fraction.

4. THE HTR-PROTEUS FACILITY

The PROTEUS zero-power experimental facility is located at the Paul Scherrer Institute in Switzerland. The facility has been used for a variety of critical experiments involving both light-water and gas-cooled reactor cores. The various critical assemblies are usually configured in PROTEUS as a subcritical test zone in the centre of an annular thermal driver zone. However, for the LEU-HTR experiments, the facility was set up as a critical pebble-bed core surrounded radially and axially by a graphite reflector. PROTEUS was initially prepared for the HTR experiments between January and August 1980, but was subsequently reconfigured to accommodate advanced light-water reactor experiments. The facility was rebuilt for the LEU-HTR tests in 1991 [4-1], and the experimental program continued until 1996. [4-2]

4.1 **Description of the PROTEUS Facility**

The HTR-PROTEUS facility consists of a graphite cylinder with a central cavity. The height of the cylinder is 3304 mm and its radius is 3262 mm. The cavity starts 780 mm above the bottom of the lower axial reflector, and is a 22-sided polygon with a flat-to-flat separation distance of 1250 mm. The removable upper axial reflector is a 780 mm-high graphite cylinder inside an aluminium tank, which fits onto an aluminium safety ring located 1764 mm above the floor of the cavity. An air gap is present between the upper reflector and the pebble-bed core. [4-3, 4-4]

The radial reflector has numerous channels, which accommodate absorber rods and instrumentation. The facility uses eight shutoff rods located on a radius of 689 mm, four

control rods on a radius of 789 mm or 906 mm, and one servo-driven regulating rod at a distance of 900 mm from the core centre. The shutoff rods are made of 35 mm-diameter borated-steel (5 wt%) rod sections enclosed in stainless-steel tubes with an outer diameter of 40 mm. For the first core, the control rods were the Zebra-type made of aluminium with cadmium shutters. However, these were replaced with standard stainless-steel control rods for all subsequent cores. A photograph showing a top view of the HTR-PROTEUS facility appears in Figure 4-1, while Figure 4-2 provides a schematic side view

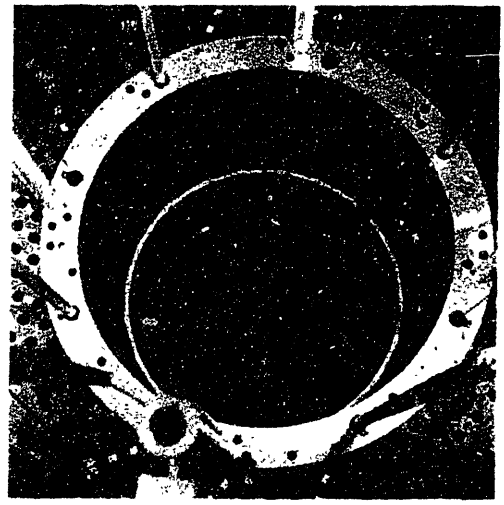


Figure 4-1. Top View of HTR-PROTEUS Facility

The reflector consists of graphite of various ages and moisture content. Table 4-1 gives the atom densities for the reflector used in the MCNP models of the facility. These values were later revised to incorporate a higher concentration of impurities (expressed as an equivalent natural boron content) resulting in a 2200 m/s cross-section of 4.09 mbarn. An average value of 1.763 g/cm^3 was recommended for the density of the graphite.

Table 4-1
Atom Densities in PROTEUS Graphite Reflector

	nuclei/barn-cm	
Nuclide	*Axial Reflectors*	*Radial Reflector*
^{10}B	9.00e-09	9.20e-09
^{11}B	3.60e-08	3.70e-08
Carbon	8.61e-02	8.84e-02

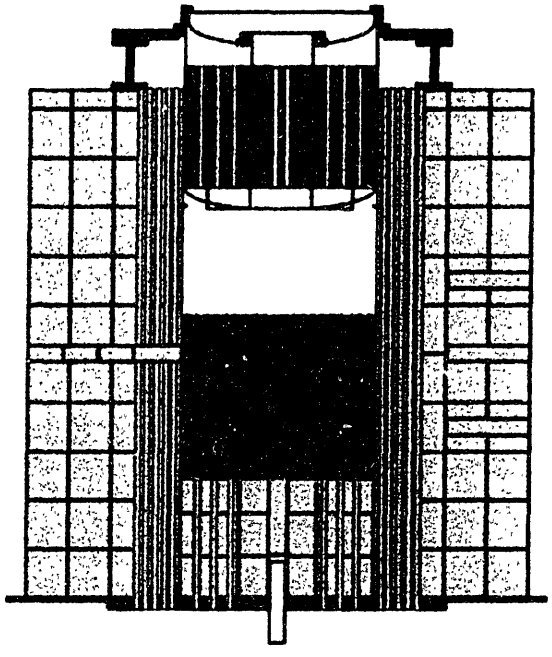


Figure 4-2. A schematic Representation of the HTR-PROTEUS Facility

4.2 Fuel and Moderator Spheres

The geometry and mass specifications of the LEU-HTR fuel spheres and moderator spheres are summarized in Table 4-2. The 6 cm-diameter fuel spheres contain TRISO coated fuel particles, with 16.7 wt% enriched UO_2, embedded in a graphite matrix. The atom densities in the fuel and moderator spheres are given in Tables 4-3 and 4-4, respectively. The presence of impurities in the graphite is approximated by a boron

content that results in an effective 2200 m/s absorption cross section of 4.79 mbarn. The presence of moisture in the spheres is ignored in these specifications, because the moisture content was shown to be less than 0.01 wt%. The diameter and mass of the fuel pebbles was measured at the beginning and end of the experiments to address concerns regarding the potential erosion of the graphite during loading and unloading operations. No change in mass occurred, although some surface indentation was observed. [4-4]

Table 4-2
LEU-HTR Fuel and Moderator Sphere Data

Property	*Value*	
Mass of uranium per fuel pebble	5.966	g
^{235}U mass per fuel pebble	1.000	g
Mass of carbon per fuel pebble	193.1	g
Radius of fuel pebble fuelled zone	2.5	cm
Radius of fuel/moderator pebble	3.0	cm
Radius of UO_2 fuel kernel	0.02510	cm
Thickness of carbon buffer coating	0.00915	cm
Thickness of inner PyC coating	0.00399	cm
Thickness of SiC coating	0.00353	cm
Thickness of outer PyC coating	0.00400	cm
Density of UO_2 fuel	10.88	g/cm^3
Density of carbon buffer coating	1.100	g/cm^3
Density of inner PyC coating	1.900	g/cm^3
Density of SiC coating	3.200	g/cm^3
Density of outer PyC coating	1.890	g/cm^3
Number of CFPs per fuel sphere	9393	
Mass of carbon in moderator sphere	189.1	g
Radius of moderator sphere	3.0	cm

Table 4-3
Atom Densities in HTR-PROTEUS Fuel Spheres

Nuclide	*Atom Density (nuclei/barn-cm)*		
	UO_2 kernel	*Graphite Matrix*	*Graphite Shell*
^{10}B	0.0	2.45968e-08	2.47855e-08
^{11}B	0.0	9.96296e-08	1.00394e-07
Carbon	0.0	8.57982e-02	8.64563e-02
Oxygen	4.86157e-02	0.0	0.0
Silicon	0.0	4.94711e-04	0.0
^{235}U	4.11729e-03	0.0	0.0
^{238}U	2.01906e-02	0.0	0.0

Table 4-4
Atom Densities in HTR-PROTEUS Moderator Spheres

Nuclide	*Atom Density (nuclei/barn-cm)*
^{10}B	2.40326e-08
^{11}B	9.73442e-08
Carbon	8.38302e-02

4.3 The Stochastic Cores

As summarized in Table 4-5, a total of eleven cores were investigated during the HTR-PROTEUS experimental program. The majority of the cores utilized deterministic sphere arrangements, which facilitated the studying of effects such as neutron streaming, moderation and water ingress (simulated with polyethylene rods) because of the easy access to the core. Moreover, because k_∞ and the related spectral indices are independent of the pebble-bed geometry, it was possible to use the deterministic cores for the zero-leakage neutron balance measurement. [4-5]

However, criticality measurements were also carried out on three stochastic cores (4.1, 4.2 and 4.3), which used a 1:1 fuel-to-moderator (F/M) sphere ratio to achieve criticality

at a reasonable core height. The experimental results for these cores are summarized in Table 4-6 (the control-rod reactivity worths were also measured but are not reported here) [4-2]. The reported k_{eff} are on the order of 1.013, because of corrections for various experimental effects and control-rod insertions needed to maintain criticality [4-6].

Table 4-5
HTR-PROTEUS Experimental Core Configurations

Core	*F/M*	*Packing*	*Prominent Feature*
1	2:1	HCP†	Used Zebra Cd/Al shutters instead of control rods.
1A	2:1	HCP	
2	2:1	HCP	Investigated influence of upper reactor cavity.
3	2:1	HCP	Water ingress using 8.9 mm OD polyethylene rods.
4	1:1	Random	Stochastic cores.
5	2:1	POP‡	
6	2:1	POP	Simulated water ingress with polyethylene/copper rods.
7	2:1	POP	Water ingress using 8.3 mm OD polyethylene rods.
8	2:1	POP	Partial water ingress using 15 cm-long polyethylene rods.
9	1:1	POP	
10	1:1	POP	Water ingress using 6.5 mm OD polyethylene rods.

† Hexagonal Close Packed; ‡ Point-on-Point (column hexagonal).

Table 4-6
Experimental Results for HTR-PROTEUS Stochastic Cores

Parameter	*Core 4.1*	*Core 4.2*	*Core 4.3*
k_{eff}†	1.0134 ± 0.0011	1.0129 ± 0.0010	1.0132 ± 0.0010
Critical loading (F, M)	5020, 5020	4940, 4940	4900, 4900
Critical height	1.58 ± 0.01 m	1.52 ± 0.01 m	1.50 ± 0.01 m
Neutron flux	5×10^7 n/cm^2/s	5×10^7 n/cm^2/s	5×10^7 n/cm^2/s
Air temperature	19.8°C	19.6°C	21.2°C
Air pressure	975 mbar	980 mbar	980 mbar
Humidity	44%	50%	50%

† Corrected for the presence of control rods in the radial reflector.

The packing fractions of the three cores differed because the spheres were loaded differently [4-7]. Core 4.1 was prepared by clamping the fuel and moderator sphere delivery tubes together in parallel, and each sphere was allowed to fall into the core from its respective tube. To avoid any unwanted ordering effects, a second method was used to load cores 4.2 and 4.3 for which the fuel and moderator sphere channels were combined by means of a simple funnel arrangement. The pebble bed was lightly flattened after each loading step, and its height was determined by measuring the average distance from the safety ring to the bottom of a rod placed horizontally on top of the core. A 1 cm error is associated with this procedure at the 1σ confidence interval.

4.4 The MCNP4B Model

A detailed MCNP4B model of the HTR-PROTEUS facility was prepared based on the calculational benchmark specifications given in Reference 4-4. This physics benchmark was part of the IAEA Coordinated Research Program (CRP) on the "Validation of Safety Related Reactor Physics Calculations for Low-Enriched HTGRs." To simplify the modeling task, details of the channels in the reflector tank and the absorber rods were not included in the specifications. Moreover, an equivalent core radius was provided, which proved crucial for defining a sphere exclusion zone. However, the removable upper axial reflector was modeled accurately. Figures 4-3 and 4-4 are vertical and horizontal plan views of the MCNP4B model, and further generic details of the core region appear in Chapter 3. Table 4-7 summarizes the pebble-bed lattice parameters.

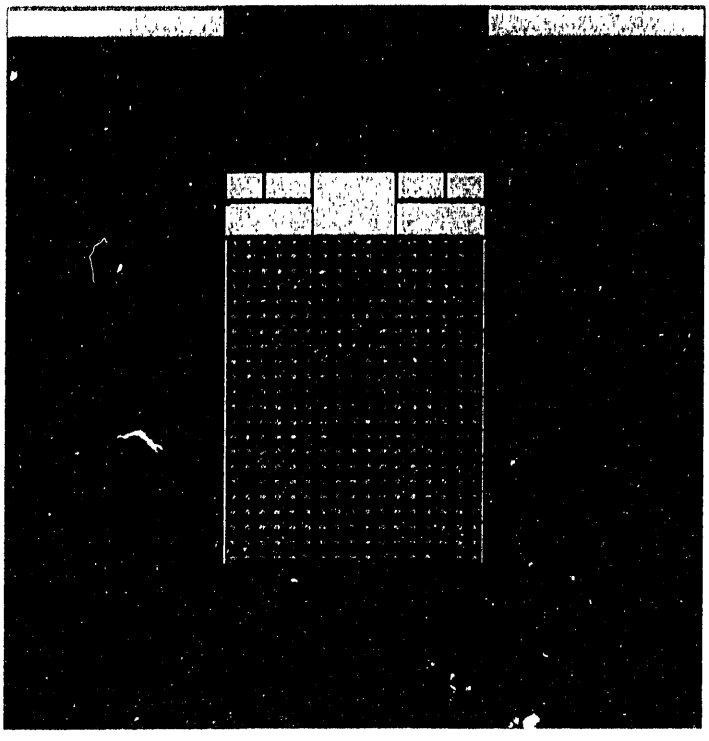


Figure 4-3 Vertical View of MCNP4B Model of HTR-PROTEUS

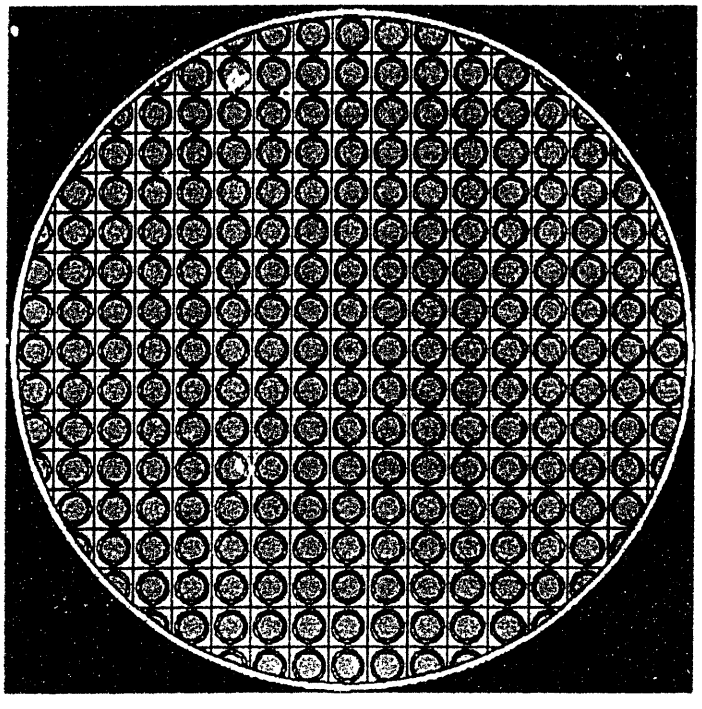


Figure 4-4. Horizontal View of MCNP4B Model of HTR-PROTEUS

A 1.5 cm sphere exclusion zone was used to compensate for the presence of partial spheres (with a 1:1 fuel-to-moderator sphere ratio) around the core periphery. The three MCNP4B models for cores 4.1 through 4.3 are included as Appendices A-1, -2 and –3.

Table 4-7
Lattice Parameters for MCNP4B Model of Stochastic HTR-PROTEUS Cores

Core	*Packing Fraction*	*Cell Size (cm)*
4.1	0.60	7.223988
4.2	0.615	7.164773
4.3	0.618	7.153160

The results of the MCNP4B criticality analyses are summarized in Table 4-8, along with the measured k_{eff} and the results of an MCNP-BALL analysis carried out by Murata [4-7]. The two sets of calculations are seen to be in excellent agreement, although the cores are predicted to be more reactive than measured. The over-estimation of the calculated k_{eff} has been attributed to the specified composition of the graphite reflector [4-6].

Table 4-8
HTR-PROTEUS Criticality Analysis

Core	*Critical Height (cm)*	*Packing Fraction*	*Effective Multiplication Constant*		
			Experiment	*MCNP4B*†	*MCNP-BALL* [6]
4.1	158	0.600	1.0134±0.0011	1.0208±0.0011	1.0206±0.0011
4.2	152	0.615	1.0129±0.0008	1.0172±0.0010	1.0168±0.0011
4.3	150	0.618	1.0132±0.0007	1.0176±0.0011	1.0172±0.0011

† Using ENDF/B-VI cross-section data evaluated at 300 K; 0.5 million neutron histories.

4.5 Summary

The HTR-PROTEUS experiments involving stochastic cores were modeled successfully using a BCC lattice and a 1.5 cm exclusion zone. The calculated critical heights of the three experiments agreed closely with the predictions MCNP-BALL, a Japanese code that models the irregularly packed pebble-bed cores exactly. Because the model was based on incorrect PSI specifications of the impurity content in the reflector, the resulting effective multiplication constants were larger than those measured by approximately 0.7% $\Delta k/k$. The correct equivalent boron concentrations were not available. The success of this modeling methodology justified its application to the analysis of the HTR-10 reactor described in Chapter 5.

5. THE HTR-10 REACTOR

The HTR-10 is an experimental 10 MW(t) pebble-bed reactor recently constructed at the Institute of Nuclear Energy Technology (INET), Beijing. The main objectives of this high-temperature gas-cooled reactor project are as follows [5-1]:

- to acquire technical expertise in the design, construction and operation of pebble-bed reactors;
- to provide an experimental facility for the testing of spherical fuel elements;
- to demonstrate the inherent safety features of the modular pebble-bed reactor;
- to develop cogeneration and closed-cycle gas-turbine technology; and
- to investigate high-temperature process heat applications.

The safe operation of the reactor requires the ability to calculate accurately its neutron physics parameters using computer codes. These codes are typically validated using data from critical experiments performed both in zero-power research reactors and during the commissioning of the actual reactor. To facilitate this validation process for HTGRs, the International Atomic Energy Agency (IAEA) sponsored two benchmark problems in two separate Coordinated Research Programs (CRPs). The first was already discussed in Chapter 4. The second, which is entitled "Evaluation of High-Temperature Gas-Cooled Reactor Performance," is related to the commissioning of the HTR-10 reactor and is the subject of this Chapter [5-2].

5.1 Description of the HTR-10 Reactor

The HTR-10 is a pebble-bed reactor that uses spherical fuel elements with embedded coated fuel particles. The fuel particles contain kernels with low-enriched uranium (17% ^{235}U) whose design burnup is 80,000 MWd/t. Detailed specifications of the graphite fuel elements are given in Table 5-1. The full core consists of approximately 27,000 fuel elements randomly packed in a cylindrical cavity with a mean height of 1.97 m, a diameter of 1.8 m and a volume of 5.0 m^3. The core is surrounded by a structure consisting of a graphite reflector and a borated carbon shield. The radial reflector, which is 100 cm thick, contains penetrations for ten control rods, seven absorber ball units, three irradiation sites and twenty coolant channels. Helium gas flows up these coolant channels before reversing direction at the top of the core and flowing downward into the pebble bed. The core inlet and outlet coolant temperatures are 250°C and 700°C, respectively, at a pressure of 3.0 MPa. Vertical and horizontal cross sections of the core are shown in Figures 5-1 and 5-2.

The initial approach to critical was achieved on December 1, 2000. The discharge tube and the cone at the bottom of the core was filled with moderator pebbles, then a mixture of fuel and moderator pebbles was added randomly until the critical height was reached with the control rods fully withdrawn. The ratio of fuel balls to moderator pebbles used was 57% to 43%, and the initial loading was carried out at room temperature (15°C) and in atmospheric air. The critical loading was 9627 fuel spheres and 7263 moderator spheres for a total of 16,890 spheres [5-3].

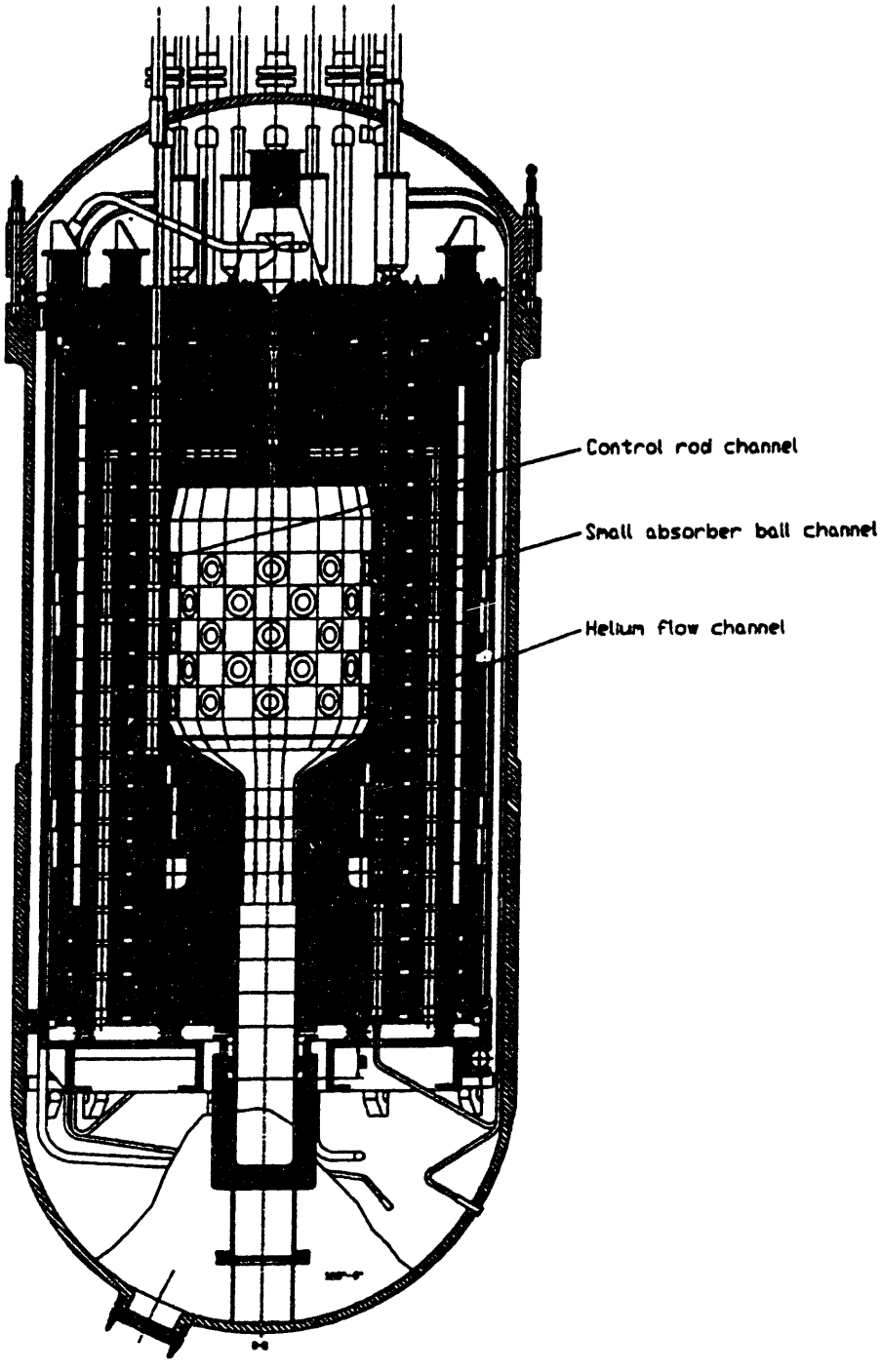


Figure 5-1. Vertical Cross Section of the HTR-10 Reactor [5-2]

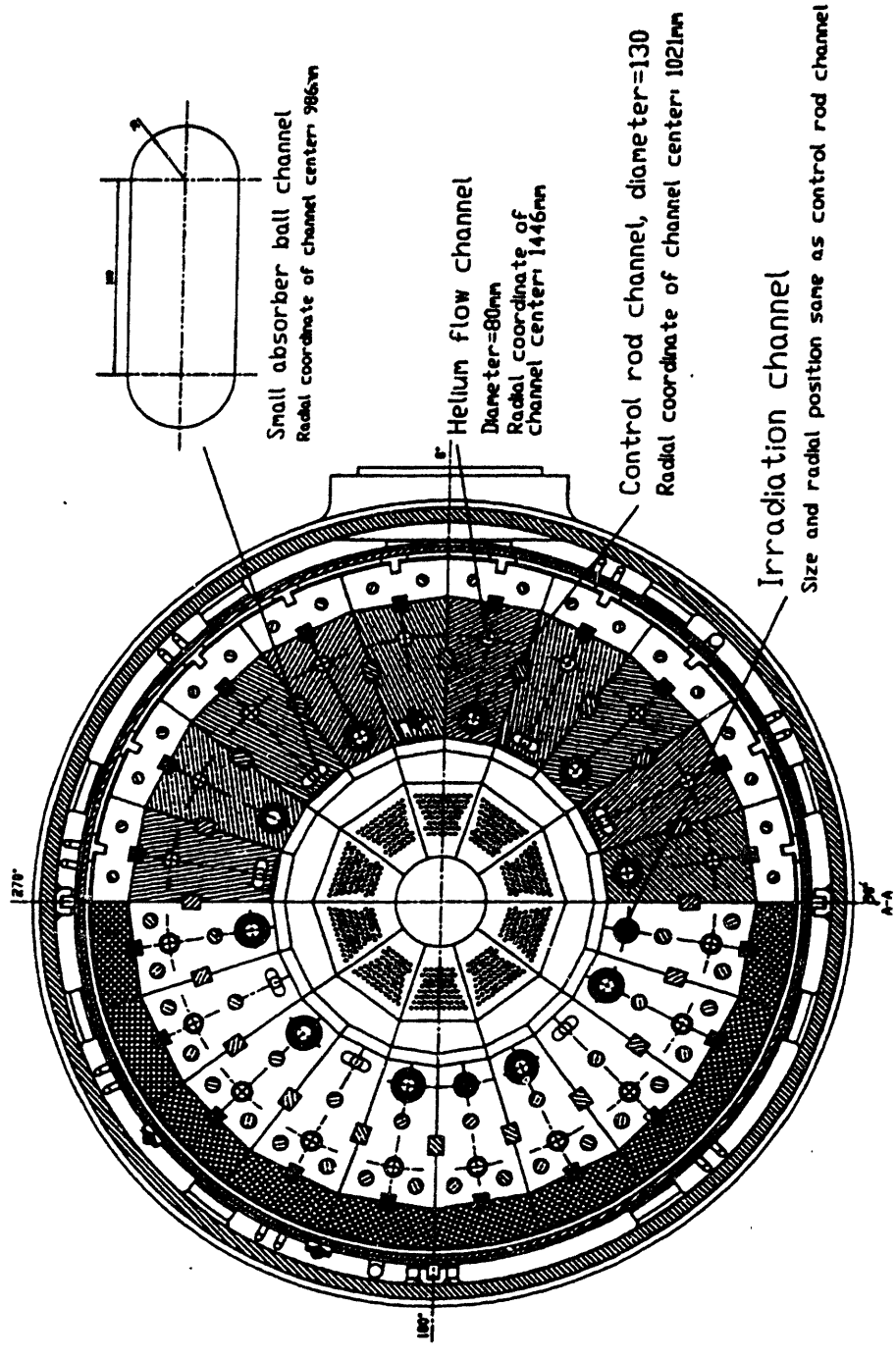


Figure 5-2. Horizontal Cross Section of the HTR-10 Reactor [5-2]

Table 5-1
HTR-10 Reactor Core Parameters

Parameter	*Value*	*Units*
Structure		
Density of reflector graphite	1.76	g/cm^3
Equivalent boron content of reflector graphite impurities	4.8366	ppm
Density of borated carbon brick (including B_4C)	1.59	g/cm^3
Weight ratio of B_4C in borated carbon brick	5	%
Moderator Pebbles		
Diameter of moderator pebble	6.0	cm
Density of graphite	1.84	g/cm^3
Equivalent natural boron content of impurities in graphite	0.125	ppm
Fuel Pebbles		
Diameter of fuel pebble	6.0	cm
Diameter of fuel zone	5.0	cm
Density of graphite in matrix and outer shell	1.73	g/cm^3
Uranium loading per fuel pebble	5.0	g
Enrichment of ^{235}U	17.0	wt. %
Equivalent natural boron content of impurities in uranium	4	ppm
Equivalent natural boron content of impurities in graphite	1.3	ppm
Volumetric filling fraction of balls in the core	0.61	
Coated Fuel Particle		
Radius of fuel kernel	0.025	cm
UO_2 density	10.4	g/cm^3
Thickness of first pyrolytic carbon coating	0.009	cm
Thickness of second pyrolytic coating	0.004	cm
Thickness of silicon-carbide coating	0.0035	cm
Thickness of third pyrolytic carbon coating	0.004	cm
Density of first pyrolytic coating	1.1	g/cm^3
Density of second pyrolytic coating	1.9	g/cm^3
Density of silicon-carbide coating	3.18	g/cm^3
Density of third pyrolytic coating	1.9	g/cm^3

With the control rods inserted, the core will then be pressurized and completely filled using the same mixture of fuel and moderator balls. The initial critical core height was chosen so as to limit the maximum excess reactivity held down by the control absorber

rods to the amount required to provide sufficient xenon override. The excess reactivity margin will be controlled subsequently by the continuous refuelling of the reactor.

5.2 Physics Benchmark Problems

INET proposed the following benchmark problems for the HTR-10 to test the accuracy of physics codes in calculating the effective multiplication factor for various pebble-bed reactor configurations [5-2]. These are designated B1, B2, B3 and B4:

a) **Problem B1**. Predict the initial cold critical loading ($k_{eff} = 1.0$), either in terms of the number of pebbles or the height of the pebble bed, with the control absorbers fully withdrawn. Assume a core temperature of 15°C and atmospheric air.

b) **Problem B2**. Calculate the effective multiplication factor, k_{eff}, of the core filled completely to a height of 1.97 m under a helium pressure of 3.0 MPa and at the following core temperatures: 20°C (**B21**), 120°C (**B22**) and 250°C (**B23**). Assume that all control absorbers are fully withdrawn.

c) **Problem B3**. Calculate the total reactivity worth of the ten control rods (**B31**) and of one control rod (**B32**) for a full core at a temperature of 20°C and a helium pressure of 3.0 MPa.

d) Problem B4. Calculate the total reactivity worth of the ten control rods (**B41**) and the differential reactivity worth of one control rod (**B42**) for a core loading height of 126 cm at a temperature of 20°C and a helium pressure of 3.0 MPa.

These calculations are to be performed for the specified fuel-to-moderator pebble ratio of 57% to 43%. The given core temperatures assume a uniform temperature profile throughout the reactor, including the fuel pebbles and the surrounding graphite structure. The height of the core refers to the fuelled portion only, *i.e.*, excluding the conus filled with moderator pebbles. The accuracy of the codes was to be determined by comparing the code predictions with measurements during the initial approach to critical and low-power physics commissioning tests at the HTR-10 facility.

5.3 Reference Core Physics Model

A simplified reactor description was included in the physics benchmark specification to provide a common starting point for the modeling of the HTR-10 with a variety of codes. Figure 5-3 shows the recommended two-dimensional model of the reactor with zone identification numbers, and Table 5-2 gives the corresponding spatially homogenized material compositions of the reactor structure.

Benchmark problems B3 and B4 require the explicit modeling of the control rods. The design of the control rod is depicted in Figure 5-4, and its geometry and material specifications are summarized in Table 5-3. Boron carbide (B_4C) is used as the neutron absorber. Each control rod contains five B_4C annular segments with outer stainless-steel sleeves, and which are joined together by stainless steel joints.

5.4 MCNP4B Model of HTR-10

The HTR-10 physics benchmark problem was specified in a manner suitable for both diffusion-theory and Monte Carlo codes. The resultant simplification of the reactor

model (see Section 5-3) reduces the accuracy with which MCNP4B can reproduce experimental measurements. Moreover, the specification of a fuel-to-moderator pebble ratio of 57% to 43% further reduces the accuracy with which the repeated-structure

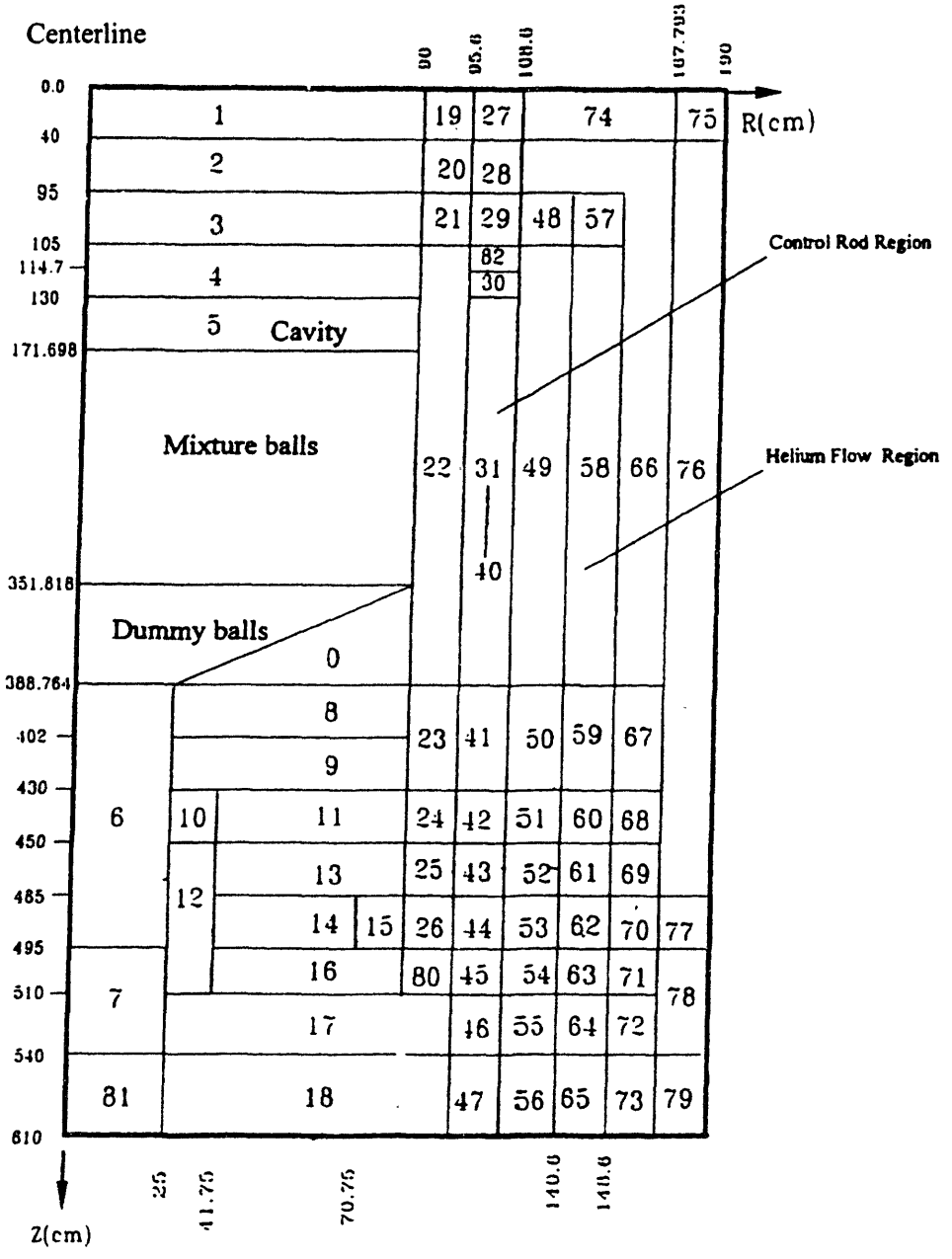


Figure 5-3. Reference Core Physics Calculation Model [5-2]

Table 5-2

Homogenized Nuclide Densities in Reflector Zones (nuclei/barn-cm)

Zone	*Carbon*	*Boron*	*Description*
0	8.51047E-02	4.56926E-07	Bottom reflector with hot helium flow borings
1	7.29410E-02	3.29811E-03	Borated carbon bricks
2	8.51462E-02	4.57148E-07	Top graphite reflector
3	1.45350E-02	7.80384E-08	Cold helium chamber
4	8.02916E-02	4.31084E-07	Top reflector
5	0.00000E+00	0.00000E+00	Top core cavity (helium filled)
6, 7	5.38275E-02	2.88999E-07	Dummy balls (= graphite with reduced density)
8	7.81408E-02	4.19537E-07	Bottom reflector structure
9	8.23751E-02	4.42271E-07	Bottom reflector structure
10	8.43647E-02	2.98504E-04	Bottom reflector structure
11	8.17101E-02	1.56416E-04	Bottom reflector structure
12	8.50790E-02	2.09092E-04	Bottom reflector structure
13	8.19167E-02	3.58529E-05	Bottom reflector structure
14	5.41118E-02	5.77456E-05	Bottom reflector structure
15	3.32110E-02	1.78309E-07	Bottom reflector structure
16	8.81811E-02	3.58866E-05	Bottom reflector structure
17, 55, 72, 74, 75, 76, 78, 79	7.65984E-02	3.46349E-03	Borated carbon bricks
18, 56, 73	7.97184E-02	0.00000E+00	Carbon bricks
19	7.61157E-02	3.44166E-03	Borated carbon bricks
20	8.78374E-02	4.71597E-07	Bottom reflector structure
21	5.79696E-02	3.11238E-07	Bottom reflector structure
22, 3, 25, 49 50, 52, 54, 66, 67, 69, 71, 80	8.82418E-02	4.73769E-07	Bottom reflector structure
24, 51, 68	8.79541E-02	1.68369E-04	Bottom reflector structure
26	8.46754E-02	4.54621E-07	Bottom reflector structure
27	5.89319E-02 (8.18911E-02)[1]	2.66468E-03 (3.70281E-03)	Borated carbon bricks
28, 82	6 78899E-02 (9.43390E-02)	1.40000E-05 (1.94542E-05)	Bottom reflector structure
29	4.03794E-02 (5.61108E-02)	1.40000E-05 (1.94542E-05)	Bottom reflector structure
30	6.78899E-02 (9.43390E-02)	3.64500E-07 (5.06505E-07)	Bottom reflector structure
31-40	6.34459E-02 (8.81637E-02)	3.40640E-07 (4.73350E-07)	Graphite reflector with control rod holes
41a	6.78899E-02 (9.43390E-02)	3.64500E-07 (5.06505E-07)	Bottom reflector structure
41b	6.78899E-02	3.64500E-07	Bottom reflector structure
42	6.76758E-02	1.25331E-04	Bottom reflector structure
43, 45	8.61476E-02	4.62525E-07	Bottom reflector structure
44	8.29066E-02	4.45124E-07	Bottom reflector structure
46	7.47805E-02	3.38129E-03	Borated carbon bricks
47	7.78265E-02	0.00000E+00	Carbon bricks
48	5.82699E-02	3.12850E-07	Bottom reflector structure
53	8.55860E-02	4.59510E-07	Bottom reflector structure
57	7.28262E-02	3.91003E-06	Bottom reflector structure
58, 59, 61, 63	7.60368E-02	4.08240E-07	Graphite reflector, cold helium flow region
60	7.57889E-02	1.45082E-04	Graphite reflector, cold helium flow region
62	7.37484E-02	3.95954E-07	Graphite reflector, cold helium flow region
64	6.60039E-02	2.98444E-03	Borated carbon bricks
65	6.86924E-02	0.00000E+00	Carbon bricks
70	8.61500E-02	4.62538E-07	Graphite reflector structure
77	7.49927E-02	3.39088E-03	Borated carbon bricks
81	7.97184E-02	0.00000E+00	Dummy balls (modeled as carbon bricks)

[1] Values in brackets are atom densities adjusted to account for channels in the graphite structure.

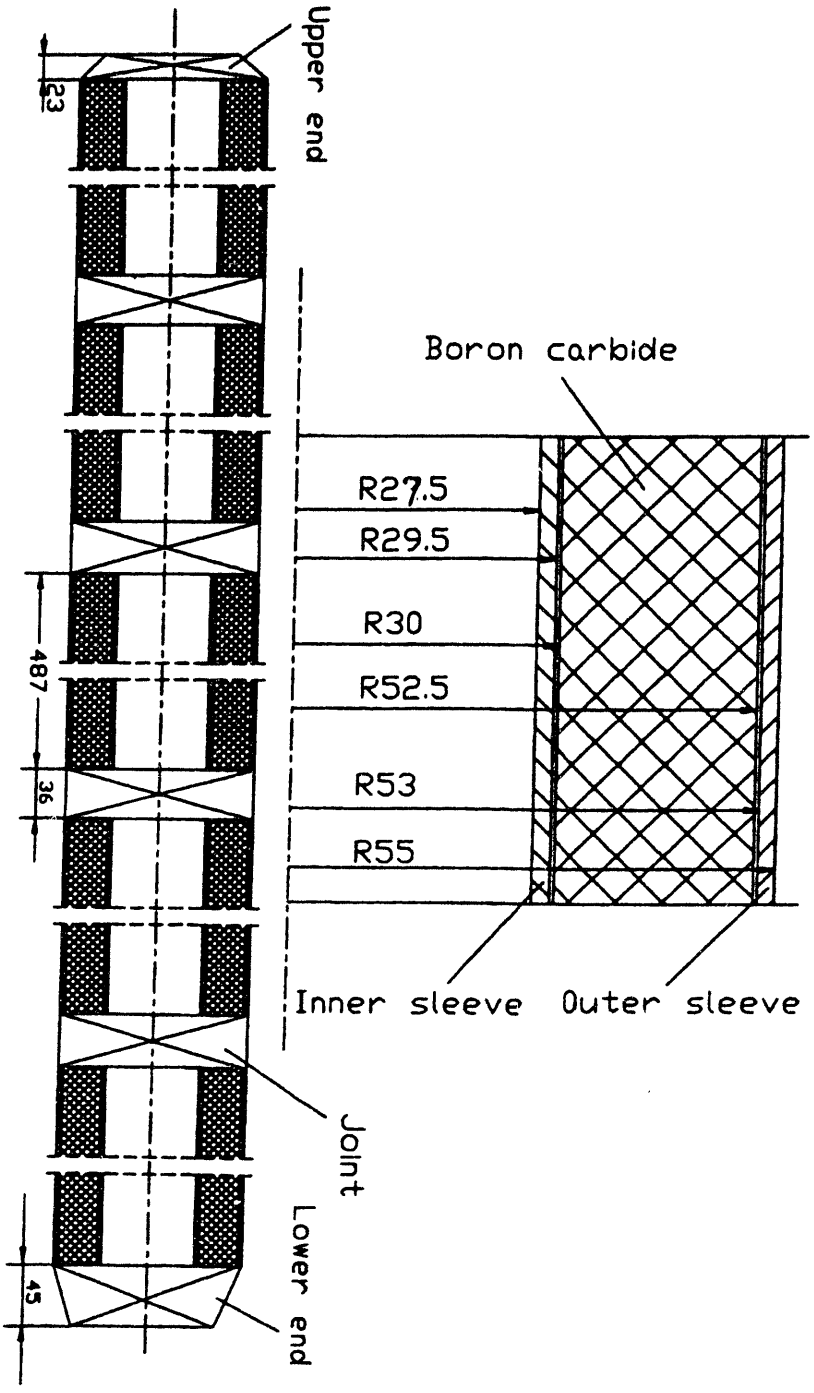


Figure 5-4. Structure of the HTR-10 Control Rod [5-2]

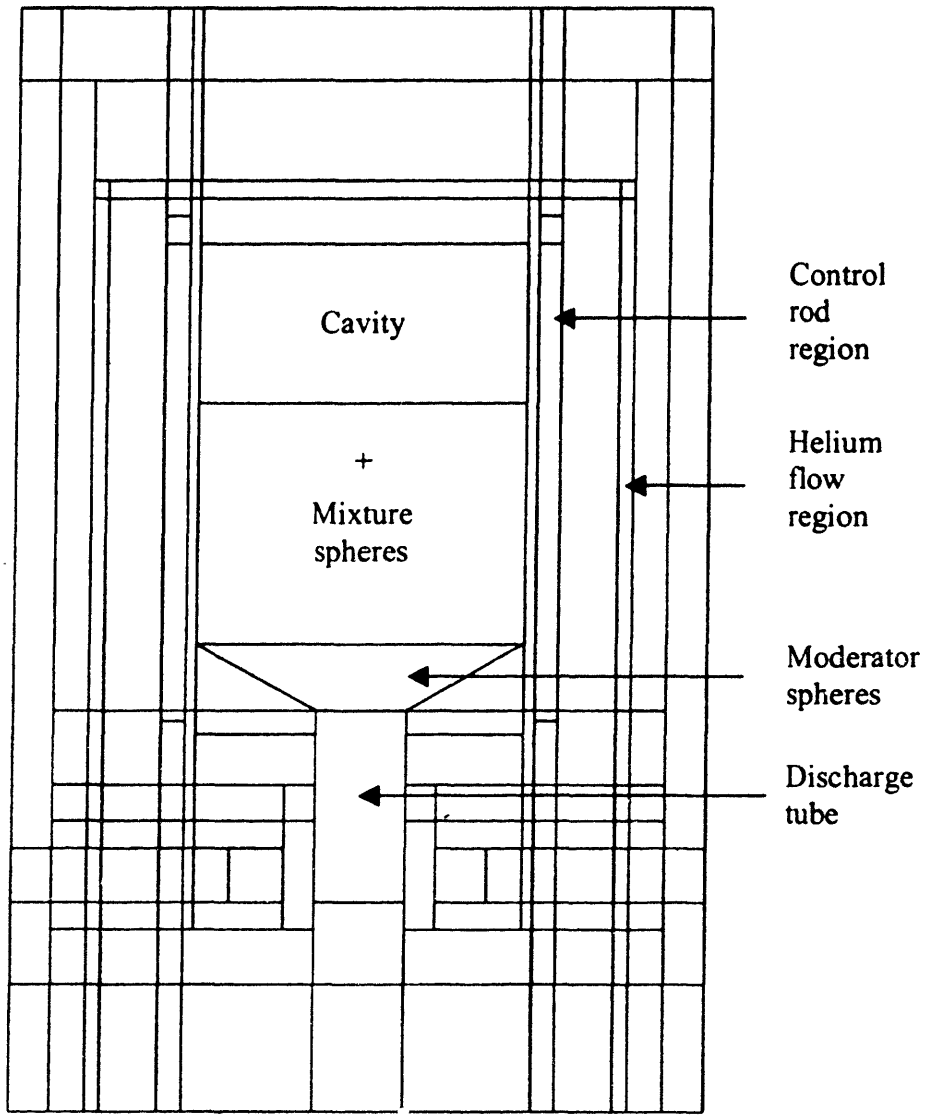


Figure 5-5. Vertical Cross Section of the MCNP Model of HTR-10

feature in MCNP4B can model the pebble-bed core, because all regular packings of mono-sized spheres except for simple-hexagonal have even coordination numbers [5-4]. This fuel-to-moderator sphere ratio was selected by INET to ensure criticality of the full core.

5.4.1 Reactor Structure

The MCNP model consists of the reactor structure, which includes the graphite reflector and the borated carbon bricks that surround the reflector, and the pebble-bed core. A vertical cross-sectional view of the modeled structure is shown in Figure 5-5. This model is identical to Figure 5-3 (including the zone numbers) except for the presence of control, irradiation and coolant channels. These channels are shown in the horizontal cross-sectional view of the reactor (Figure 5-6).

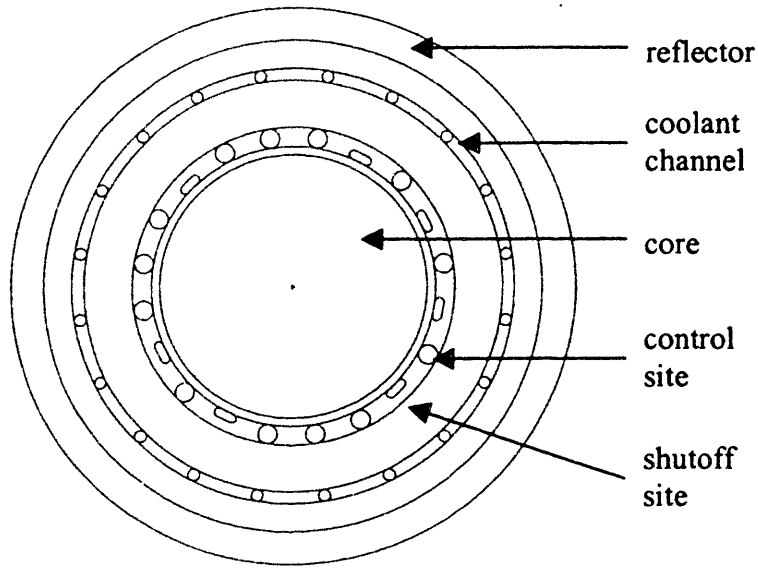


Figure 5-6. Horizontal Cross Section of the MCNP Model of HTR-10

5.4.2 Control Absorbers

Details regarding the stainless-steel joints between the control absorber segments were not included in the benchmark problem definition. The model was prepared assuming that the joints preserve the annular geometry of the absorber segments to allow coolant flow. The composition of the stainless steel is given in Table 5-3, and the geometry of the control-rod channels is otherwise modeled as specified in Table 5-4. The MCNP4B model of a control rod is shown in Figure 5-7. The vertical position of each control rod can be changed individually.

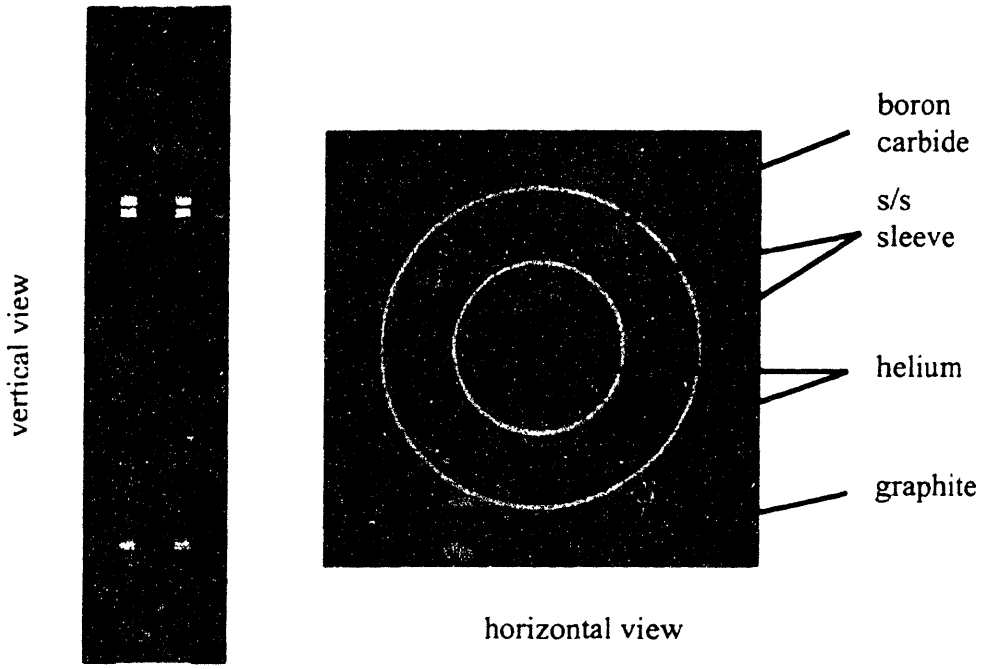


Figure 5-7. MCNP4B model of HTR-10 control rod

Since information about the control-rod drive shafts was also not provided, the control rods were modeled without such components. The absorber-ball and irradiation channels

were assumed to be empty (helium filled). The atom densities of the spatially homogenized zones that contain the various channels were corrected for the presence of these holes (shown in Table 5-2 in brackets).

Table 5-3
HTR-10 Composition of Control-Rod Stainless Steel
(density = 7.9 g/cm^3)

Element	*Wt%*
Cr	18
Fe	68.1
Ni	10
Si	1
Mn	2
C	0.1
Ti	0.8

Table 5-4
HTR-10 Control Rod Geometry and Material Specifications

Description	Value	Units
Control rod channel radius	6.5	cm
Radial position of channel centre	102.1	cm
Length of B_4C segment	48.7	cm
Length of bottom metallic end	4.5	cm
Length of metallic joints	3.6	cm
Length of top metallic end	2.3	cm
Inside radius of inner stainless-steel sleeve	2.75	cm
Thickness of stainless-steel sleeve	0.2	cm
Thickness of gap between sleeve and B_4C	0.05	cm
Thickness of B_4C annulus	2.25	cm
Density of B_4C	1.7	g/cm^3
Length of control rod	264.7	cm

5.4.3 Core

The specification of a 57:43 fuel-to-moderator pebble percent ratio for the initial HTR-10 core loading complicates the modeling of the core using the repeated-structure feature of

MCNP4B. Except for the simple (point-on-point) hexagonal packing, regular lattices constructed of simple unit cells with equal-sized spheres are characterized by even coordination numbers and, therefore, cannot be used to model an uneven fuel-to-moderator ratio while preserving the original geometry of the pebbles. As discussed in Chapter 3, three approaches are available. If a single BCC unit cell is used, then either the size or the density of the graphite moderator sphere can be reduced in a manner that reproduces the specified fuel-to-moderator sphere ratio. Alternatively, a 'super' unit cell can be used containing a total of 100 spheres, which permits the explicit loading of 57 fuel spheres and 43 moderator spheres.

In the first method, the radius of the moderator sphere is reduced from 3 cm to 2.731 cm, and the size of the unit cell must be reduced from 7.1843 cm to 6.8772 cm in order to preserve the packing fraction ($f = 0.61$). This procedure assures that the fuel loading, the mass of heavy metal per unit core volume, is the same as for the 57:43 percent random packing. The two-sphere content of the BCC unit cell minimizes the size adjustment for the moderator pebbles. The original size of the fuel sphere was maintained to preserve the effect of the single heterogeneity on the ^{238}U resonance escape probability, which is expected to dominate reactivity effects, while minimizing the perturbation due to the double heterogeneity of the lattice. This method was used for the analysis presented in this report. In the second method, which has not been attempted to date, the graphite density would have to be reduced to $\frac{43}{50} \times 1.84 = 1.58$ g/cm^3.

The super unit cell was constructed from $2 \times 5 \times 5 = 50$ unit BCC cells, with $a = 7.1843$ cm. Therefore, the repeating cell spans the following ranges: $-17.96075 \le x \le 17.96075$,

$-7.1843 \le y \le 7.1843$ and $-17.96075 \le z \le 17.96075$. Because each BCC unit cell contains two spheres, the large repeating cell holds 100 spheres in total. The 57 fuel and 43 moderator spheres were distributed deterministically but evenly among the cell lattice points. The calculated k_{eff} of the core was essentially identical to the unit BCC model (1.00081 ± 0.00080 at a core height of 128.0 cm *vs.* 1.00050 ± 0.00089 at 127.5 cm), although the execution time of the super cell model was nearly an order of magnitude longer. Because the results were generally found to be sensitive to the pattern used to distribute the spheres (see discussion in Chapter 6), the primitive unit cell approach is recommended. Details of the model may be found in the MCNP4B input file included in Appendix B.

A sphere exclusion zone was used around the sides and at the top of the core (see Chapter 3). The dimensions of the exclusion zone are $3 \times \frac{57}{100} = 1.71$ cm. An exclusion zone was not required at the bottom of the fuelled portion of the core, because the conus was filled entirely with moderator spheres. Thus, fuel spheres could be positioned such that only moderator spheres overlapped the bottom boundary of the fuelled core.

The individual TRISO coated fuel particles, which were modeled, were distributed in the fuelled region of the fuel pebbles using a simple-cubic lattice explicitly. The dimensions of the SC unit cell were chosen to reproduce the specified uranium loading of 5 g per fuel pebble. Table 5-5 summarizes the geometry specifications of the pebble-bed core as modeled with MCNP4B. Details of the MCNP4B model appear in Chapter 3.

Table 5-5
HTR-10 Model Pebble-Bed Geometry Specifications

Parameter	Value	Units
Fuel-to-moderator pebble volume ratio	1.3256	–
Radius of fuel pebble	3.0	cm
Radius of fueled region	2.5	cm
Packing fraction	0.61	–
Moderator pebble radius	2.7310	cm
BCC unit cell size	6.8773	cm
SC unit cell size	0.19876	cm

The material compositions of the fuel kernels and the graphite moderator that were used in the MCNP model are given in Table 5-6. The compositions of the pyrolytic carbon and silicon carbide layers in the TRISO coating of the fuel kernels are as specified in the benchmark problem specification (Table 5-1).

Table 5-6
Material Compositions of HTR-10 Pebble-Bed Core

Isotope	*Atom Density (1/b-cm)*
Graphite moderator:	
C	8.674169E-02
^{10}B	2.244010E-08
^{11}B	9.032424E-08
total	8.674180E-02
Fuel kernel:	
^{235}U	3.992067E-03
^{238}U	1.924449E-02
O	4.647329E-02
^{10}B	1.849637E-08
^{11}B	7.445022E-08
total	6.970994E-02

5.4.4 Boron Content

Impurities in graphite and uranium are specified in the benchmark problem definition in terms of equivalent concentrations of natural boron. The absolute isotopic abundance of ^{10}B is not given and the nominal value of 19.9% was used. This is a significant source of modeling uncertainty, since a natural variation in ^{10}B from 19.1% to 20.3% has been measured [5-5].

5.5. MCNP4B Calculations

The HTR-10 physics benchmark problems comprise a set of criticality calculations, in which the effective multiplication factor (k_{eff}) is determined for several core configurations. These configurations are achieved by varying the height of the pebble bed, adjusting the position of the control rods, or changing isothermally the temperature of the core.

Determination of the initial critical loading is subject to the uncertainty associated with the partial fuel spheres at the core boundaries. Moderator spheres play no role in the determination of the exclusion zone next to a graphite reflector. It was possible to set up the lower level of the fuelled region precisely, because the bottom of the core is filled with moderator spheres only. However, a separate correction is still required at the top of the core because of the overlapping of spheres in the BCC lattice. The critical loading is calculated using the reduced core volume, but the top exclusion distance should not be used when determining the critical height.

The total reactivity worth of the ten control rods is derived from k_{eff} values with the control rods first fully inserted and then fully withdrawn; similarly for a single control rod. The differential reactivity worth of a single control rod is determined by calculating the k_{eff} for different insertion depths. The temperature-dependent MCNP calculations in this study (benchmark problems B21, B22 and B23) did not include the reactivity effect due to the isothermal expansion of the reflector.

Benchmark problems B1, B3 and B4 were analyzed using the standard ENDF/B-VI cross-section data processed at 300 K. Benchmark problems B22 and B23, which correspond to 393.15 K (120°C) and 523.15 K (250°C) respectively, were estimated using temperature-dependent cross sections prepared at the University of Texas at Austin [5-6]. Benchmark problem B21 was analyzed using both libraries. All the cross-section libraries were originally evaluated using the NJOY nuclear data processing system [5-7].

The University of Texas cross-section libraries (UTXS) are only available at 300 K, 450 K and 558 K in the temperature range of interest. The predictions for benchmark problems B21, B22 and B23 were therefore obtained by interpolation using a polynomial fit of the k_{eff} values determined at the UTXS temperatures. Problem B21 was calculated using both the standard ENDF/B-VI and UTXS libraries in order to determine the bias associated with the different nuclear data evaluations.

In addition, the UTXS libraries do not include all the nuclides in the stainless steel used in the control rods. Instead, the UTXS cases (B21, B22 and B23) used iron with a reduced density of 5 g/cm^3 as was specified in the earlier version of the benchmark

problem definition [5-8]. The associated bias was determined by running problem B41 with the iron control rods for both the ENDF/B-VI and UTXS cross-section libraries.

The results for these cases are presented in Tables 5-7 and 5-8, and the differential reactivity worth of a single control rod appears in Figure 5-7. The results are based on 1 million (active) neutron histories per case, which reduced the estimated 1-σ statistical uncertainties to ~ 0.1%. Twenty non-active cycles, with 5000 neutrons per cycle, were used to establish a uniform source distribution.

Table 5-7
MCNP4B Simulation Results for HTR-10

Case	Critical Height (h) / k_{eff} (k)	Cross Sections	Comments
B1	h = 127.5 cm k = 1.00050 ± 0.00089	ENDF/B-VI	300 K; air ~16,841 spheres‡
	h = 128.0 cm k = 0.99964 ± 0.00084	ENDF/B-VI	He, 3 MPa ~16,907 spheres‡
B2	k = 1.12744 ± 0.00082 k = 1.12605 ± 0.00083 k = 1.12249 ± 0.00087 k = 1.11892 ± 0.00096	ENDF/B-VI UTXS UTXS UTXS	300 K 300 K 450 K 558 K
B21 B22 B23	k = 1.12806 k = 1.12446 k = 1.12005	UTXS UTXS UTXS	293.15 K; polynomial fit† 393.15 K; polynomial fit 523.15 K; polynomial fit
B31 B32	k = 0.96028 ± 0.00090 k = 1.10588 ± 0.00091	ENDF/B-VI ENDF/B-VI	$\Delta\rho_{rods}$ = 154.4 mk; 300 K $\Delta\rho_{one}$ = 14.9 mk; 300 K
B41	k = 0.85300 ± 0.00086 k = 0.84764 ± 0.00089 k = 0.85119 ± 0.00090	ENDF/B-VI ENDF/B-VI UTXS	$\Delta\rho_{rods}$ = 172.8 mk; s/s CR Equivalent iron CRs Equivalent iron CRs

† $k(T) = 1.13965 + 4.22152E\text{-}05*T + 9.08699E\text{-}09*T^2$, (T in °K); error not calculated.
‡ Actual initial critical loading was 16,890 (fuel and moderator) spheres [5-3].

Table 5-8
Calculated Differential Reactivity Worth of HTR-10 Control Rod

Insertion Depth (cm)	k_{eff}	$\Delta\rho$ (mk)†
0.000	1.01195 ± 0.00091	0.00
111.118	1.00895 ± 0.00089	-2.94
159.818	1.00429 ± 0.00094	-7.54
163.418	1.00390 ± 0.00085	-7.92
212.118	0.99704 ± 0.00081	-14.78
213.918	0.99724 ± 0.00086	-14.58
215.718	0.99611 ± 0.00087	-15.71
217.518	0.99565 ± 0.00085	-16.18
264.418	0.99497 ± 0.00087	-16.86

† mk = 1000 × Δk/k

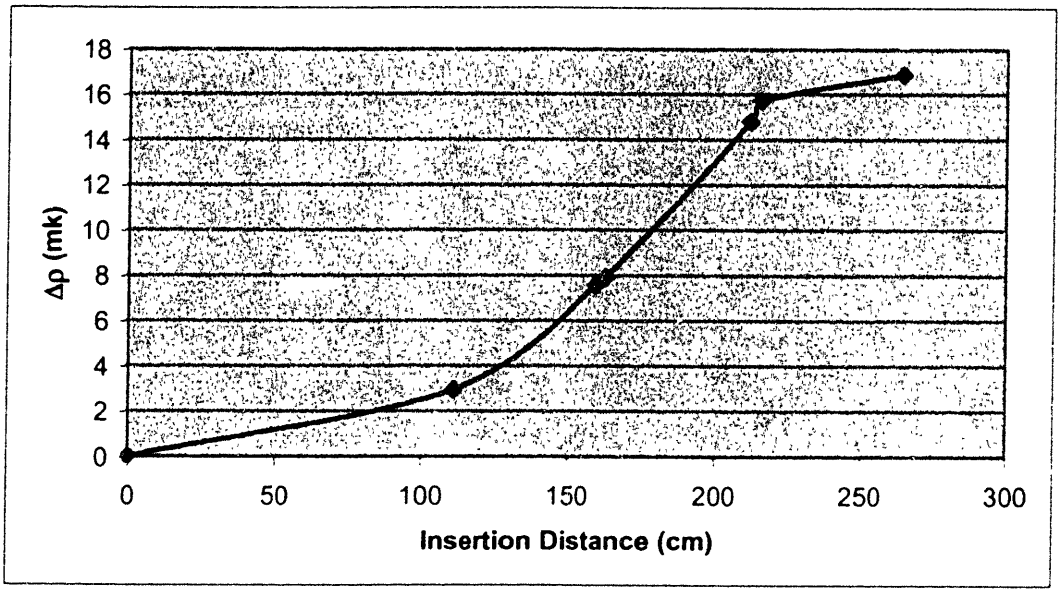


Figure 5-8. Calculated Differential Reactivity Worth of a Control Rod

5.6. **Discussion**

Tables 5-9 and 5-10 summarize the preliminary HTR-10 physics benchmark results reported at the IAEA Research Coordination Meeting for the Coordinated Research Project on the "Evaluation of High Temperature Gas-Cooled Reactor Performance," held

October 18-22, 1999, in Beijing [5-1]. Both diffusion-code and MCNP results calculated by several international organizations are shown.

There is considerable uncertainty in the prediction of the initial critical loading with MCNP4B, because of the approximations needed to account for the partial spheres at core boundaries. The approach followed at MIT has been to model the pebble bed as accurately as possible within the limitations of the regular lattice representation of the irregularly packed core. However, the randomness of the core also leads to the cancellation of errors, which allows coarser approximations. For example, the MCNP4A model developed at INET uses a simple hexagonal lattice and ignores partial spheres; the smaller packing fraction and the more leaky core appear to compensate for the additional fuel.

Table 5-9
Diffusion Code Benchmark Results by Other CRP-5 Participants

Case	China[1]	Indonesia/Japan[2]	Russia[3]	Comments
B1	125.81 cm	107.0 cm	179.6 cm	Critical height
B21	1.1197	1.2193	1.0290	k-eff 20°C
B22	1.1104	1.1983	1.0112	k-eff 120°C
B23	1.0956	1.1748	0.9938	k-eff 250°C
B31	152.4 mk	–	146.6 mk	All CRs - full core
B32	–	–	–	CR1 - full core
B41	182.7 mk	–	–	All CRs - 126 cm
B42	16.2 mk	–	–	CR1 - 126 cm

[1]VSOP [5-9]; [2]DELIGHT/CITATION-1000VP [5-10, 5-11]; [3]WIMS-D4/JAR [5-12]

Table 5-10
MCNP Benchmark Results for Other Participants and MIT

Case	China[1]	Russia[2]	MIT[3]	Comments
B1	126.116 cm	164.6 cm	127.5 cm	Critical height
	16,821	–	16,890	Critical loading
B21	–	1.0364 ± 0.0008	1.1261 ± 0.0008 [(4)]	k-eff 20°C
B22	–	1.0198 ± 0.0008	1.1225 ± 0.0009 [(4)]	k-eff 120°C
B23	–	1.0005 ± 0.0009	1.1189 ± 0.0010 [(4)]	k-eff 250°C
B31	165.6 mk	167.1 mk	155.9 mk	All CRs - full core
B32	14.1 mk	–		CR1 - full core
B41	193.6 mk	–	181.2 mk	All CRs - 126 cm
B42	17.9 mk	–	16.9 mk	CR1 - 126 cm

[1]MCNP4A and ENDF/B-V; [2]MCNP4A and ENDF/B-VI; [3]MCNP4B and ENDF/B-VI ([4]UTXS).

There is clearly large variation in the overall benchmark results. Nevertheless, there is excellent agreement between the MIT criticality calculations using MCNP4B and the VSOP predictions at INET. This lends credibility to the MIT modeling approach because VSOP had been previously validated through usage at the AVR and THTR. However, the absence of planned flux measurements in the HTR-10 reflector precludes the opportunity to test the ability of MCNP4B to model deep neutron penetration in graphite.

The analysis of the HTR-10 initial core using MCNP has identified several deficiencies in the definition of the physics benchmark problem. The isotopic composition of natural boron in the graphite moderator and reflector has not been specified. Similar uncertainty is believed to be the main reason for the inaccurate prediction of initial criticality in the Japanese HTTR reactor. Insufficient information is provided on the design of the control rods, specifically the stainless-steel joints and the drive shaft. The presence of the control rods is completely ignored in the INET reference model, because the all-rods-out case is simulated in VSOP using a region with low density (homogenized graphite plus void).

An increase in the temperature of the reflector is expected to reduce the reactivity of the core, because the decrease in the graphite density would reduce the number of thermal neutrons scattered back into to the core. This effect was investigated for benchmark problem B23 by assuming a uniform expansion of the graphite reflector corresponding to an increase in temperature from 27°C to 285°C. The resulting decrease in reactivity of approximately 0.1% Δk/k is inconsequential.

Finally, criticality calculations using the University of Texas at Austin cross-section library (UTXS) were found to differ from the corresponding results obtained with standard ENDF/B-VI data. The UTXS-derived results are approximately 0.14 to 0.49 % Δk/k more reactive, with the worst agreement (0.49% Δk/k) observed for benchmark problem B41 in which all ten control-rods were fully inserted. The use of reduced-density iron instead of stainless steel for the control-rod sleeves appears to be an acceptable approximation, the reactivity difference being less than 0.1% Δk/k.

5.7 Summary

The MCNP4B modelling methodology described in the previous chapters was applied successfully to the HTR-10 start-up core. This work was performed at MIT as part of the US contribution to the IAEA Coordinated Research Program on the evaluation of HTGR performance. The predicted initial critical loading agreed with the actual loading within 0.3% (16,841 total spheres *versus* 16,890 measured). Measured control-rod reactivity worths were not available at this report's writing time; however, the values calculated with MCNP4B agree well with VSOP predictions reported by INET.

6. THE ASTRA CRITICAL FACILITY

A single fuelled zone, a binary mix of fuel and moderator spheres, and a circular core characterized the core configurations analyzed in the previous two chapters. A much more complicated situation is encountered in the core design of the Pebble Bed Modular Reactor (PBMR), which includes an inner reflector region made of moderator spheres and a transition zone between the pure moderator and fuel zones [6-1]. Because this represents a significant departure from other pebble-bed core designs, a set of critical experiments were commissioned by PBMR (Pty) Limited in the ASTRA facility at the Russian Research Centre–Kurchatov Institute, Moscow, on a mock-up of the annular PBMR core [6-2]. The MCNP4B analysis of these experiments is the subject of this chapter.

6.1 **Description of the ASTRA Facility**

The ASTRA facility consists of a graphite cylinder with an outer diameter of 380 cm and a height of 460 cm [6-3]. This graphite structure, which serves as both the radial and lower reflectors, surrounds an octagonal core that is located 40 cm above the bottom and with an equivalent outer diameter of 181 cm. The core was loaded stochastically with fuel, moderator and absorber spheres. A special rig was used to ensure a clear separation between an inner reflector zone, a mixed fuel and moderator zone, and an outer fuel zone [6-4]. The procedure used to fill the core resulted in random dense loading with a packing fraction of 0.636. Experiments were performed both with and without an upper reflector. The unreflected critical core height was determined to be 269 cm, which yields a height-

to-radius ratio of 3. A horizontal cross-sectional view of the facility is shown in Figure 6-1, while a vertical cross-sectional view appears in Figure 6-2.

Absorber spheres were added to fuel spheres in the ratio of 5 to 95 to compensate for the relatively high uranium enrichment (21% ^{235}U) used in the fuel spheres. The absorber spheres consisted of boron-carbide kernels embedded in a graphite matrix. Thus, the transition zone contained a 50:47.5:2.5 mixture of moderator spheres (MS), fuel spheres (FS) and absorber spheres (AS) spheres. The impurities in the graphite of the spherical elements were specified by an equivalent natural-boron content of 1 ppm (by weight). Details on the core loading and the various types of spheres appear in Tables 6-1 and 6-2 [6-3].

Table 6-1
ASTRA Core Specifications

Item	*Value (cm)*
Inside radius of inner reflector zone	5.25
Outside radius of inner reflector zone	36.25
Outside radius of mixed zone	52.75
Corner points of core octagon	(87.5, 37.5), (37.5, 87.5), (-37.5, 87.5) (-87.5, 37.5), (-87.5, -37.5), (-37.5, -87.5) (37.5, -87.5), (87.5, -37.5)
Average packing fraction	0.636
Relative amounts of fuel and absorber spheres in fuel zone	95/5
Relative amounts of moderator, fuel and absorber spheres in mixed zone	50/47.5/27.5

The facility has a large number of channels to accommodate control and shutoff absorbers, instruments and sources. The radial reflector consists of individual graphite blocks (25 cm × 25 cm × 460 cm) each with a 5.7 cm-radius axial channel, which can be

sealed using a graphite plug. There are five steel-clad boron-carbide control rods, eight similar shutoff rods and one aluminum regulating-rod.

Table 6-2
ASTRA Spherical Elements

Sphere Type	*Outer Radius (cm)*	*Fill Radius (cm)*	*Density of Graphite (g/cm^3)*	*Loading (g/sphere)*
MS	3.0	–	1.68	–
FS	3.0	2.5	1.85	2.44 U
AS	3.0	2.5	1.75	0.1 B

The Kurchatov Institute has to date provided only limited details on the geometry of these absorber rods. The control and shutoff rods consist of two sets of 15 half-height (187.5 cm) steel tubes arranged in a circle (7.6 cm radius) and held together by a spider (see Figure 6-3). The tubes contain boron carbide (B_4C) powder whose density is 1.53 g/cm^3. The overall height of the control-rod assembly is 389.9 cm. A hollow aluminum cylinder serves as the manual regulating-rod (see Figure 6-4). Specifications for the control and shutoff rods appear in Reference 6-3. The composition of the regulating rod appears in Table 6-3.

Table 6-3
ASTRA Regulating Rod Material Specification

Element	*Wt. %*
Cu	0.1 – 0.5
Zn	≥ 0.2
Si	0.5 – 1.2
Cr	0.25
Mn	0.15 – 0.35
Fe	0.5
Al	Remainder

There are six vertical experimental tubes that extend the entire height of the core: a large aluminum tube in the centre of the reflector with an inner radius of 5 cm; and five small aluminum tubes, with an inner radius of 0.5 cm, which are located in line radially 5.5 cm, 25 cm, 45 cm, 65 cm and 80 cm from the centre of the core. Four additional small experimental channels are located in the reflector along the same radial line as the in-pile tubes.

6.2 Description of Experiments Performed at ASTRA Facility

A large number of experiments were carried out on the annular pebble-bed core in the ASTRA critical facility. The goal of these experiments was to generate data suitable for the validation of computer codes used for the neutronic design of pebble-bed reactors. These experiments included the following:

- Determination of the critical height for a given core loading.
- Investigation of the total reactivity worth of control rods:
  - individual control rods,
  - dependence of rod worth on radial position in the reflector,
  - interference between control rods.
- Determination of the differential reactivity worth of a control rod.
- Investigation of the effect of varying the core height on control-rod worth with and without an upper reflector.
- Measurement of the spatial distribution of relative reaction rates in the core.
- Measurement of the reactivity worth of core components.

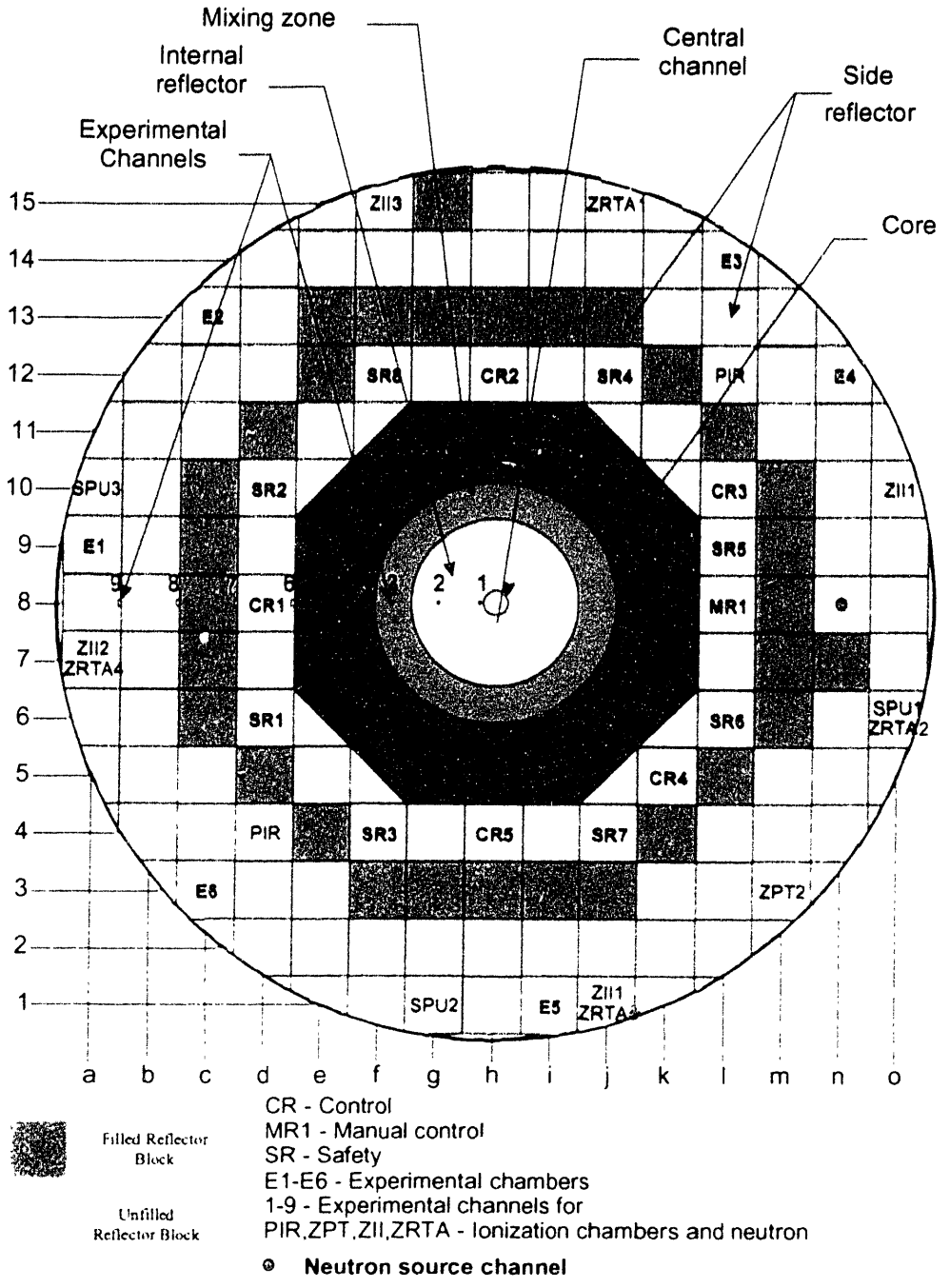


Figure 6-1. Horizontal Cross-Sectional View of ASTRA Facility [6-3]

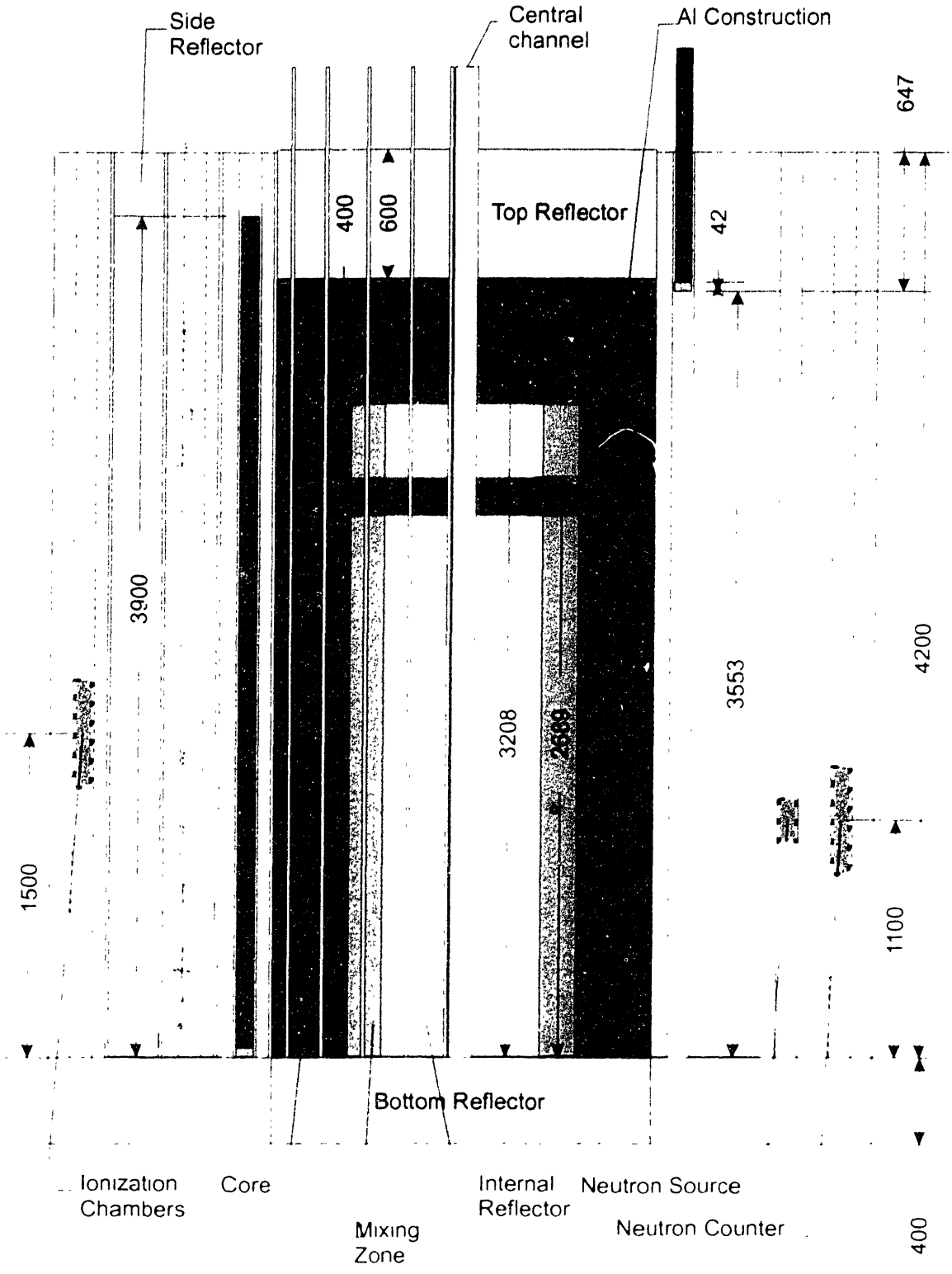


Figure 6-2 Vertical Cross-sectional View of ASTRA Facility [6-3]

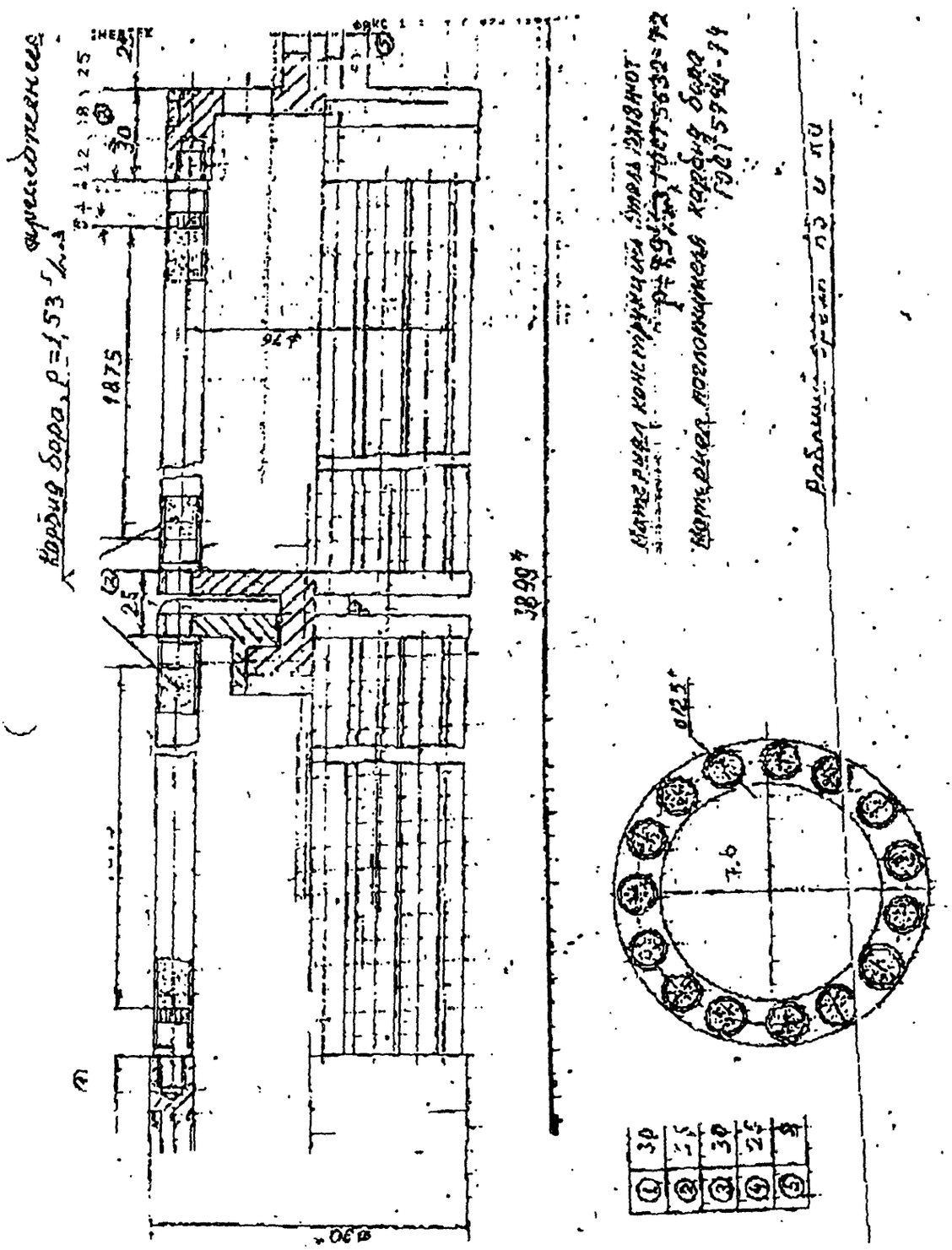


Figure 6-3. Engineering Drawing of ASTRA Control Rod

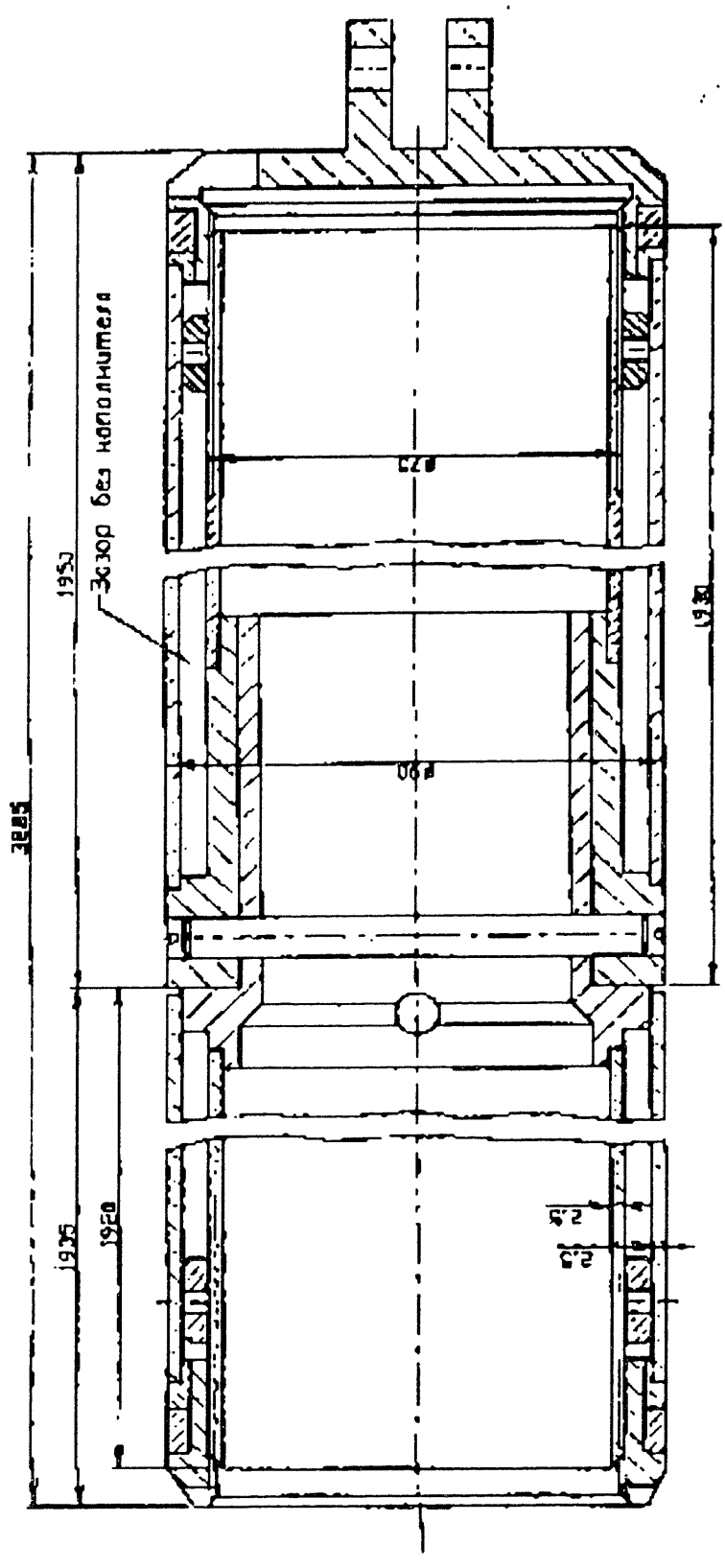


Figure 6-4. Engineering Drawing of ASTRA Manual Regulating Rod

Full details of the preliminary results of measurements and calculations may be found in References 6-4 and 6-5. As was the case for the analysis of the HTR-PROTEUS and HTR-10 in previous chapters, only experiments related to the determination of control-rod reactivity worths in the reference core are considered below [6-6]. The reactivity worths were measured using a reactivity meter based on the solution of the inverse point-kinetics equations; the accuracy of the reactivity measurement was within 0.5% β_{eff} [6-4]. Table 6-4 summarizes the basic critical configuration investigated at the ASTRA facility, which corresponds to a total of 38,584 spheres loaded according to the specifications given in Table 6-1 and without the top reflector.

Table 6-4
Basic Critical Configuration of ASTRA Facility

Item	*Value*
Number of spheres (FE/ME/AE/Total)	27,477 / 9,659 / 1,448 / 38,584
Average height of pebble bed (cm)	268.9
Position of all control rods	Fully withdrawn
Position of all shutoff rods	Fully withdrawn
Position of manual regulating rod (cm)	326.5 ± 26
Measured k-eff	1.000

6.3 MCNP4B Model of the ASTRA Facility

This section describes the model of the ASTRA facility that was developed using MCNP4B. It was possible to model the structural components of the facility very accurately, although assumptions had to be made regarding the engineering design of the control-rod assemblies. However, most of the modelling effort focused on the representation of the core. Both 'super' cell and simple BCC lattices were investigated.

6.3.1 Structural Components

A very detailed MCNP4B model of the ASTRA facility has been prepared, which reproduces accurately the structural components of the critical assembly (see Figure 6-5). Because documentation provided by the Kurchatov Institute did not include a complete description of the control-rod support structure, the model incorporates a hypothetical design of the assembly that holds the boron-carbide tubes (see Figures 6-6 to 6-12). In addition, no information was available on air humidity during the experiments. Therefore, the HTR-PROTEUS conditions were assumed to apply (see Chapter 4). Details of the MCNP4B model may be found in the input file in Appendix C.

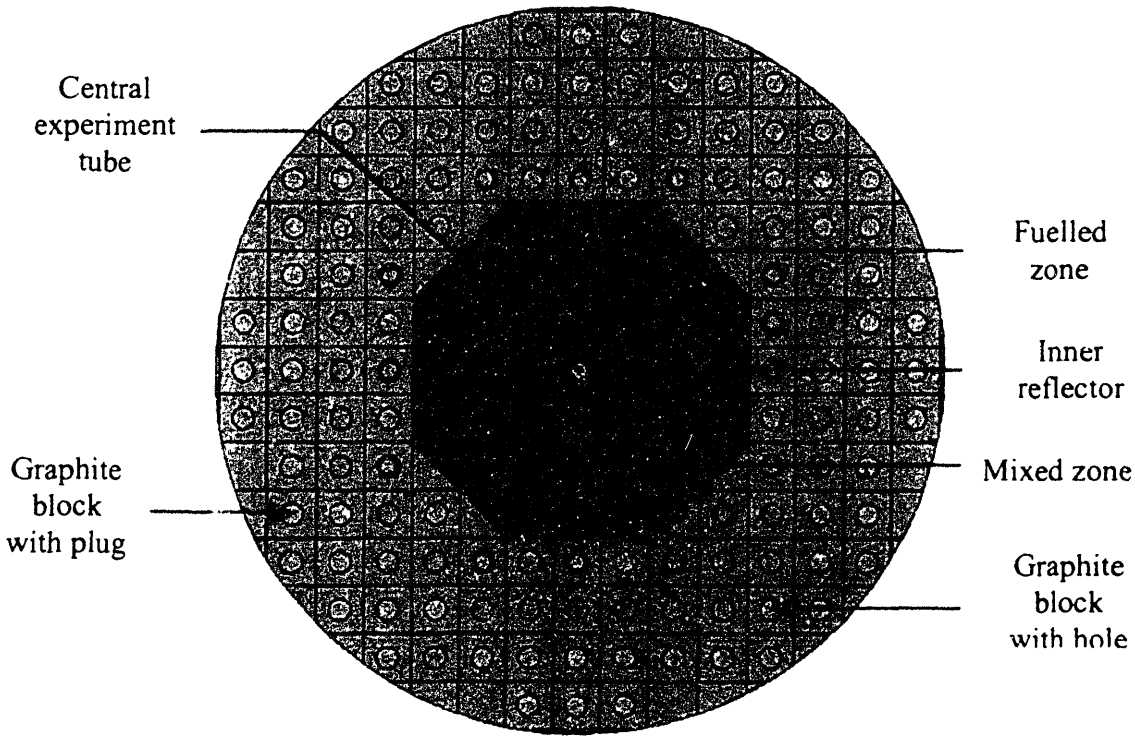


Figure 6-5. MCNP4B Model of ASTRA Facility—Horizontal View

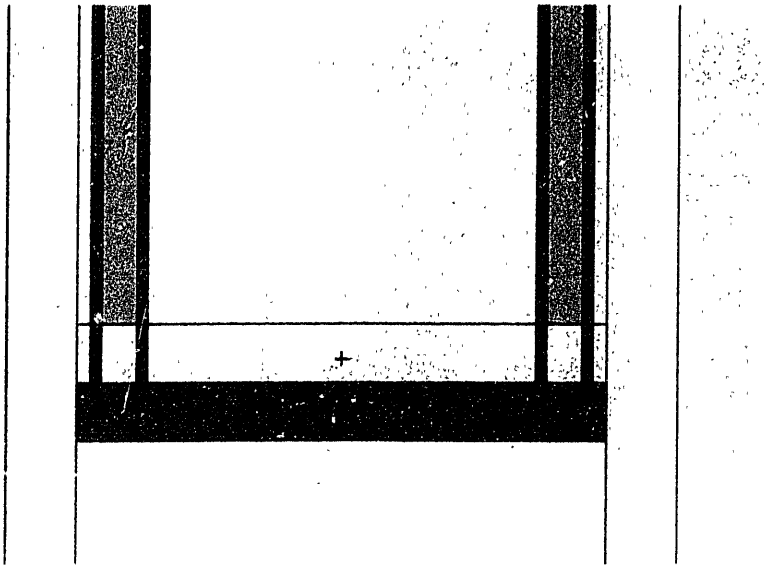


Figure 6-6. Bottom of ASTRA Control Rod---Vertical View

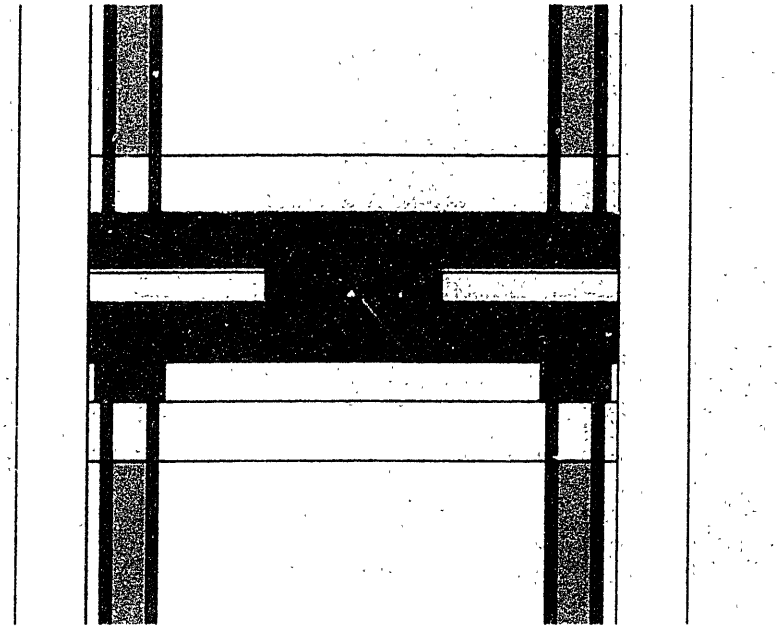


Figure 6-7. Joint Between Two Halves of ASTRA Control Rod—Vertical View

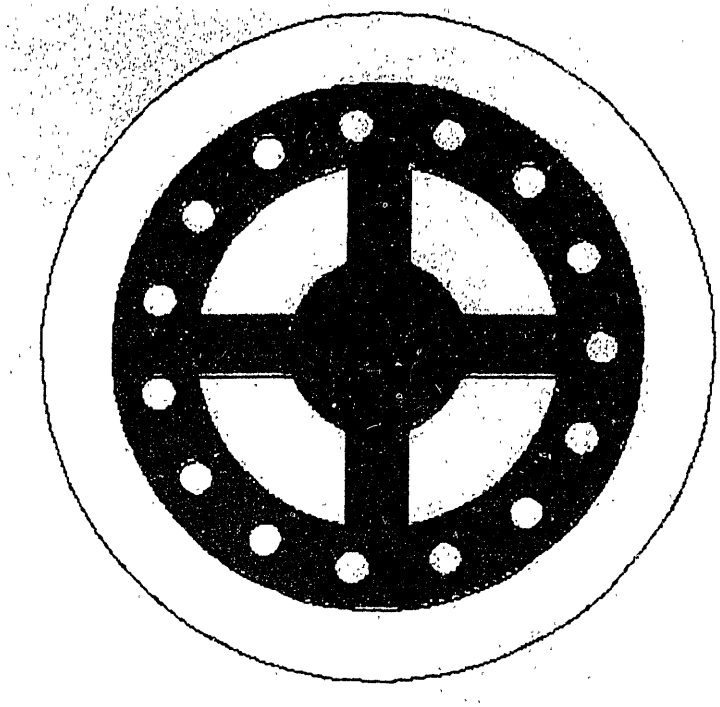


Figure 6-8. Lower Pin Holder in ASTRA Control Rod—Horizontal View

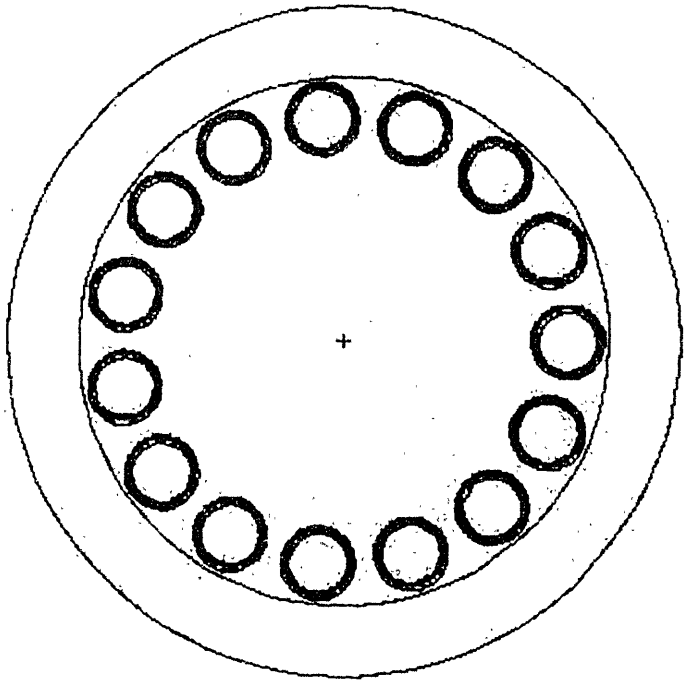


Figure 6-9. Air-Filled Section of Pins in ASTRA Control Rod--Horizontal View

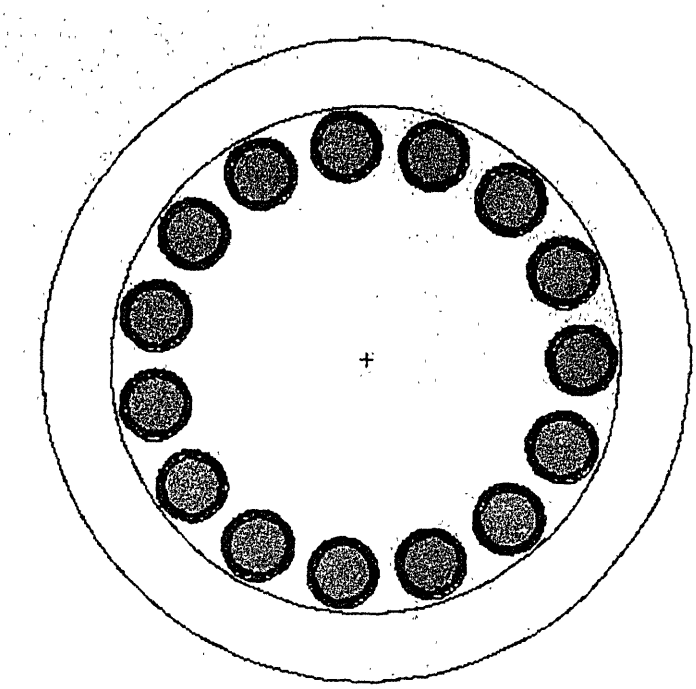


Figure 6-10. Absorber Sections of Pins in ASTRA Control Rod—Horizontal View

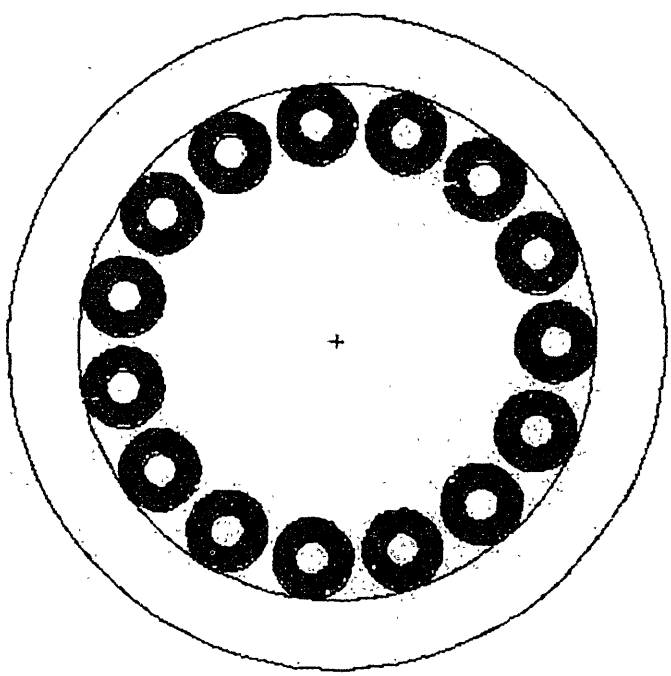


Figure 6-11. Upper Pin Holder in ASTRA Control Rod—Horizontal View

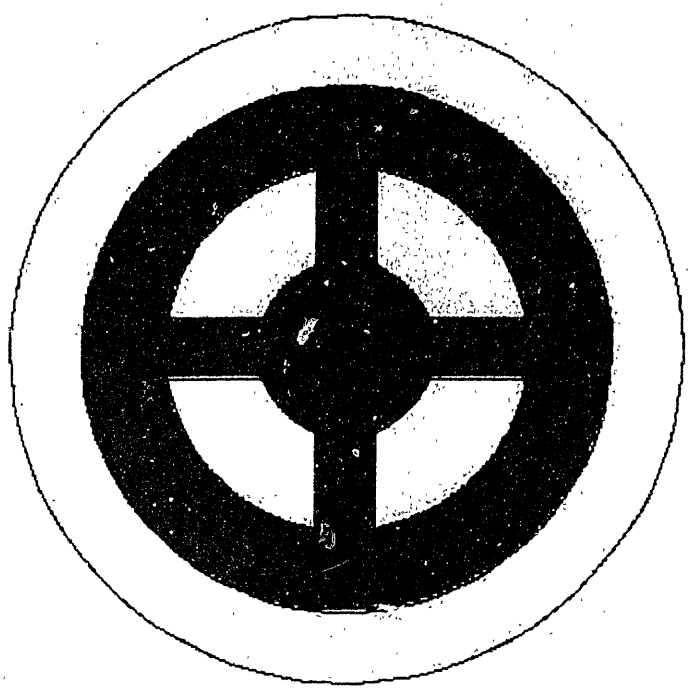


Figure 6-12. Spider at Top of ASTRA Control-Rod Assembly

6.3.2 Core

Three aspects of the ASTRA annular core must be addressed when developing the MCNP4B model. First, a regular lattice representation of the randomly packed core must be chosen that applies evenly across the three zones. The model is complicated by the presence of absorber spheres, which preclude the use of a simple BCC lattice if an exact model of these spheres is required. Second, provisions should be made for the partial spheres that arise at the periphery of the core when using the repeated-structure feature of the code. Third, the overlapping of fuel and absorber spheres at the interfaces between zones must be approximated.

The only direct representation of the mixture of moderator, fuel and absorber spheres possible is a 'super' cell containing 40 spheres. Such a repeating cell was constructed from $4 \times 5 = 20$ unit BCC cells, among which the three types of spheres were distributed. Other unit cells were also investigated, including hexagonal close packed (HCP) and body-centred tetragonal (BCT) lattices. A cell based on an HCP lattice proved to be too complex for the MCNP4B geometry routines. Moreover, because all the spheres in the HCP unit cell are located along the cell edges, the continuity of different types of spheres across cell boundaries cannot be guaranteed. The BCT lattice has been used successfully by others [6-7], but is characterized by two degrees of freedom—the width and height of the unit cell. This introduces a degree of arbitrariness into the model, because the choice of cell dimensions affects the core leakage. Therefore, the BCC unit cell was kept as the basis for the core representation, with the size of the cubic cell adjusted so as to reproduce the required packing fraction. The basic dimensions of the unit cell and other key parameters appear in Table 6-12.

Table 6-5
ASTRA Core Lattice Parameters

Parameter	*Units*	*Value*
Packing fraction	–	0.625
Spheres:		
Dimension of BCC unit cell	cm	3.5631775
X-axis range of supercell	cm	$-7.126355 \leq x \leq 7.126355$
Y-axis range of supercell	cm	$-7.126355 \leq x \leq 7.126355$
Z-axis range of supercell	cm	$-17.8158874 \leq z \leq 17.8158874$
Coated Fuel Particles:		
Dimension of SC unit cell	cm	0.124988
Absorber Kernels:		
Dimension of SC unit cell	cm	0.02072235

The repeated cell was constructed by stacking five layers of four BCC unit cells each. The loading of each unit cell depended on the core zone under consideration. Thus, in the inner reflector zone, only graphite moderator spheres appeared in the unit cells. In the fuel zone, the repeated cell consisted of eighteen fuel-only unit cells and two fuel unit cells with an absorber sphere in the centre position. The two fuel-with-absorber unit cells were located diagonally apart in the second and fourth layers of the supercell. The mixed zone repeated cell consisted of nineteen moderator unit cells with a fuel sphere in the centre position, and one moderator unit cell with an absorber sphere in the centre position. The latter unit cell was located in the third layer of the repeated cell. The exact details may be found in the MCNP4B input file in Appendix C.1, and cross-sectional views of the core appear below in Figures 6-13 to 6-15 (blue spheres are moderator, purple are fuel and green are absorber spheres).

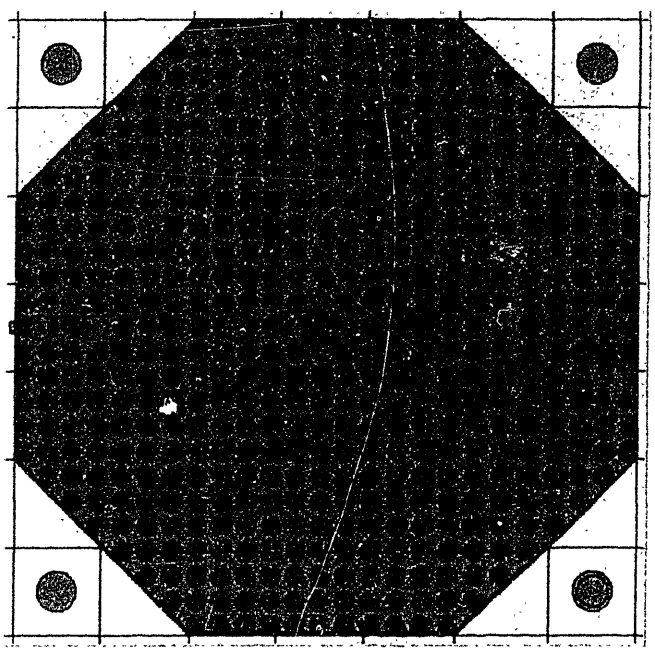


Figure 6-13. ASTRA Detailed MCNP4B Model—Horizontal View 1

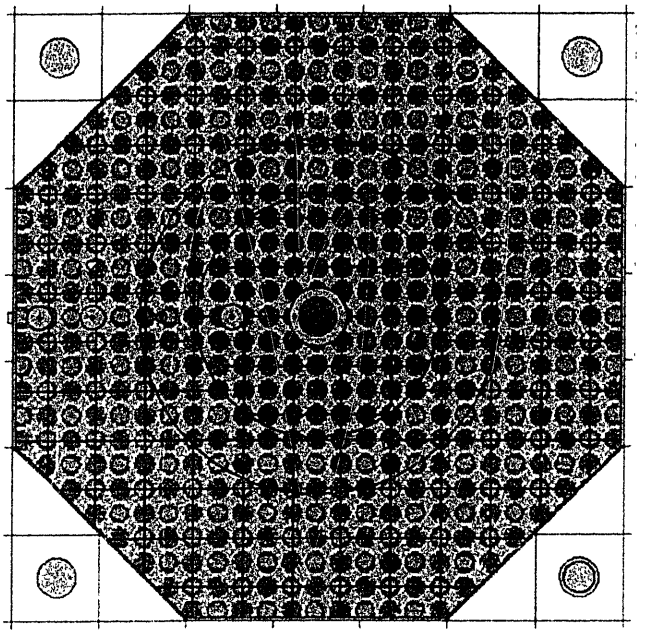


Figure 6-14. ASTRA Detailed MCNP4B Model—Horizontal View 2

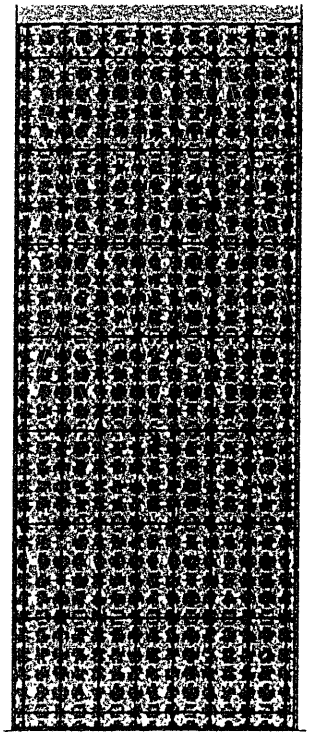


Figure 6-15. ASTRA Detailed MCNP4B Model –Vertical View

However, numerical experiments with the 'super' cell model have shown that the results are overly sensitive to the manner in which the absorber spheres are distributed within the repeated cell. This arbitrariness, as well as the long execution times, led to the conclusion that an approximate representation using a simple BCC unit cell with borated fuel spheres is more appropriate.

In the simplified model, the boron contained in the absorber spheres is smeared into the graphite shells of the fuel spheres (see Figures 6-16 and 6-17). Because of significant self-shielding among the boron carbide kernels, calculations were performed using infinite lattices of fuel spheres with explicitly modelled absorber spheres and borated fuel spheres. The boron concentration in the homogenized case was reduced by 17% in order to match the exact k_∞ results, and the same borated boron composition was used in the ASTRA model. The MCNP4B model of the infinite lattice with a 'super' cell representation of the fuelled core region appears in Appendix C.2, that of the corresponding approximate infinite lattice in Appendix C.3, and of ASTRA with borated fuel spheres in Appendix C.4.

The octagonal shape of the ASTRA core precludes the use of an exclusion zone as a means for eliminating the contribution of partial spheres at the core boundaries (see Chapter 3). However, an alternative approach is to reduce the packing fraction of the pebble bed. The packing fraction of 0.625, which is specified in the ASTRA critical facility configuration report, already appears to include such a correction. The actual packing fraction of 0.636 can be calculated from the known core loading and volume.

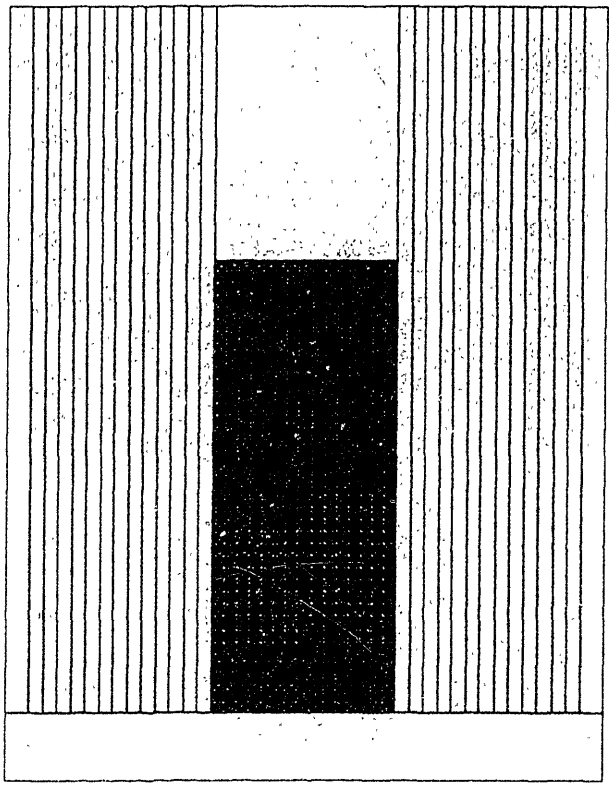


Figure 6-16. Approximate MCNP4B Model of ASTRA Facility—Vertical View

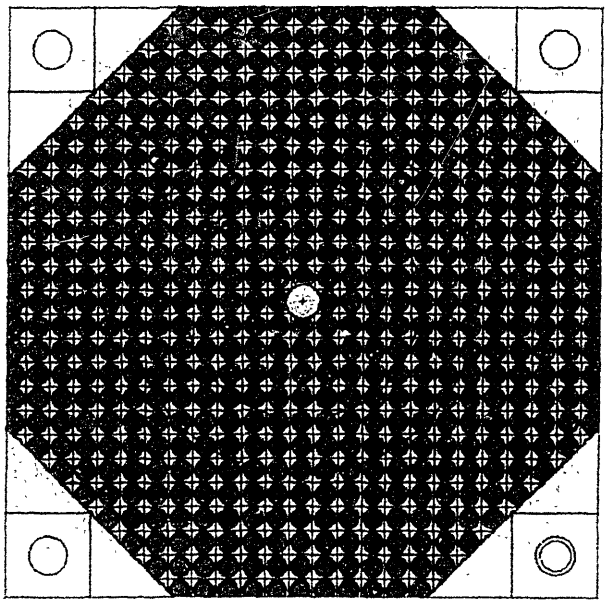


Figure 6-17. Approximate MCNP4B Model of ASTRA Facility—Horizontal View

A related modelling consideration involves the treatment of the (circular) interfaces between the core zones. Because of the overlapping of spheres and the different proportions of (borated) fuel and moderator spheres in the various zones, the boundaries between these zones should be shifted. Thus, applying the reverse approach to that used in the HTR-PROTEUS and HTR-10 models, the outer radii of the inner reflector and mixed zones are shifted inward by 1.5 cm to 34.75 cm and 51.25 cm, respectively. For example, the spheres in the fuelled zone would penetrate on average 3 cm into the mixed zone, while the fuel and absorber spheres in the mixed zone would penetrate into the fuelled zone by 1.5 cm on average. Therefore, the net inward adjustment of the interface is $3-1.5=1.5$ cm. The interface between the mixed and inner reflector zones is also shifted inwards by 1.5 cm, because of the 50% moderator sphere loading in the mixed zone. The resulting k_{eff} of the reference core confirms the validity of these modelling choices.

6.4 Results of MCNP4B Analysis

The results of the MCNP4B criticality analysis of the ASTRA core presented below were generated with the approximate model, which used fuel spheres with borated shells and no exclusion zones. The effective multiplication constant (k_{eff}) for the reference critical height of 268.9 cm was calculated to be 0.99977 ± 0.00082 with all the absorber rods fully withdrawn. All cases were run for a total of 1 million active histories from a source file generated in a separate run. The reactivity worths of individual control rods are given in Table 6-6, pairs of rods in Table 6-7, and combinations of three rods in Table 6-8. The differential reactivity worth of control rod CR5 appears in Table 6-9 and Figure 6-18.

Table 6-6

Individual Control Rod Worths in ASTRA Facility

Control Rod	*Reflector Position*	*Reactivity Worth (% Δk/k)*	
		Measured	*Calculated*
CR1	D8	-1.77 ± 0.01	-1.72 ± 0.11
CR2	H12	-1.84 ± 0.01	-1.89 ± 0.11
CR4	K5	-1.40 ± 0.01	-1.56 ± 0.11
CR5	H14	-1.83 ± 0.01	-2.01 ± 0.12
MR1	I8	-0.372 ± 0.002	-0.11 ± 0.12

Table 6-7

Reactivity Worth of Two-Rod Combinations in ASTRA

Control Rods	*Reactivity Worth (% Δk/k)*	
	Measured	*Calculated*
CR1 + CR5	-3.72 ± 0.019	-3.73 ± 0.12
CR2 + CR5	-4.01 ± 0.020	-3.97 ± 0.12
CR4 + CR5	-3.11 ± 0.016	-3.14 ± 0.12

Table 6-8

Reactivity Worths of Three-Rod Combinations in ASTRA

Control Rods	*Reactivity Worth (% Δk/k)*	
	Measured	*Calculated*
CR1 + CR2 + CR5	-6.06 ± 0.030	-6.15 ± 0.13
CR1 + CR4 + CR5	-5.16 ± 0.026	-5.36 ± 0.12
CR2 + CR4 + CR5	-5.45 ± 0.027	-5.41 ± 0.13

Table 6-9
Differential Worth of ASTRA Control Rod CR5

Control Rod Position	*Control Rod Insertion (cm)*	*Reactivity Worth (% Δk/k)*	
		Measured	*Calculated*
1	0	0	0
2	128.1	-0.0806 ± 0.0004	-0.150 ± 0.120
3	145.6	-0.149 ± 0.001	-0.234 ± 0.121
4	181.2	-0.384 ± 0.002	-0.458 ± 0.117
5	198.6	-0.545 ± 0.003	-0.759 ± 0.112
6	224.7	-0.823 ± 0.004	-0.912 ± 0.118
7	244.9	-1.058 ± 0.005	-1.248 ± 0.120
8	261.6	-1.251 ± 0.006	-1.439 ± 0.123
9	276.9	-1.404 ± 0.007	-1.525 ± 0.116
10	284.4	-1.488 ± 0.007	-1.552 ± 0.119
11	300.5	-1.622 ± 0.008	-1.765 ± 0.119
12	342.7	-1.831 ± 0.009	-2.006 ± 0.118

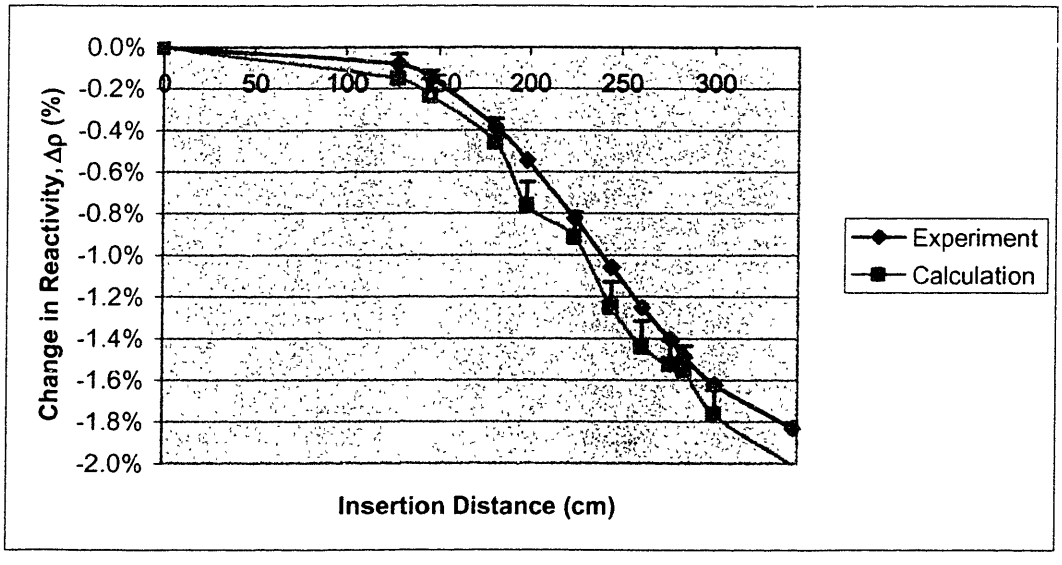


Figure 6-18. Differential Worth of ASTRA Control Rod CR5

The radial position dependence of the reactivity worths of control rods CR2 and CR4 is given in Table 6-10. Shown in the table are the reflector positions of the control rods and the distance from the core boundary.

Table 6-10
Dependence of ASTRA Control Rod Worth on Distance from Core

Control Rod	*Reflector Position*	*Distance (cm)*	*Reactivity Worth (% Δk/k)*	
			Measured[†]	*Calculated*
CR2	H12	12.5	-1.80	-1.89 ± 0.11
CR2	H13	37.5	-0.63	-0.76 ± 0.11
CR2	H14	62.5	-0.16	-0.12 ± 0.11
CR2	H15	87.5	-0.02	-0.03 ± 0.11
CR4	K5	17.7	-1.40	-1.56 ± 0.11
CR4	L4	53.0	-0.25	-0.29 ± 0.12

[†] The relative error is 2.5% (β_{eff} = 0.0072 ± 0.0002).

6.5 **Discussion**

The ASTRA critical experiments have highlighted the limitations of applying MCNP4B to the modeling of pebble-bed reactors. The ASTRA core has the following features, which were not found in the HTR-PROTEUS facility or the HTR-10 reactor: *(a)* an octagonal core vessel; *(b)* absorber spheres that make up 5% of the fuelled portion of the core; and *(c)* an annular core. Polygonal cores are not common in actual reactor designs, but absorber spheres may be required in start-up cores.

The octagonal core precluded the inclusion of a buffer zone to compensate for the appearance of partial spheres at core boundaries, and a reduced packing fraction (given by the experimenters) was used instead. The procedure used by the Kurchatov Institute to estimate the reduced packing fraction is unknown, but the resulting model correctly predicted the critical height of the core.

However, the mixing of absorber spheres with the fuel spheres complicated the construction of an exact core model considerably. The effective multiplication constant of

the core was found to depend strongly on the manner in which the relatively small number of absorber spheres was distributed in the core lattice, especially in the narrow mixed zone where the required ratio of absorber to fuel spheres is more difficult to realize because of boundary effects. The resulting variability in k_{eff} (~ ±1% $\Delta k/k$) and the long running time (~24 h) of the detailed model led to the development of a more approximate but equally accurate model, in which the boron from the boron carbide kernels was dispersed in the graphite shells of the fuel spheres.

Because dispersed boron leads to more absorptions than lumped boron carbide, its effective atom density should be reduced by an appropriate amount. The need for this correction can be demonstrated by considering the optical path of a neutron in the absorber sphere. For a spherical B_4C kernel with a diameter of 30 μm, the average chord length is $l_0 = \frac{4V_0}{S_0} = 0.002$ cm. The optical thickness for a single kernel is $\tau_0 = \Sigma_a l_0 = (83.45)(0.002) \approx 0.17$, and the thermal flux depression in the absorber kernel relative to the moderator is approximately given by the semi-empirical correlation $\frac{\bar{\phi}_m}{\bar{\phi}_a} \approx 0.87\tau_0 + \exp(-0.35\tau_0) \approx 1.09$ [6-8]. As noted earlier, the actual atom density correction of 17% was deduced from direct numerical experiments.

The annular core appears to pose a more serious computational challenge for MCNP4B partly because of the fuzzy interfaces between core zones, but also because of the greater neutronic decoupling caused by the large central reflector region and the presence of boron absorber among the fuel spheres. The decoupling was evident from the sensitivity of the MCNP4B results on the definition of starting fission source and the number of

neutron histories used to determine the effective multiplication constant. This possibly explains the differences observed in the reactivity worths of the symmetrically positioned control rods CR2 and CR5. There appears to be a flux tilt across the core, which changed the reactivity worths of CR4 and CR5 by ~10%, CR2 by 2.72% and CR1 by -2.82%. Other deviations between the calculated and measured reactivity worths are related to the uncertain design of the control rods and the manual regulating rod, which show up as biases of ~0.15% $\Delta k/k$ (see Figure 6-14) and 0.27% $\Delta k/k$, respectively.

Values of the interference coefficient ξ for the two-rod and three-rod combinations can be calculated from the results in Tables 6-6 to 6-8. The interference coefficient is defined as $\xi = \Delta R \Big/ \sum_{i=1}^{n} \rho_i$, where ΔR is the total reactivity worth of the entire rod system, ρ_i is the worth of control rod i, and n is the number of control rods in the system [6-4]. The results are presented in Table 6-11.

Table 6-11
Interference Coefficients for ASTRA Rod Combinations

Control Rods	ξ	
	Measured	*Calculated*
CR1 + CR5	1.03	1.00
CR2 + CR5	1.09	1.02
CR4 + CR5	0.96	0.88
CR1 + CR2 + CR5	1.11	1.09
CR1 + CR4 + CR5	1.03	1.01
CR2 + CR4 + CR5	1.07	0.99

As discussed in Reference 6-4, Table 6-11 shows that a complex pattern of interference exists between the control rods in the ASTRA facility. For control rods CR2 and CR5,

which are positioned symmetrically 180° apart, the interference coefficient is greater than unity ($\xi = 1.09$). Yet for control rods CR4 and CR5, which are 45° apart, the interference coefficient is less than unity ($\xi = 0.96$). The largest interference coefficient was measured for the combination of CR1, CR2 and CR5 ($\xi = 1.11$).

6.6 Summary

A detailed MCNP4B model was developed of the PBMR mock-up in the ASTRA critical facility at the Kurchatov Institute. This is an annular core composed of an inner reflector zone, a fuelled zone with 5% absorber spheres, and a transition zone with 50% moderator, 47.5% fuel and 2.5% absorber spheres. A primitive BCC lattice represents the randomly packed core, with the boron from the absorber spheres smeared into the shells of the fuel spheres. A simple-cubic lattice is used to arrange the explicitly modelled coated fuel particles inside the fuel spheres. The model predicts the critical height of the reference core exactly (0.99977 ± 0.00082), although the more neutronically decoupled annular core appears to make the spatial flux shape sensitive to the starting fission source and number of neutron histories. As a result, the reactivity worth of some control rods was predicted only within 10% of measurement. Greater accuracy would be required before this MCNP4B methodology can be applied to the annular PBMR core.

7. MCNP4B MODELLING OF PEBBLE BED CORES WITH BURNUP

The previous chapters established a method for the MCNP modelling of pebble-bed cores with fresh fuel. However, reactor design and analysis is most frequently carried out using a core with an equilibrium burnup distribution. The isotopic composition of the fuel in most reactors can be determined using a Monte Carlo burnup code like MONTEBURNS [7-1] or MOCUP [7-2], which couple MCNP4B [7-3] to ORIGEN2 [7-4]. However, the recycling of fuel spheres in pebble-bed reactors complicates this calculation considerably, because of the continuous movement and mixing of fuel in the core. An alternative approach is presented in this chapter, which utilizes a link between MCNP4B and VSOP94 [7-5]. The fuel management routine in VSOP94 is used to establish the equilibrium core, and the program MCARDS is used to prepare the corresponding MCNP4B material cards from the nuclide atom densities of the depleted fuel that were calculated by VSOP94. This method is demonstrated on the Pebble Bed Modular Reactor.

7.1 **The Pebble Bed Modular Reactor**

The 268 MW(t) Pebble Bed Modular Reactor (PBMR) currently being designed in South Africa is the latest development in the continuing evolution of pebble-bed reactors [7-6]. The advantages of modular HTGRs were already recognized by the 1980s, even though higher fuel enrichments are required to compensate for greater neutron leakage [7-7]. The inherent safety of a small reactor unit (~ 200 MWt) has the potential for significant cost reductions, because of its simpler design, standardization and the elimination of a gastight containment building. Two modular pebble-bed reactors were designed and licensed in

Germany by the late 1980s: the 80 MW(e) HTR-MODUL by Siemens/Interatom [7-8] and the 100 MW(e) HTR-100 by HRB/BBC. Interest in an inner reflector surfaced in the early 1990s, with the inclusion of a central graphite column in the 500 MW(e) Advanced High Temperature Reactor [7-9]. The ability to locate control rods in the central column of the AHTR-500 eliminated the need for the THTR-style in-core rods, which had to be pressed into the pebble bed [7-10]. An annular geometry was also proposed for increasing the power of a modular pebble-bed reactor from 200 MW(t) up to 350 MW [7-11]. The flux flattening effect of the central reflector also increases the reactivity worth of control rods located in the side reflector.

The PBMR features 18 control rods and 17 small-absorber-ball shutdown channels in the static side reflector, and a moving inner reflector created by dropping only graphite moderator spheres into the centre top of the core. Vertical and horizontal cross-sectional views of the reactor are shown in Figures 7-1 and 7-2, and detailed specifications of the PBMR reference core and fuel sphere appear in Tables 7-1 and 7-2 [7-6].

Fuel spheres are dropped into the core from nine equally spaced feeders located on a circle of 164.5 cm radius, and are removed from the core through a discharge tube at the bottom of the vessel. The fuel spheres are scanned with a γ-detector to determine the burnup and are reinserted at the top if the desired discharge burnup has not been reached.

Table 7-1
PBMR Reference Core Specifications

Parameter	*Value*
Thermal power rating	268 MW
Core diameter	3.5 m
Average core height	8.52 m
Average burnup	80,000 MWd/tU
Refuelling strategy	Multiple pass (× 10)
Fuel	8.13 at. % (^{235}U)
Average irradiation time of fuel	874 days
Number of fuel zones	2
Moderation ratio (N_C/N_U)	428
Number of fuel spheres	334,000
Number of graphite spheres	110,000
Percent fuel in central/mixed/fuel zones	0/50/100
Thickness of top reflector	1.35 m
Thickness of bottom reflector	2.61 m
Width of radial zones in side reflector	6/13/22.5/19/14.5 cm
Graphite density in top reflector	1.54 g/cm^3
Graphite density in bottom reflector	1.53 g/cm^3
Graphite density profile in side reflector	1.7/1.17/1.7/1.48/1.7 g/cm^3

Table 7-2
Reference Specifications for PBMR Fuel Elements

Parameter	*Value*
Fuel Sphere (FS):	
Pebble radius	3.0 cm
Radius of fuelled zone	2.5 cm
Uranium loading	9.0 g/FS
Graphite density	1.75 g/cm^3
Coated Fuel Particle:	
Diameter of UO_2 kernel	500 μm
Density of UO_2	10.4 g/cm^3
Coating materials	C/PyC/SiC/PyC
Layer thicknesses	95/40/35/40 μm
Layer densities	1.05/1.90/3.18/1.90 g/cm^3

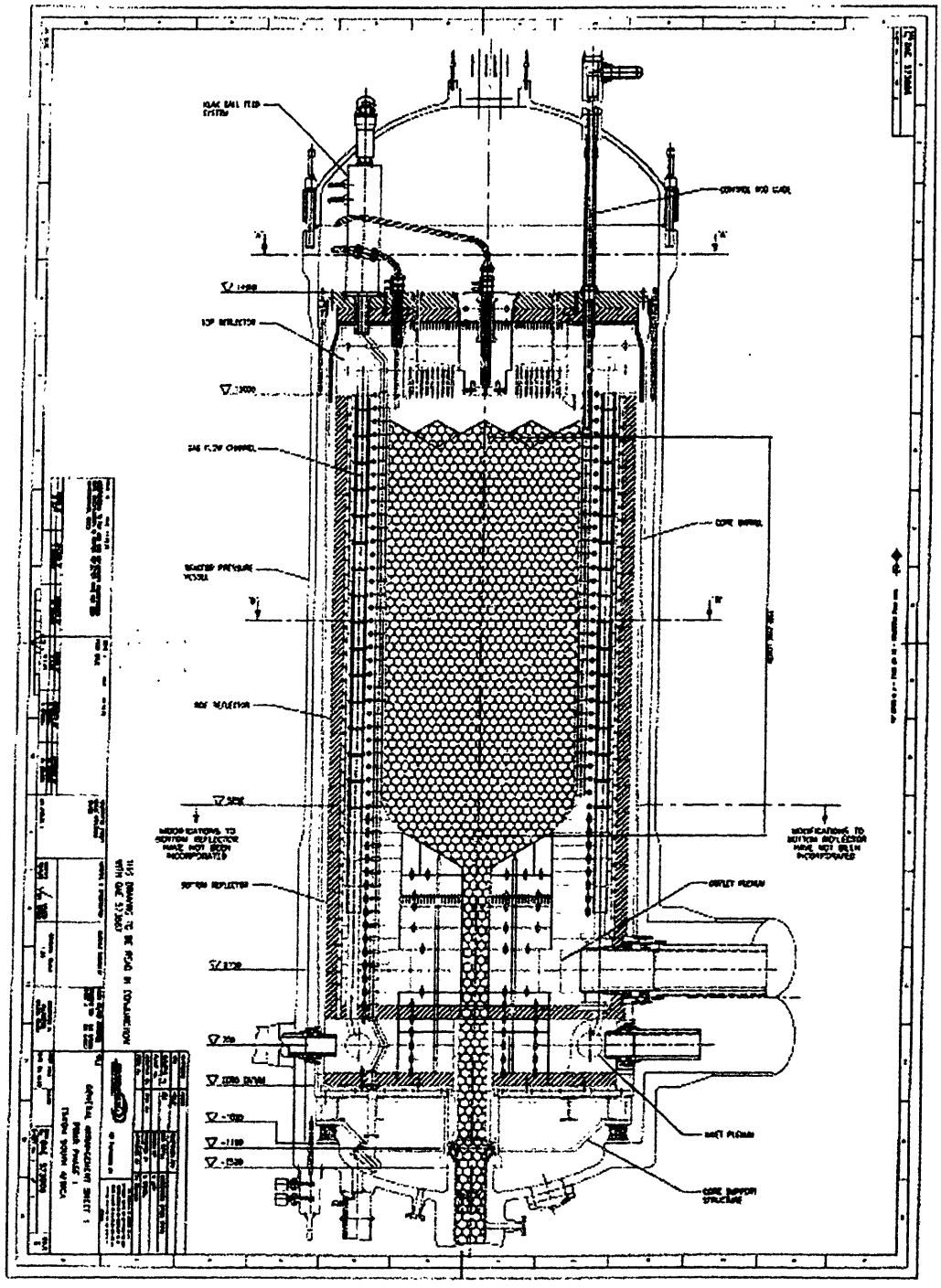


Figure 7-1. A Vertical View of the PBMR [7-6]

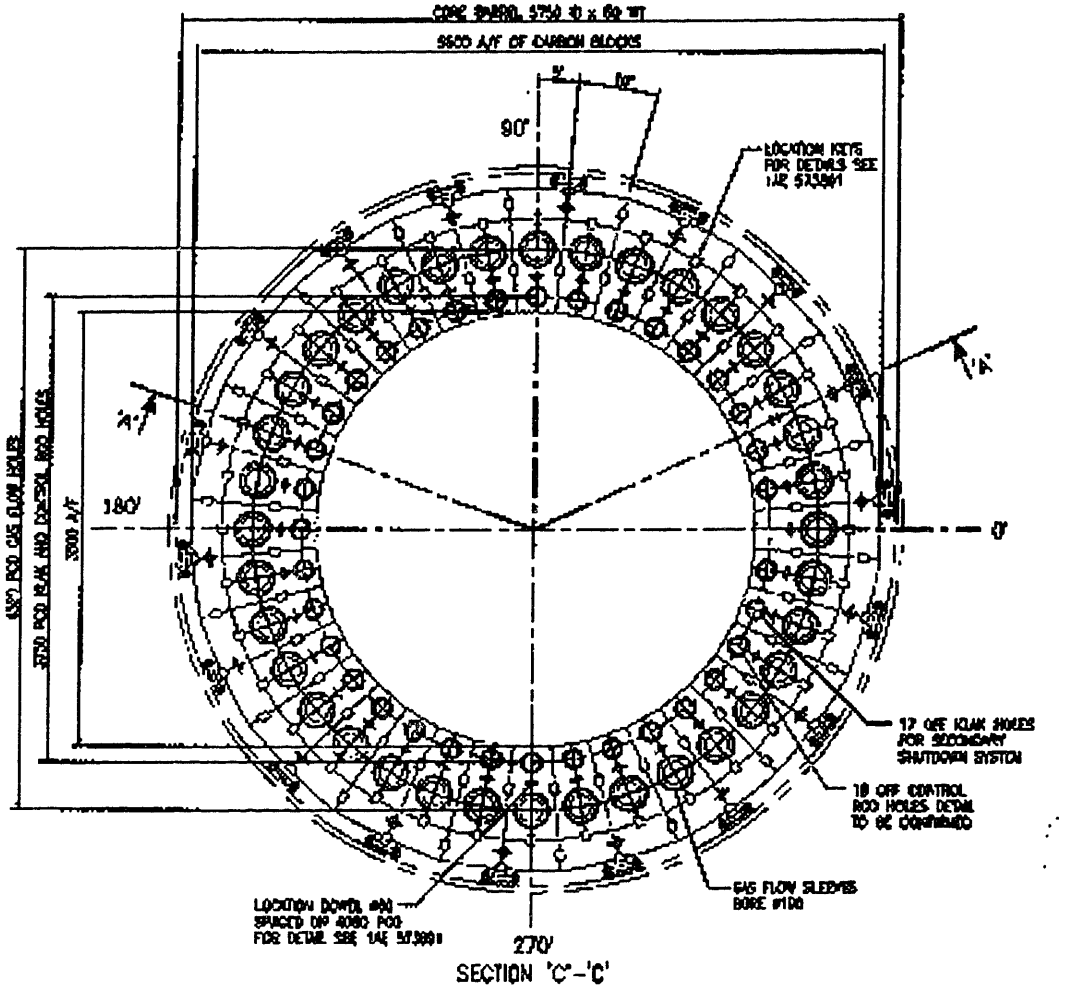


Figure 7-2. A Horizontal View of the PBMR Core [7-6]

7.2 The VSOP94 Model of the PBMR

The two-dimensional (R-Z geometry) VSOP94 model of the reference PBMR core is shown schematically in Figure 7-3 [7-6].† The model includes details of the core, the reflectors and the borated carbon thermal shields. The reactor pressure vessel, the core barrel and the associated helium gaps are lumped together in a single annular region. The

† The VSOP model of the PBMR was kindly provided by Dr. E.J. Mulder, PBMR (Pty) Limited.

control rods are modelled by homogenizing the boron carbide absorber into the surrounding graphite material. The various channels for the shutdown system and helium coolant are modelled by reducing the density of the appropriate graphite regions.

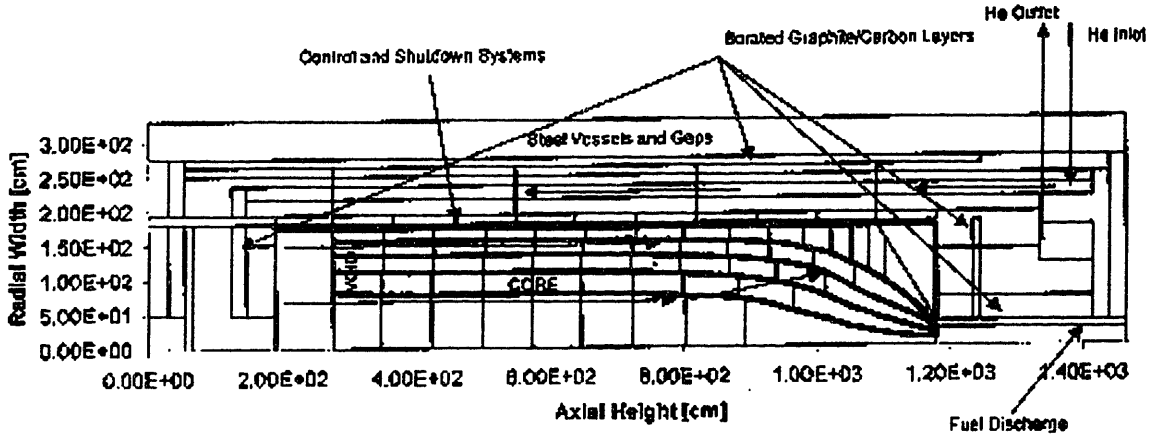


Figure 7-3. VSOP94 Model of the PBMR [7-6]

The model of the core comprises 57 equally sized regions called *layers*, each of which contains a mixture of 10 different fuel *batches*.[‡] These batches represent the number of times that the fuel spheres have been through the core, from the first pass (batch 1) to the last pass (batch 10). The burnup of each batch is calculated individually using a fission-product chain of 44 isotopes (see Table 7-3). The second member of the chain is a non-saturating fission product chosen by comparison with ORIGEN-JÜL-II code predictions, which corresponds to low absorbing fission products not modeled explicitly [7-12]. The 43 explicit fission products cover 98.02% of the total fission-product absorptions, while the non-saturating fission product accounts for the remaining 1.98%.

[‡] Each layer also contains an 11th batch in order to accommodate the presence of moderator spheres in the inner reflector.

Table 7-3
Fission Product Chain 44 in VSOP94

No.	*Nuclide*	*No.*	*Nuclide*	*No.*	*Nuclide*	*No.*	*Nuclide*
1	^{135}Xe	12	^{105}Rh	23	^{143}Pr	34	^{149}Sm
2	FP-44	13	^{105}Pd	24	^{143}Nd	35	^{150}Sm
3	^{136}Xe	14	^{108}Pd	25	^{144}Nd	36	^{151}Pm
4	^{83}Kr	15	^{109}Ag	26	^{145}Nd	37	^{151}Sm
5	^{95}Zr	16	^{113}Cd	27	^{146}Nd	38	^{152}Sm
6	^{95}Mo	17	^{131}I	28	^{147}Pm	39	^{153}Eu
7	^{97}Mo	18	^{131}Xe	29	^{148}Pm/m	40	^{154}Eu
8	^{99}Tc	19	^{133}Xe	30	^{148}Pm/g	41	^{155}Eu
9	^{101}Ru	20	^{133}Cs	31	^{147}Sm	42	^{155}Gd
10	^{103}Ru	21	^{134}Cs	32	^{148}Sm	43	^{156}Gd
11	^{103}Rh	22	^{141}Pr	33	^{149}Pm	44	^{157}Gd

Fuel depletion is modelled by means of burnup steps. Thus, approximately every 9 days, each layer and its associated batches are moved down to the position of the next layer. This movement of fuel occurs in *channels*, which are used to reproduce the characteristic flow of pebbles within the core vessel. This flow pattern was established by Pohl and Neubacher during the operation of the AVR [7-13], and from measurements performed by Kleine-Tebbe during the final defuelling of the THTR [7-14]. The layers at the bottom of the core are discharged, and corresponding batches (*i.e.*, with the same number of passes through the core) from different channels are grouped and mixed together. The batch numbers are then incremented (to initiate an additional pass through the core) and reinserted into the various channels. The oldest batches are discharged from the core, while a tenth of the volume of each top layer is filled with fresh fuel.

The neutronic calculation is performed using 29 spectral zones, which consist of user-specified groupings of layers. A similar procedure is used for the reflector regions where 25 spectrum zones are defined. The temperatures of the spectral zones are established

using the thermal-hydraulics module in VSOP94. The reference VSOP94 input file is included as Appendix D.1.

7.3 Link Between VSOP94 and MCNP4B

A convenient way to model an equilibrium pebble-bed core with MCNP4 is to perform a fuel management study with VSOP94 and transfer the resulting fuel compositions to an MCNP4B model of the same reactor. The most accurate method for establishing a link between the two codes would be to create a supercell VSOP94 model of a fuel kernel in a given layer, and deplete the fuel to the burnup determined from a separate VSOP94 fuel management study (see Section 7.6 for further details). The resulting fuel compositions could then be used in a detailed MCNP4B model of the pebble-bed core, which would include an explicit representation of the coated fuel kernels and the fuel spheres. A more approximate but direct approach is presented here, in which the nuclide densities obtained from a whole-core VSOP94 calculation are used directly in an MCNP4B model of the reactor.

An MCNP4B model of the PBMR equilibrium core was developed, which uses a regular lattice of spheres with homogenized fuel and graphite interiors. This lattice is subdivided into annular regions that reproduce exactly the core regions of the VSOP94 model. The fuel compositions used in these regions are the corresponding batch-averaged VSOP94 nuclide densities, which are adjusted to allow for the effect of fuel homogenization on resonance absorptions in ^{238}U and ^{240}Pu.

7.3.1 Modifications to VSOP94

Several modifications had to be made to VSOP94 in order to extract the necessary fuel compositions. These changes affected subroutine CH1 in chain 1 where the main problem definition data are read, and subroutine VORSHU in chain 7 where fuelling operations are simulated.

Subroutine VORSHU is called before fuel shuffling takes place. It reads instructions for the next burnup cycle, calculates average batch properties and accounts for isotope decay during the reshuffling. The subroutine was modified to calculate the total atom numbers and reaction rates for each isotope per layer, and write this information to data files FORT.98 and FORT.99, respectively. Also written to file FORT.98 is the cycle number, the layer number, the total number of all nuclides in the given layer, the volume of the layer, and the packing fraction. Two fields were added to the printout options card V21 [7-5], which specify the refuelling cycle whose fuel compositions are required. The specifications of the modified card are shown in Table 7-4, and listings of the source code are included as Appendix D.2.

7.3.2 Program MCARDS

VSOP94 output file FORT.98 contains, for each layer, the total number of all nuclides, the volume and the packing fraction. This is followed by the number of atoms for each nuclide used in the VSOP94 calculation (65 nuclides are used in the PBMR model). Output file FORT.99 contains the total absorption reaction rates that correspond to these nuclides. The FORTRAN program MCARDS reads these data and prepares an MCNP4B

material card for each layer. Because a one-to-one mapping does not exist between the nuclides available in the VSOP94 and MCNP4B libraries, ^{10}B is added such that the total absorption reaction rate in each layer is preserved. The materials cards are written consecutively to file MCARDS.DAT starting at material label M100 for the first layer with comment cards that specify the total atom density for the given layer, which can be "cut and pasted" into the MCNP4B input file. The listings of the source code are included as Appendix D.3.

7.4 MCNP4B Model of the PBMR

Because detailed engineering drawings of the PBMR were not available, the MCNP4B model was based on the two-dimensional VSOP94 model of the reactor. Key aspects of the VSOP94 model of the PBMR core and structural components were duplicated, including the pebble flow channels and layers (Figures 7-4 and 7-5).

The control rods, and the shutdown and helium coolant channels in the side reflector were modelled explicitly. However, the HTR-10 control rods described in Chapter 5 were used instead of the proprietary PBMR design (Figure 5-7). The model also uses the oval shutdown channels from the Chinese reactor (Figure 7-6). A simple BCC lattice without exclusion zones was used to represent the randomly packed pebble bed. This lattice was subdivided into layers exactly as in the VSOP94 model of the core. The spheres in each layer consisted of the homogenized mix of carbon, silicon, heavy metal and fission-product nuclides prepared with program MCARDS from the corresponding VSOP94 layer-averaged atom densities. Further details may be found in the MCNP4B input file included as Appendix D.4.

Table 7-4
Modified VSOP94 Card V21

Card V21		Format (18I4)
1	IPRIN(1)	Spectrum calculation: = 0: Thermal self shielding factors only. = 1: Same as 0, plus averaged thermal cross sections. = 2: Same as 1, plus fine-group neutron fluxes. = 3: Same as 2, plus broad-group averaged cross Sections for materials with concentration > 0. = 4: Same as 3, for all materials.
2	IPRIN(2)	= 0: No output. = 1: Print layout of batches before shuffling. = 2: Same as 1, plus atom densities (only in combination with IPRIN(3) ≥ 0).
3	IPRIN(3)	Burnup calculation: = -1: Global neutron balance. = 0: Detailed neutron balance. = 1: Same as 0, plus characteristic data for all fuel batches.
4	IPRIN(4)	= 0: Skip spectrum calculation if a set of cross sections is available. Instructions on card V22 are neglected. = 1: Repeat spectrum calculation as defined on Card V22. = 2: Same as 1, but only for the thermal spectrum. = 3: Same as 1, but not for zones without heavy metal (reflectors). = 4: Same as 2, but not for zones without heavy metal (reflectors).
5	IPRIN(5)	Cycle whose fuel compositions are to be written to file.
6	IPRIN(6)	= 0: Do not write fuel compositions to file. = 1: Write fuel compositions to file.

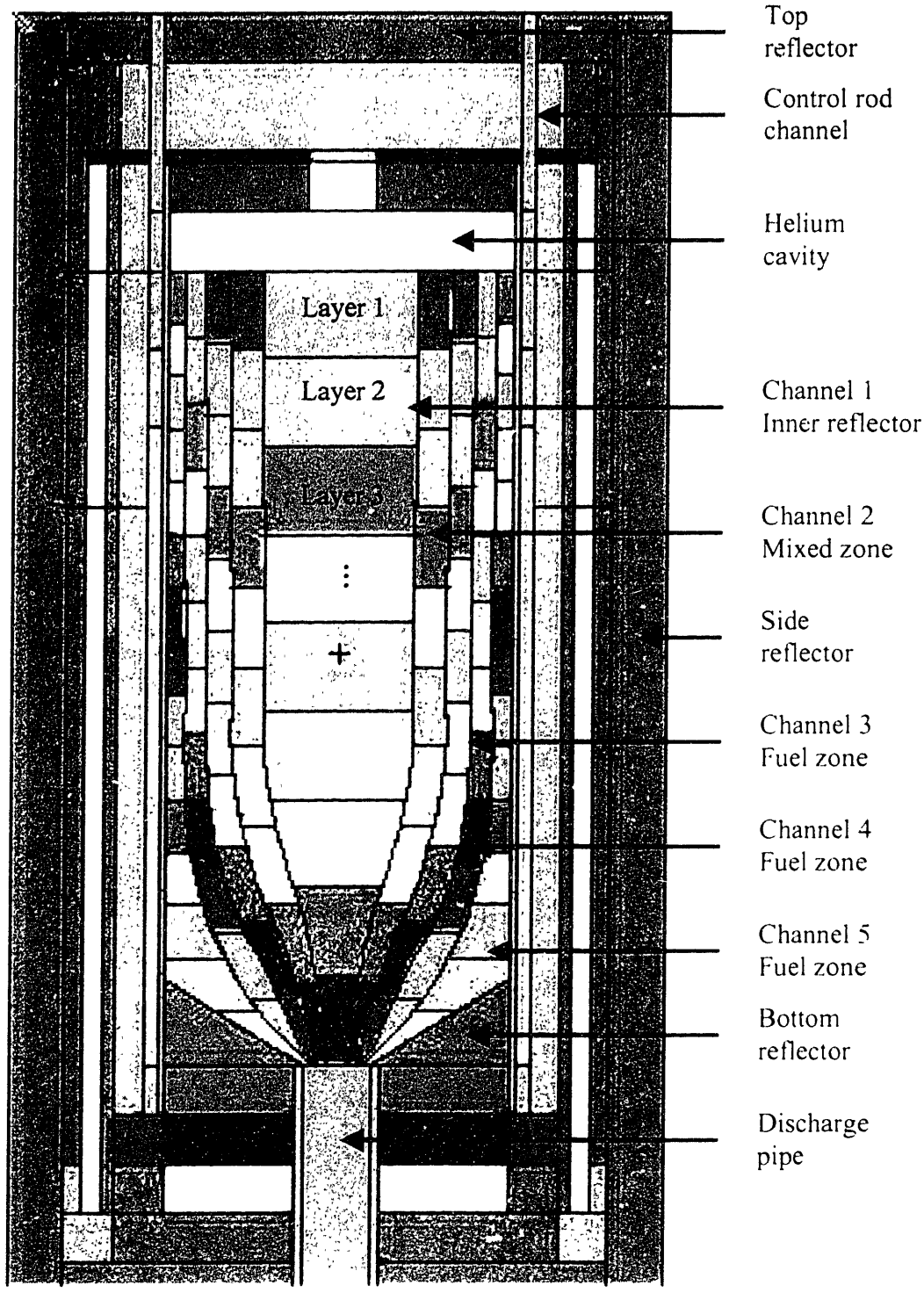


Figure 7-4. MCNP4B Model of the PBMR—Vertical View

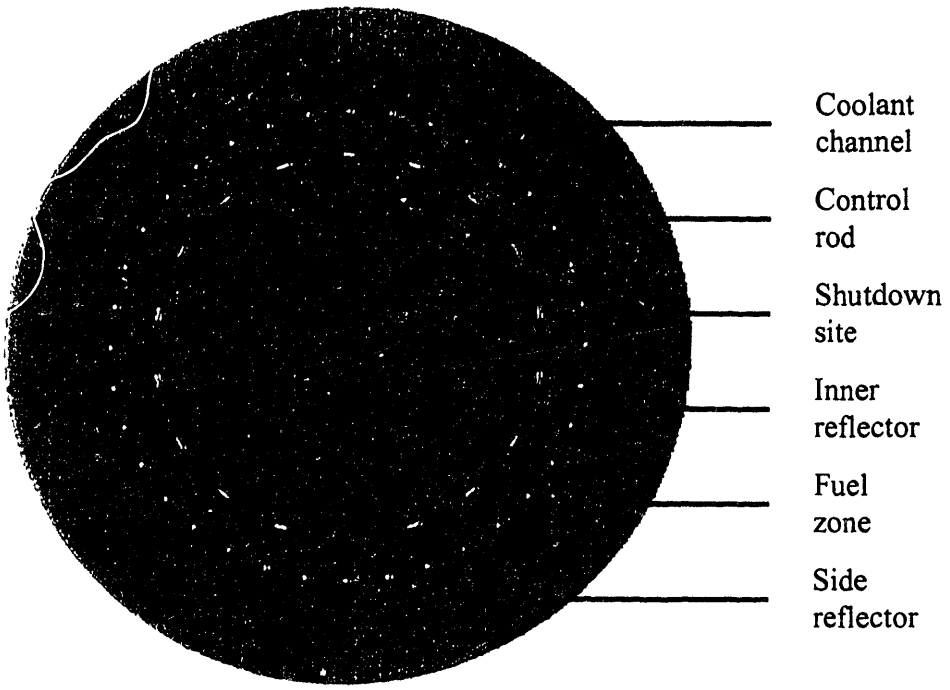


Figure 7-5. MCNP4B Model of the PBMR—Horizontal View

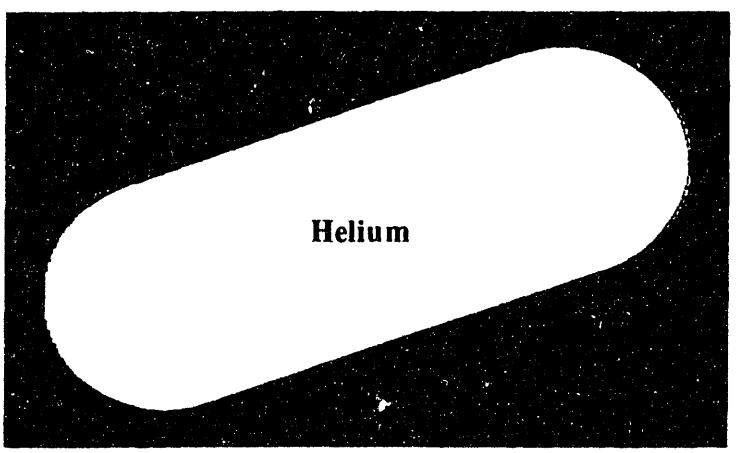


Figure 7-6. Channel for Small Absorber Balls in MCNP4B Model of PBMR

7.5 MCNP4B/VSOP94 Results

Preliminary analysis of the PBMR using the MCNP4B/VSOP94 model described above, but with unadjusted VSOP94 nuclide densities, yields an effective multiplication constant of 1.00873 ± 0.00096. Typical core power and neutron flux distributions are shown in Figures 7-7 to 7-9 for fully homogenized layers. MCNP4B was unable to generate prompt fission power (F7) and neutron flux (F4) tallies for segments defined via an FS tally segmentation card for the detailed core. Although this result demonstrates in principle the linkage between VSOP94 and MCNP4B, further developments are needed before the method can be applied to actual reactor analysis.

VSOP94 performs the diffusion calculations on homogenized regions of the core, with self-shielding factors used to correct for double heterogeneity and a diffusion correction to allow for neutron streaming in core voids (see Chapter 2). Neutron streaming is handled in MCNP4B by modelling explicitly the lattice of spheres.

Figure 7-7. Power Density in PBMR Equilibrium Core
Control Rods 1/4 Inserted (z = 201.25 cm)

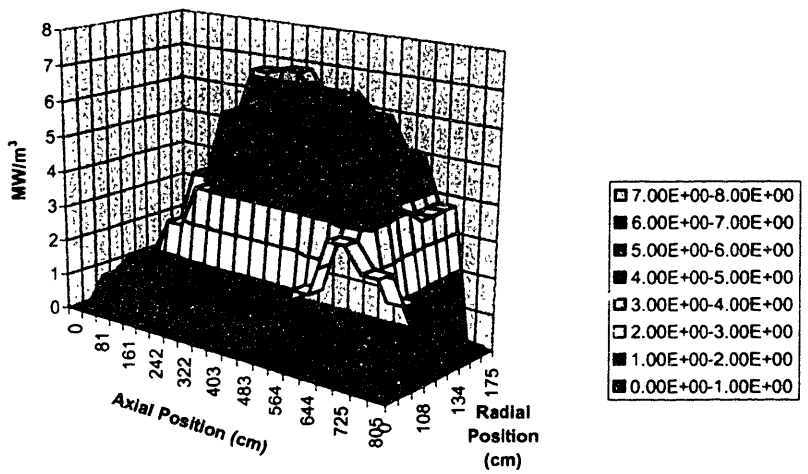


Figure 7-8. Fast Neutron Flux in PBMR Equilibrium Core
Control Rods 1/4 Inserted (z = 201.25 cm)

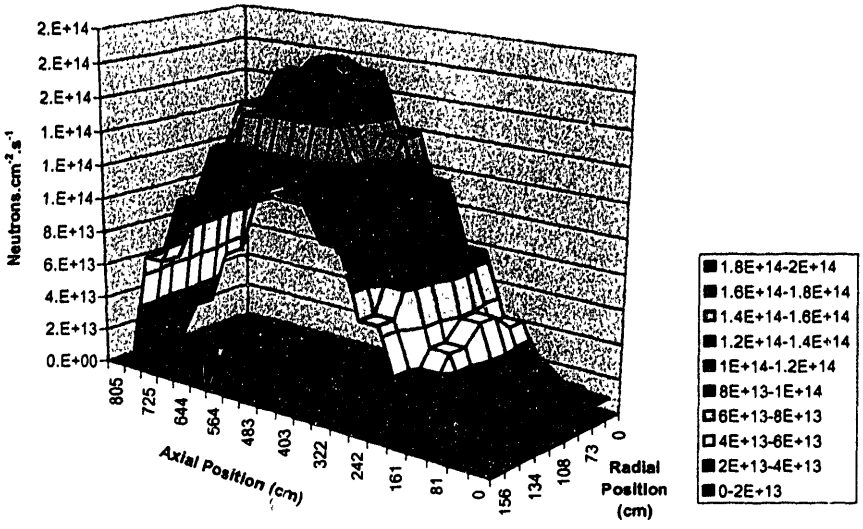
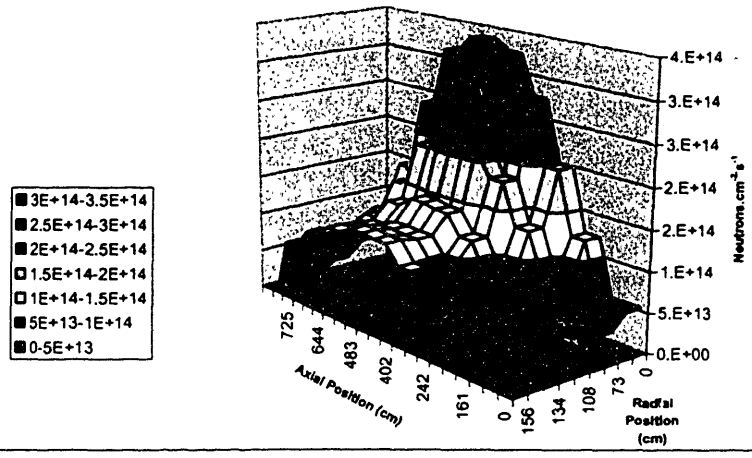


Figure 7-9. Thermal Neutron Flux in PBMR Equilibrium Core
Control Rods 1/4 Inserted (z = 201.25 cm)



However, the nuclide densities calculated by VSOP94 for each layer must also be adjusted to compensate for the approximate MCNP4B representation of fuel-sphere interiors. The effect of this homogenization was shown to decrease the reactivity of the core ~4% $\Delta k/k$ by using an identical MCNP4B model in which the core layers were fully homogenized. Therefore, the ^{238}U (and ^{240}Pu that contributes to the resonance absorptions at high burnup) atom densities calculated by VSOP94 should be reduced (*i.e.*, adjust $\Sigma_i=N_i\sigma_i$ by modifying N_i instead of σ_i) to compensate for this change in reactivity. This would result in a k_{eff} of ~1.04 if temperature effects are not included in the simulation. Two-dimensional VSOP analysis of the PBMR core has established a total temperature reactivity coefficient of -4.17×10^{-5} Δk/°C (see Table 7-5) [7-6], which would reduce the reactivity of the core by ~4% $\Delta k/k$ assuming an average fuel temperature of 950°C. The MCNP4B calculations reported here were performed at room temperature, because cross-section libraries at typical HTGR operating temperatures were not available.

Table 7-5
Temperature Reactivity Coefficients in the PBMR [7-6]

Reactor Component	$\Delta k/°C$
Fuel	-3.28×10^{-5}
Moderator in fuelled region of core	-3.30×10^{-5}
Central reflector	$+0.93 \times 10^{-5}$
Outer reflectors	$+1.48 \times 10^{-5}$
Total	-4.17×10^{-5}

7.6 Discussion

Monte Carlo methods are becoming the tool of choice for the physics design and analysis of nuclear reactors. Models prepared with a Monte Carlo code such as MCNP4B are capable of calculating very accurately all key core parameters, including the effective multiplication constant, the reactivity worths of control rods and shutdown absorbers, fission powers and neutron fluxes. The ability of MCNP4B to transport photons also makes it useful for shielding and heat deposition calculations. Furthermore, advances in computer hardware have made lengthy Monte Carlo runs cost effective.

Full-core calculations are increasingly being performed with code systems that couple Monte Carlo and stand-alone fuel depletion codes. An example of such a Monte Carlo burnup code is MOCUP, which couples MCNP4B and ORIGEN2. However, this code cannot be currently applied to pebble-bed reactors for several reasons: *(a)* the recirculation of fuel spheres in the core; *(b)* modelling the 10^4 discrete fuel particles in each fuel sphere in a large pebble-bed core is beyond the capabilities of the codes; and *(c)* the number of MCNP4B runs required to reach an equilibrium burnup distribution would be computationally prohibitive. Therefore, the best approach at this time is to perform the fuel management study separately using a diffusion- or transport-theory code and use the resulting fuel compositions in a snapshot MCNP4B calculation with a very detailed model of the reactor.

The method described in this chapter for obtaining the MCNP input for the composition of fuel spheres in a pebble-bed core with burnup is limited in its accuracy, because of the need to account for the effects of homogenization on resonance absorptions. Therefore, a

different approach is needed if the resulting MCNP4B model is to be of benchmark quality. Such a model should treat the double heterogeneity of the pebble bed core with the same degree of accuracy as the HTR-PROTEUS and HTR-10 models described in Chapters 4 and 5 (although one possible simplification is to lump the coatings of the fuel kernels together with the graphite matrix [7-15]). The composition of the fuel kernels could be generated directly using a lattice code with an accurate burnup capability, or a Monte Carlo burnup code. The proposed method is shown schematically in Figure 7-10 for the Dutch WIMS/PANTHERMIX code system (see Chapter 2), although VSOP94 could also be used to perform these calculations.

In the suggested procedure, a fuel management study would be performed to determine the burnup distribution in the core for a given refuelling strategy. These burnups (in MWD/THM) would be calculated using diffusion theory for a finite number of core regions (or layers in VSOP94). A neutronics code would then be used to deplete the fuel to the required burnup with a standard supercell model consisting of a single fuel sphere, with an explicit representation of the coated fuel particles, surrounded by a driver region. This procedure is similar to the single pebble, multi-kernel burnup calculations reported in References 7-15 and 7-16. Because each fuel sphere is expected to visit every region of the core during its multiple passes, an average fuel composition corresponding to the equilibrium core could be used for the driver fuel.

Any number of codes may be used to perform the supercell depletion calculation, including MOCUP and WIMS [7-18]. The model would have to be run to generate

separate fuel compositions for the burnup in each core region, and the MCNP4B material cards would be prepared with a modified version of MCARDS.

A more direct approach, which does not rely on a diffusion-theory code, would be to use the MONTEBURNS Monte Carlo burnup code to perform the entire fuel management study. The core would be modeled as in Section 7.4, although with an explicit representation of the double heterogeneity. Simple annular zones could be used to simplify the generation of flux and power distributions. The same fuel composition would be used in all fuel spheres in a given core region. MONTEBURNS already has the capability for shuffling fuel, but the code would have to be modified to perform the mixing of fuel spheres with different burnup that occurs when discharged fuel spheres are reinserted at the top of the core.

7.7 Summary

An approximate method for the MCNP4B modelling of pebble-bed reactors with burnup was presented. In this approach, the nuclide densities of the homogenized layers in the VSOP94 model of the reactor are used in the corresponding MCNP4B model with an adjustment for its explicit representation of the sphere lattice. The method was demonstrated in principle on the PBMR equilibrium core, although temperature-dependent cross sections would have to be generated for MCNP4B before the model can be applied to reactor design problems.

Two alternative approaches were proposed, which takes advantage of the ability to model the double heterogeneity of the PBMR core directly with MCNP4B. In the first method,

which uses a lattice code such as WIMS or the Monte-Carlo burnup code MOCUP, a supercell model of a fuel kernel would be used to deplete the fuel to the desired burnup in a representative core environment. The resulting nuclide densities could then be used without adjustment in a detailed (doubly heterogeneous) MCNP4B model. In both this and the MCNP4B/VSOP94 approaches, average fuel compositions are generated for a finite number of core regions (similar to the layers of VSOP94) to make the problem computationally manageable. In the second method, the Monte Carlo burnup code MONTEBURNS would be used to perform the entire fuel management study directly. However, this approach would require modifications to the code to facilitate the recycling of fuel spheres with different burnup.

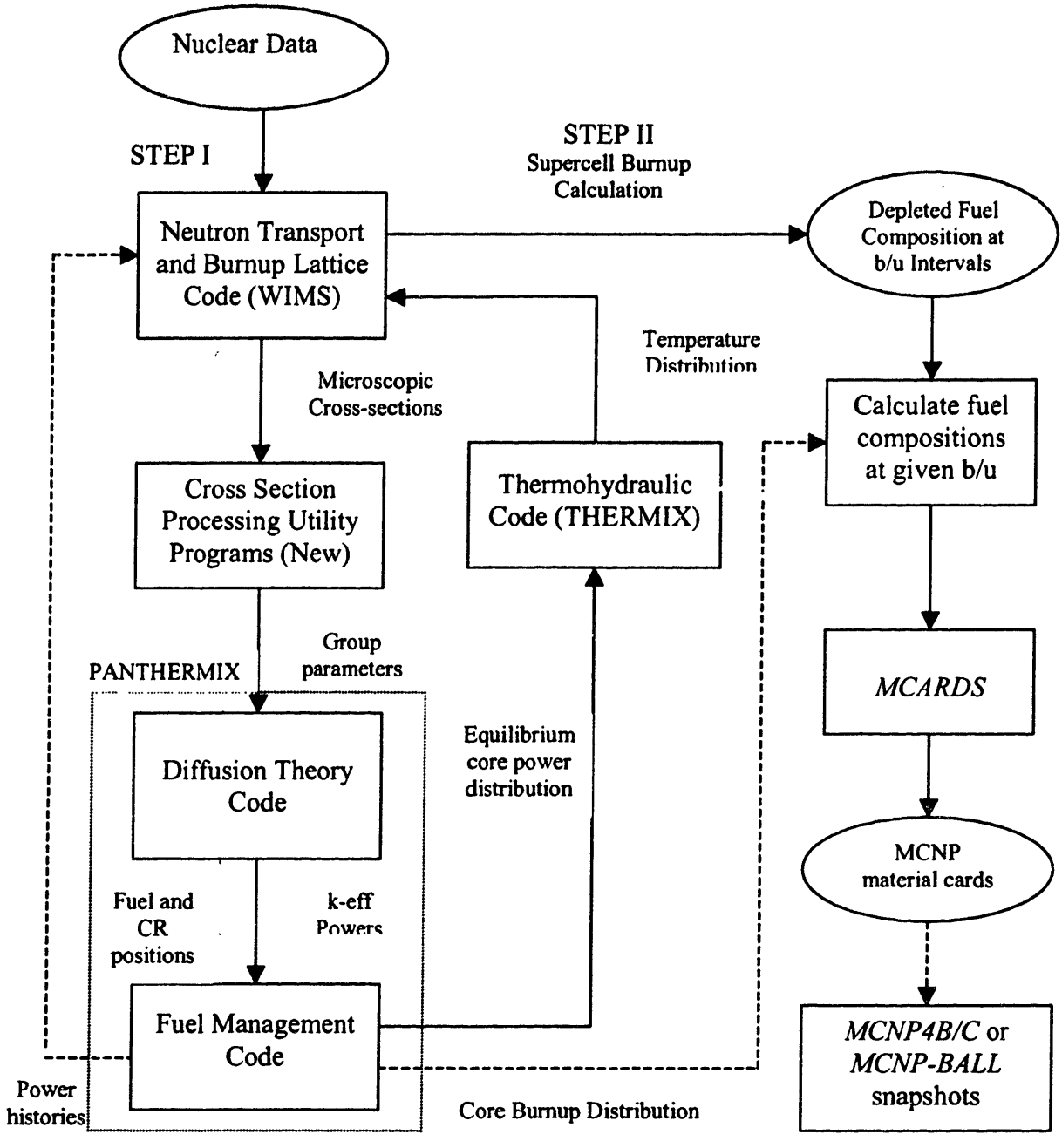


Figure 7-10. Proposed MCNP-Based Code System for Pebble-Bed Reactors with Burnup

8. PLUTONIUM PRODUCTION IN A PEBBLE BED REACTOR

Nuclear power is expected to play a significant role in meeting future electricity needs while reducing emissions of air pollutants and greenhouse gases [8-1]. However, several issues continue to trouble government and industry policymakers and segments of the public. These include nuclear power plant safety, waste, economics and weapons material proliferation. The modular pebble-bed reactor is a leading contender in a new generation of nuclear reactors, and is recognized for its simple design, thermodynamic efficiency, natural safety and environmental friendliness. The graphite pebbles with the embedded TRISO coated fuel particles serve as an excellent waste form for the direct disposal of spent fuel in a geological repository [8-2]. The focus of this chapter is the proliferation resistance of pebble-bed reactors.

Preliminary calculations were performed with the VSOP94, MCNP4B and ORIGEN2 physics codes to estimate the production of plutonium in a pebble-bed reactor. The ESKOM Pebble Bed Modular Reactor (PBMR) was used as the reference reactor [8-3]. The study examined the isotopic composition of normally discharged fuel, first-pass fuel spheres and depleted-uranium production spheres[1].

8-1. **Modeling Methods**

A description of the VSOP94 and MCNP4B physics codes appears in Chapter 2. The VSOP94 suite of codes, which relies on diffusion theory to solve the neutron transport equation, can be used to perform fuel management studies for pebble-bed reactors with multiple-pass refuelling strategies [8-4]. The Monte Carlo code MCNP4B is capable of accurate calculations involving the transport of neutrons and photons, including the determination of ^{238}U capture rates [8-5].

[1] The concept of depleted-uranium production spheres was proposed by J.S. Herring of the INEEL.

ORIGEN2 is a general-purpose point-depletion and generation code for calculating isotopics, decay heat, radiation source terms and radioactivity levels [8-6]. MOCUP is a Monte Carlo burnup code that couples MCNP4B and ORIGEN2 [8-7].

Models of the PBMR were used to examine the amount and isotopic composition of plutonium present in the normally discharged fuel spheres, fuel spheres diverted after a single pass through the core, and special production spheres loaded with depleted UO_2. The analysis consisted of a supercell calculation of plutonium production with special spheres using MCNP4B, and a full-core simulation of normal fuel spheres using VSOP94[2].

8.1.1 Supercell Model

The supercell model represents an attempt to represent accurately the environment that the production pebble experiences during its passage through the core. It consists of an MCNP4B model, in which a single production pebble is placed in the center of a reflected spherical core consisting of a regular lattice of driver fuel pebbles (see Figure 8-1).

The nuclide concentrations of the driver fuel were extracted from the VSOP94 model of the PBMR and corresponded to an average over all regions of the equilibrium core (see Chapter 7). The size of the supercell was adjusted to yield a critical assembly ($k_{eff} \sim 1$), and its power was normalized so as to match the VSOP94 core-averaged total neutron flux. The ^{239}Pu production is estimated from a tally of the $^{238}U(n,\gamma)^{239}U$ reaction rate for the stand-alone MCNP4B, or by tracking the isotopic composition of the production ball in a MOCUP depletion calculation; the composition of the driver fuel is static. The supercell model permits the modeling of the inner reflector and transition zones.

[2] The VSOP model of the PBMR reference core was provided by Dr. E.J. Mulder, PBMR (Pty) Ltd.

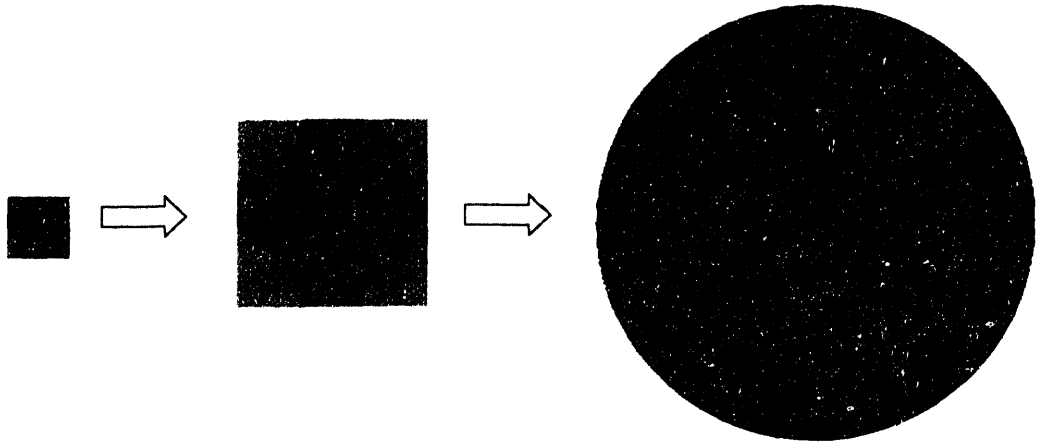
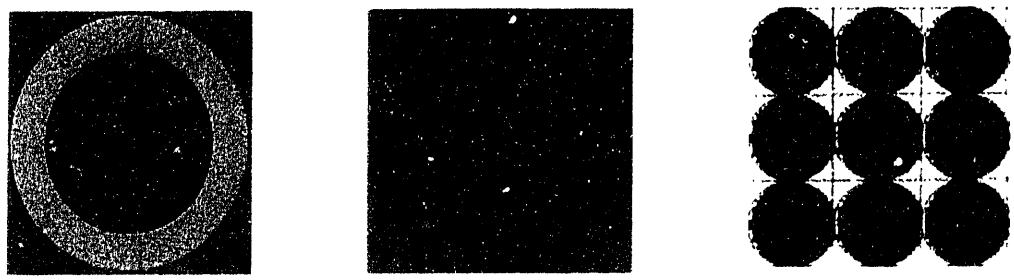


Figure 8-1. Supercell MCNP4B Model of Production Sphere

8.1.2 Production Pebbles

Three configurations of plutonium production pebbles containing depleted (0.2% ^{235}U) UO_2 were considered (see Figure 8-2): *(a)* a solid core (2.1 cm radius); *(b)* ten alternating shells (2 mm thick) of depleted fuel and pyrolytic carbon; *(c)* a densely packed simple cubic array of BISO coated depleted fuel particles (0.025 cm inner and 0.038 cm outer radius of pyrolytic carbon coating, and a 0.5 packing fraction). The BISO coating does not incorporate a silicon-carbide layer, and using such fuel particles would avoid problems associated with the removal of silicon carbide during reprocessing (the depleted uranium will not add a significant amount of fission-product contamination to the reactor cooling system).



(a) *(b)* *(c)*

Figure 8-2. Different configurations of production pebbles:
(a) solid core; *(b)* shells; *(c)* dense BISO.

8.2 **Analysis and Results**

The following sections provide some details of the analysis performed and a summary of the results obtained. Plutonium production in regular fuel pebbles was analyzed with VSOP94, while the special production pebbles was investigated using the supercell model described above. A further discussion of the proliferation resistance of pebble-bed reactor fuel cycles appears in Reference 8-8, and the simple-cell MCNP4B and MOCUP analysis of plutonium production in pebble-bed reactors performed at the INEEL may be found in Reference 8-9.

8.2.1 Regular Fuel Pebbles

VSOP94 analysis of the reference PBMR core showed (see Appendix E.2) that a diversion of 157,000 spent fuel pebbles would be needed over 1.2 years to obtain 6 kg of ^{239}Pu (which is taken to be a weapon's worth of plutonium). However, as is shown in Table 8-1 for a fuel discharge burnup of 80 MWd/kgU, the isotopic composition of plutonium in spent fuel at high burnup is not well suited for nuclear weapons production. Moreover, the percentage of ^{239}Pu is lower than 40%, which is a recognized level for lower proliferation risk [8-9].

Table 8-1
Plutonium Isotopic Composition of PBMR Spent Fuel at 80 MWd/kgU†

Isotope	%
^{238}Pu	1.9
^{239}Pu	36.8
^{240}Pu	27.5
^{241}Pu	18.1
^{242}Pu	15.7

† Calculated with VSOP94.

Fuel pebbles, which are diverted after a single pass through the core, have a more favourable plutonium isotopic composition (Table 8-2). However, because of the shorter irradiation times (on average 73 days per pass), as many as 258,000 fuel pebbles would have to be diverted for 6 kg of ^{239}Pu (the amount of ^{239}Pu needed for a weapon varies between 4 and 8 kg). Since fuel pebbles are normally reinserted at the top of the core, the diversion of all first-pass fuel pebbles would result in an excessive loss of reactivity. Therefore, the duration of the diversion would be longer than the two years calculated for the normal discharge rate of such pebbles unless fresh fuel can be added.

Table 8-2
Plutonium Isotopic Composition of PBMR First-Pass Fuel†

Isotope	%
^{238}Pu	~0
^{239}Pu	82.8
^{240}Pu	15.2
^{241}Pu	1.9
^{242}Pu	0.1

† Calculated with VSOP94 for reference fuel cycle.

8.2.2 Supercell Analysis of Production Pebbles

The purpose of using a supercell model of the production pebble is to simulate more accurately the neutron flux and spectrum that the pebble would experience during its single pass through the core. Calculations were performed for the three designs of production pebble described in Section 8.1.2, using a driver-fuel assembly representative of *(a)* the PBMR average core and *(b)* the PBMR inner reflector region. The MCNP4B analysis included tallies of the $^{238}U(n,\gamma)$ reaction rates in the depleted uranium target and the eighth of a driver fuel pebble in each of the eight corners of the BCC production cell. The average neutron flux in the production cell was also tallied. In addition, a MOCUP depletion calculation was carried out for the production pebble with a solid UO_2 target to determine the plutonium isotopic composition at the end of the irradiation period. The results are presented in Tables 8-3 to 8-5.

Table 8-3
Neutron Fluxes Calculated With Supercell MCNP4B Model
(neutrons·cm^{-2}·s^{-1})

Case	Group 1[a]	Group 2[b]	Group 3[c]	Group 4[d]	Comments
VSOP reference	2.47e+13	4.85e+13	1.26e+13	1.18e+14	Average core
Solid UO_2 target	3.46e+13 (3.41%)	6.18e+13 (2.91%)	1.63e+13 (4.91%)	9.33e+13 (2.26%)	
UO_2 target shells	3.58e+13 (3.40%)	6.20e+13 (2.84%)	1.62e+13 (4.81%)	9.21e+13 (2.32%)	
Densely packed BISO targets	3.58e+13 (3.47%)	6.14e+13 (2.96%)	1.42e+13 (5.18%)	9.46e+13 (2.27%)	
VSOP reference	1.07e+13	2.64e+13	9.15e+12	2.02e+14	Inner reflector
Solid UO_2 target	3.41e+12 (11.3%)	1.49e+12 (24.1%)	2.55e+11 (38.4%)	2.07e+14 (1.72%)	

[a]) 0.1 MeV < E ≤ 20 MeV; [b]) 29 eV < E ≤ 0.1 MeV; [c]) 1.86 eV < E ≤ 29 eV; [d]) 0 eV < E ≤ 1.86 eV.

The standalone MCNP4B tallies were normalized using four million starting neutron histories for the core-averaged cases and eight million for the reflector case[3], while the MOCUP calculation was limited to one million neutron histories at each burnup step because of time constraints. The reported percent relative errors (shown in brackets) correspond to the 1-σ confidence interval.

Table 8-4
^{239}Pu Production Calculated with Supercell MCNP4B Model

Production Pebble	Reaction Rate (1/s) driver	target	g ^{239}Pu / pass driver	target	Pebbles for 6 kg ^{239}Pu	Comments
Solid UO_2 target	1.91e+13 (21.9%)	1.86e+14 (5.65%)	0.048 (21.9%)	0.466 (5.65%)	12,866 ± 727	Average core
Shell UO_2 targets	1.28e+13 (21.0%)	1.54e+14 (6.63%)	0.032 (21.0%)	0.386 (6.63%)	15,526 ± 1,029	
Dense BISO targets	1.27e+13 (16.2%)	1.95e+14 (6.18%)	0.032 (16.2%)	0.487 (6.18%)	12,312 ± 761	
Solid UO_2 target	3.41e+12 (4.67%)	2.12e+14 (3.86%)	0.007 (4.67%)	0.420 (3.86%)	14,132 ± 645	Inner reflector

Table 8-5
Isotopic Composition of Plutonium in Irradiated Solid UO_2 Target†

Isotope	%
^{238}Pu	~0
^{239}Pu	92.2
^{240}Pu	7.5
^{241}Pu	0.3
^{242}Pu	~0

† Calculated with supercell MOCUP model.

8.3 Discussion

The analysis has confirmed that spent fuel from pebble-bed reactors is proliferation resistant at high discharge burnup (≥80 MWd/kgU), because of its unfavourable plutonium isotopic composition and the large number of pebbles that would have to be diverted—about half a core

[3] The large number of histories is needed to reduce the relative errors of the neutron flux and reaction rate tallies to acceptable levels (ideally < 5%).

load. The isotopics of first-pass fuel pebbles are more favourable, but an even larger number would be needed to accumulate 6 kg of ^{239}Pu. In addition, the large number of coated fuel particles that must be cracked to remove the SiC coating make TRISO fuel difficult to reprocess. Such reprocessing technology is yet to be demonstrated on irradiated fuel.

However, it is also possible to produce a significant quantity of plutonium in a pebble-bed reactor by inserting special pebbles with a high loading of depleted uranium. Analysis has also shown that the production of plutonium in such pebbles is limited by γ-heating and resonance self-shielding in the target regions [8-10]. As with any new fuel concept, the manufacturing of the special pebbles would require a sophisticated fuel development program and irradiation research facilities not commonly found in countries lacking a nuclear infrastructure. Fewer pebbles would be needed (13,000 to 20,000), although the duration of the diversion will depend on the ability to compensate for their reactivity effect. If the production pebbles comprise 1% of the core inventory, it would take a minimum of 1.5 years to accumulate the required amount of material at the normal fuel-pebble removal rate. By extrapolation from HTR-10 criticality calculations[4], the reactivity worth of the PBMR core height may be estimated to be 0.02 %/cm. Therefore, the height of the core would have to be raised by approximately 50 cm to compensate for 1 $\%\Delta k/k$ loss in reactivity. It is unlikely that such a change in core height would go unnoticed in a safeguarded reactor.

The substitution of fuel pebbles with ones containing depleted uranium targets, or diverting regular pebbles after a single pass, could have a significant effect on the normal operation of the

[4] For HTR-10, $\Delta\rho/\Delta H \approx 0.5$ %/cm. Since the PBMR core is 5 times taller, then this value scales as $(1/5)^2$ assuming a cosine flux shape. Thus, $\Delta\rho/\Delta H\big|_{pbmr} \approx 0.02$ %/cm.

reactor.[5] A detailed analysis must be carried out using the VSOP94 fuel management code to model such effects, especially to determine the throughput of special pebbles. However, since the preparation of VSOP94 input files is time consuming, the preliminary calculations were performed with MCNP4B and MOCUP using simplified models of the PBMR core that limit the accuracy of the analysis. The standalone MCNP4B calculations are expected to be conservative because they neglect the depletion of bred plutonium. The supercell MCNP4B models predict a harder neutron spectrum than VSOP94 and, therefore, also tend to overestimate the $^{238}U(n,\gamma)$ reaction rate.

The potential diversion of special plutonium production pebbles requires the use of extrinsic barriers to assure nonproliferation. While there are differences in estimates of the actual number (13,000 to over 20,000) and the time needed to accumulate these pebbles (1 to 2 years), the final conclusion is that intrinsic barriers alone are not sufficient for on-line refueling of pebble-bed reactors. IAEA safeguards and enhanced monitoring systems would be required to prevent the insertion of these pebbles, monitoring devices to detect their production, and seals to avoid tampering with the closed refueling system of the plant [8-11].

As is typical for IAEA safeguards programs for light-water reactors, inspections of fuel fabrication plants and fresh fuel deliveries would be required. Automatic weighing stations would also be required for fuel pebbles prior to their insertion into the core to detect the heavier production pebbles. Pebble-bed reactors already possess on-line burnup meters and failed pebble detectors to sort pebbles for reinsertion. However, by making "defected" production pebbles, this system could also be used to remove first-pass pebbles for plutonium recovery. The detection

[5] It may be possible to design production pebbles that are reactivity neutral, *e.g.*, by adding an outer fuel shell.

system would have to be enhanced to detect spectral differences caused by the presence of production pebbles. These technologies require an additional research and development effort to ensure that nonproliferation objectives are met.

This study also suggests that additional work on fuel management strategies may be helpful in improving intrinsic barriers by reducing ^{239}Pu production through the adjustment of enrichments and neutron spectra. Alternative intrinsic barriers are the OTTO (once through then out) fuel cycles, which include the Dutch PAP (*peu-á-peu*) concept [8-12] and the proposed PAP2 fuel with burnable poison [8-13], and potentially utilizing Th/LEU fuel to provide additional proliferation resistance of spent fuel. Irradiations of short duration are not possible in such non-recirculating cores (other than by the premature dumping of the entire inventory).

A final remark is appropriate regarding the relative proliferation risk of this technology. The pebble-bed reactor is not a likely target for a terrorist or sub-national group, because of the sophisticated nature of the fabrication and reprocessing of production pebbles. Plutonium production assemblies can be inserted into any reactor. However, while a single fuel assembly may suffice in a light-water reactor, thousands of pebbles would have to be diverted from a pebble-bed reactor to produce a single weapon. Any reactor may become a national threat by a country that chooses to abdicate the NPT and IAEA safeguards inspections. It is the purpose of international safeguards to provide advanced notice of such activity.

9. Conclusions and Future Directions

The research described in this report explored the applicability of the standard version of MCNP to the neutronic modeling of pebble-bed reactors. Previous MCNP (versions 4A or 4B) investigations only considered critical experiments involving regularly packed cores [9-1, 9-2]. The key issue for the practical application of MCNP4B to pebble-bed reactors is the use of regular lattices to describe their randomly packed cores. This modeling effort was very successful for the simple core configurations encountered in the HTR-PROTEUS critical experiments and the HTR-10 start-up core. The annular ASTRA core, which is representative of modern modular HTGR designs, proved to be much more difficult to model accurately. A summary of key results is provided in Table 9-1; further details may be found in the referenced chapters.

Table 9-1
Summary of key MCNP4B Criticality Calculations

Experiment	*Parameter*	*Measurement*	*Calculation*	*Chapter*
HTR-PROTEUS				
Core 4.1	k_{eff}	1.0134±0.0011	1.0208±0.0011[†]	4
Core 4.2	k_{eff}	1.0129±0.0008	1.0172±0.0010[†]	4
Core 4.3	k_{eff}	1.0132±0.0007	1.0176±0.0011[†]	4
HTR-10	Critical load	16,890	16,841	5
ASTRA	k_{eff}	1.000	0.99977 ± 0.00082	6
Control rod 1	$\Delta\rho$	1.77 %[‡]	1.72 ± 0.11 %	6
Control rod 2	$\Delta\rho$	1.84 %	1.89 ± 0.11 %	6
Control rod 4	$\Delta\rho$	1.40 %	1.56 ± 0.11 %	6
Control rod 5	$\Delta\rho$	1.83 %	2.01 ± 0.12 %	6

[†] A reactivity bias is present because of graphite impurities; [‡] % Δk/k.

The method developed for the MCNP4B modeling of pebble-bed cores involves the use of a regular lattice of spheres, arranged either as a primitive BCC lattice or based on a repeating cell constructed from a number of BCC unit cells as shown in Figure 9-1. The

coated fuel particles are modeled in detail and are distributed over the fuelled portion of the fuel sphere using a simple cubic lattice. The enlarged cell approach is needed for modeling explicitly more complicated core configurations, especially when more than two types of spheres are present in the core (such as fuel, moderator, absorber, *etc.*). The results of such a model were found to depend very strongly on the distribution of spheres in the cell, and a generic modeling methodology is difficult to define. However, case-by-case treatment can be successful when supported by appropriate sensitivity studies.

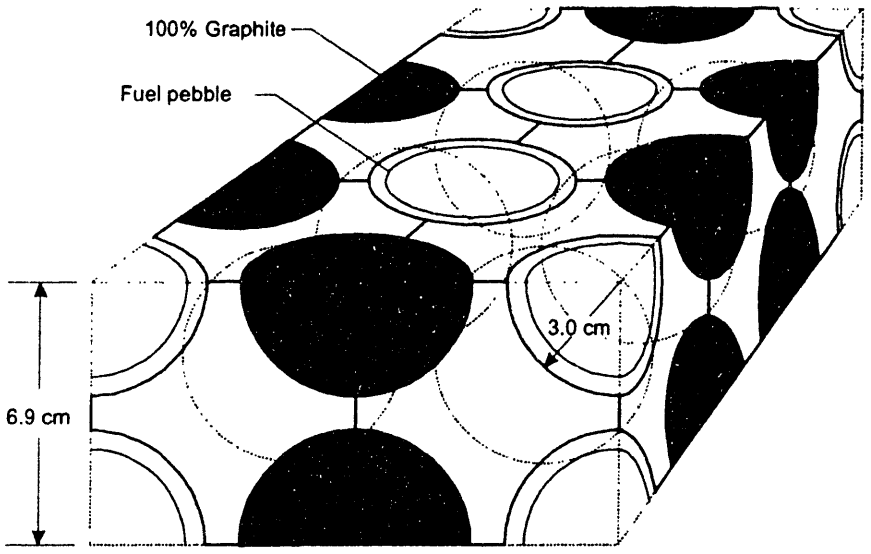


Figure 9-1. Six-cell BCC model used in the plutonium production study [9-3]

Because the repeated-structure feature of MCNP4B introduces partial spheres at the periphery of the core, a correction is required in order to eliminate excess fuel contributed by partial fuel spheres. This can be done either by reducing the volume of the core while keeping the sphere packing fraction unchanged, or by reducing the packing fraction while keeping the core volume unchanged. Both approaches rely on an exclusion zone, which balances the contributions from physically realizable and unrealizable partial spheres. For

circular cores, the procedure is straightforward because a distribution of partial spheres of various sizes exists at the core boundary. The size of the exclusion zone is given by the radius of the sphere scaled by the number ratio of fuel spheres to all spheres in the unit cell. However, such a distribution does not exist in polygonal cores and the exclusion zone must be determined explicitly from the volumes of partial spheres at the boundaries. This is possible because the positions of the spheres are known in a regular lattice, and an expression is available for the volume of a spherical segment [$V = \frac{1}{3}\pi h^2(3R-h)$, where R is the radius of the sphere and h is the height of the segment].

Ultimately of interest is the ability to model a realistic core with any number of types of spherical elements, including fuel spheres with different fissile materials, enrichments and burnup. A core representation constructed from a repeating cell with 100 spheres (arranged in 50 BCC unit cells) could be used in principle to describe such core loadings. However, as the ASTRA analysis has demonstrated, such a deterministic approach is very difficult and not likely to be accurate. If MCNP4B (or version 4C) is to be used, the recommended method is to use average material compositions in a finite number of core regions (such as the layers from the VSOP94 model), with an explicit treatment of the fuel kernels whose compositions are best generated with a separate fuel management code as discussed in Chapter 7. A 30% reduction in computation time is reportedly possible by smearing the multiple coatings of the fuel kernels into a single layer [9-4].

However, the best approach would appear to be to shift the Monte Carlo modeling effort to the stochastic geometry treatment of the MCNP-BALL code developed by JAERI [9-5], because this would eliminate the difficulties associated with specifying the pebble-bed

core explicitly. In this method, the geometry of the core is sampled during the neutron transport calculation using nearest-neighbour distribution functions (NND). Such distribution functions, which give the probability of finding the nearest neighbour in a spherical shell between radius r and $r+dr$, are generated using the Monte Carlo packing code MCRDF. (An exclusion zone is used during the sampling process to avoid including spheres that overlap the vessel boundary, although here the packing fraction is increased to achieve the correct inventory of spheres.) The NNDs are sampled during the transport of each neutron to determine its path through a sphere or coated fuel particle. This eliminates the need for the *a priori* specification of the pebble-bed geometry, because the positions of other spheres or coated fuel particles do not enter the calculation.

The current version of MCNP-BALL was developed by JAERI from MCNP3B by revising five existing subroutines and adding five new ones, and validated through analysis of the stochastic-core experiments at the HTR-PROTEUS facility [9-6]. However, all future applications and modifications of MCNP-BALL should be based on an MCNP4C implementation of the code. The most important enhancements required in MCNP-BALL relate to the modeling of separate core regions with different fuel compositions.

Apart from the recommendation to shift from MCNP4B (or 4C) to MCNP-BALL, several other aspects of the research discussed in this report require a follow-up. The most important of these concern the ASTRA critical assembly and the addition of a burnup capability to the MCNP4B modeling of pebble-bed reactors.

(a) ASTRA

The remaining experiments performed in ASTRA should be analyzed, including the investigation of critical parameters as a function of core height, the spatial distribution of relative reaction rates, and the reactivity effects of spherical elements. The latter measurements were carried out for both individual and groups of spheres (fuel, moderator and absorber) in the central channel. [9-7]

Calculation of the ASTRA control-rod worths was found to be sensitive to the number of neutron histories (both the total number and the number per cycle) and the definition of the fission source term used to initiate the run. This suggests that the annular core may be more neutronically decoupled than was previously thought to be the case. This should be investigated, including the effect of the boron absorber on the neutronic stability of the core (for example, by defining the starting fission source in one half of the core only and following the behaviour of the effective multiplication factor for successive cycles).

(b) Burnup

The method proposed in Chapter 7 for calculating the nuclide densities of depleted fuel should be implemented. This should be done initially by using VSOP94 to determine the equilibrium core burnup distribution, followed by a supercell MONTEBURNS [9-8] calculation of layer-averaged fuel compositions (see Figure 7-10). This could then be followed up by an investigation of whether MONTEBURNS could be used to perform the fuel management study directly. New routines would have to be added to

MONTEBURNS to simulate the out-of-pile decay of fission products and the mixing of fuel spheres with different burnup in each core region.

An interlaboratory burnup benchmark should be promoted similar to those done in the past for light-water reactor UOX and MOX fuel [9-9]. This would consist of a numerical benchmark comparison of the burnup reactivity and isotopics capabilities of the computer codes currently used by the international community engaged in HTGR analysis and design. The proposed benchmark would continue the work initiated in Reference 9-10, in which a single spherical unit cell was depleted with MONTEBURNS at several levels of complexity. The unit cell examined was taken from an ECN report [9-11], which modeled the LEUPRO-1 critical assembly tested at the HTR-PROTEUS facility. Such an international benchmark was recently proposed [9-12].

Several other areas also deserve further investigation. A more systematic study of neutron streaming in different types of lattices should be undertaken to determine the optimum packing order. As discussed in Chapter 3, a rhombohedral lattice is expected to provide a better representation of the arrangement of spheres in a pebble-bed reactor. A "super" lattice constructed from such unit cells was found to be too complicated for detailed modeling of the ASTRA core, but an approximate model that uses borated fuel spheres in a primitive rhombohedral unit cell may give better results than a BCC unit cell.

The predictions for the reactivity worths of the control rods in the HTR-10 reactor, which were calculated using the MCNP4B model described in Chapter 5, should be compared with the measured values when these become available. Good agreement in the worth of control rods signifies that the MCNP4B model is capable of predicting accurately the

neutron flux in the core, and, more importantly, in the radial reflector where diffusion theory treatments are suspect.

In conclusion, a comprehensive examination of the applicability of the MCNP4B Monte Carlo code to the modeling of pebble-bed reactors was undertaken in the course of this research. A modeling methodology was developed based on an analysis of three critical experiments—HTR-PROTEUS, ASTRA and the HTR-10 start-up core. The method uses a body-centred cubic core representation, and exclusion zones to compensate for the contribution of partial spheres generated by MCNP4B at the core boundaries. The critical core heights were predicted correctly in all cases. However, the calculation of the reactivity worths of control rods in the more decoupled annular ASTRA core was less accurate.

An approximate procedure was also developed for the MCNP4B modeling of pebble-bed reactors with burnup. The nuclide densities of the homogenized layers in the VSOP94 model of the reactor are used in the corresponding MCNP4B model with an explicit representation of the sphere lattice. The method was demonstrated in principle on the PBMR equilibrium core. The procedure for extracting fuel compositions from VSOP94 was also used to create a supercell MOCUP model of a special pebble loaded with depleted uranium. The model was then used to calculate the plutonium production capability of the PBMR.

For the modeling of realistic cores, the main recommendation of this report is a shift from MCNP4B (or version 4C), and its use of regular lattices of spheres to represent the core, to the stochastic geometry approach implemented in the JAERI code MCNP-BALL.

10. REFERENCES

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Appendix A

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APPENDIX A. MCNP4B Models of the HTR-PROTEUS Facility

This Appendix contains the MCNP4B input files with models of the three HTR-PROTEUS stochastic cores. A description of the MCNP4B code, model creation and input cards may be found in the manual [A-1]. Details of the HTR-PROTEUS facility appear in Chapter 4.

All the calculations reported in this report were performed on a DEC Alpha Personal Workstation 600au running under the Digital UNIX Version 4.0E operating system. MCNP4B and VSOP94 were compiled using the Digital FORTRAN 77 compiler (V5.2-171-428BH and Driver V5.2-10).

APPENDIX A.1: MCNP4B Model of HTR-PROTEUS Core 4.1

```
HTR-PROTEUS EXPERIMENT 4.1 -- IRREGULAR CORE
c
c    MCNP4B model of critical experiment 4.1 in the PROTEUS facility
c    using the detailed geometry specification from the calculational
c    benchmark. The random packing is modeled using a loose BCC, with
c    F/M ratio of one, and a detailed model of coated fuel particles.
c    Uses a 1.5 cm exclusion zone and a detailed top reflector.
c
c    J.R. Lebenhaft, MIT, January 2001
c    ------------------------------------------------------------------
c    CELL CARDS
c
c
1    0                    -1: 11: 22           $ outside world
c
c    reactor structure
c
2    1   8.61e-02          1  -2 -20           $ bottom axial reflector
3    3   6.18e-02          5  -6  16 -21       $ Al ring
4    2   8.84e-02          1 -10  20 -22  #3    $ radial reflector
5    4   5.058e-05        10 -11  20 -22       $ air above rad reflector
6    4   5.058e-05         6 -11  19 -20       $ air between Al and refl
7    3   6.18e-02          6 -11  18 -19       $ outer Al cylinder
8    3   6.18e-02          6 -11  12 -13       $ inner Al cylinder
9    3   6.18e-02          6  -7  13 -18       $ lower Al plate
10   3   6.18e-02          8  -9  13 -18       $ upper Al plate - outer
11   3   6.18e-02          8  -9 -12           $ upper Al plate - inner
12   3   6.18e-02          7  -8  14 -15       $ middle Al cylinder
13   4   5.058e-05         7  -8  13 -14       $ inner air cavity
14   4   5.058e-05         7  -8  15 -18       $ outer air cavity
15   1   8.61e-02          9 -11 -12           $ inner axial reflector
16   1   8.61e-02          9 -11  13 -18       $ outer axial reflector
c
c    core cavity
c
20   4   5.058e-05         4  -8 -12           $ air above core center
21   4   5.058e-05         4  -6  12 -20  #3    $ rest of air above core
22   4   5.058e-05         2  -4  17 -20       $ radial exclusion zone
23   4   5.058e-05         2  -3 -17           $ bottom exclusion zone
24   0                     3  -4 -17
     fill=1(1)                                 $ pebble bed
c
c    universe 1: BCC lattice of pebbles
c
31   0                  -51  52 -53  54 -55  56
     lat=1   fill=2
     u=1
c
c    universe 2: contents of unit cell
c
32   0                  -60             fill=3  u=2  $ [ 0  0  0]
33   8  8.61659e-02     -61                     u=2  $ [ 1  1  1]
34   8  8.61659e-02     -62                     u=2  $ [ 1  1 -1]
35   8  8.61659e-02     -63                     u=2  $ [ 1 -1 -1]
```

```
36   8  8.61659e-02     -64                          u=2  $ [ 1 -1  1]
37   8  8.61659e-02     -65                          u=2  $ [-1  1  1]
38   8  8.61659e-02     -66                          u=2  $ [-1  1 -1]
39   8  8.61659e-02     -67                          u=2  $ [-1 -1 -1]
40   8  8.61659e-02     -68                          u=2  $ [-1 -1  1]
41   4  5.058e-05        60  61  62  63  64              $ air between
                        65  66  67  68              u=2  $ pebbles
c
c    universe 3: contents of fuel pebble
c
45   6   8.64564e-02     85                          u=3  $ graphite shell
46   0                  -85                fill=4   u=3  $ fueled region
c
c    universe 4: embedded coated fuel particles
c
50   0                  -87  88 -89  90 -91  92
     lat=1  fill=5
     u=4
c
c    universe 5: coated fuel particle
c
51   10 -10.88          -95                          u=5  $ UO2 kernel
52   11  -1.1            95 -96                      u=5  $ PyC layer 1
53   12  -1.9            96 -97                      u=5  $ PyC layer 2
54   13  -3.2            97 -98                      u=5  $ SiC layer
55   12  -1.89           98 -99                      u=5  $ PyC layer 3
56   6    8.64564e-02    99                          u=5  $ graphite matrix
c
c    ---------------------------------------------------------------------

c    SURFACE CARDS
c
c    reactor structure surfaces
c
1    pz    0.0                      $ bottom of reactor
2    pz   78.0                      $ bottom of pebble bed
3    pz   79.5                      $ bottom exclusion zone
4    pz  234.5                      $ top of core
5    pz  251.0                      $ lower surface of Al ring
6    pz  252.0                      $ upper surface of Al ring
7    pz  252.4                      $ upper surface of bot. Al plate
8    pz  267.0                      $ lower surface of top Al plate
9    pz  267.2                      $ upper surface of top Al plate
10   pz  330.0                      $ top of radial reflector
11   pz  345.3                      $ top of reactor
12   cz   19.88                     $ inside of inner Al cylinder
13   cz   20.38                     $ outside of inner Al cylinder
14   cz   43.15                     $ inside of middle Al cylinder
15   cz   43.55                     $ outside of middle Al cylinder
16   cz   60.0                      $ inner surface of Al ring
17   cz   61.0                      $ radial exclusion zone
18   cz   61.95                     $ inside of outer Al cylinder
19   cz   62.25                     $ outside of outer Al cylinder
20   cz   62.5                      $ inner surface of radial reflector
21   cz   70.0                      $ outer surface of Al ring
22   cz  166.1                      $ outer surface of radial reflector
c
```

```
c     Pebble bed surfaces
c
c     unit cell in core
c
51    px     3.6119940                                        $ [ 1   0   0]
52    px    -3.6119940                                        $ [-1   0   0]
53    py     3.6119940                                        $ [ 0   1   0]
54    py    -3.6119940                                        $ [ 0  -1   0]
55    pz     3.6119940                                        $ [ 0   0   1]
56    pz    -3.6119940                                        $ [ 0   0  -1]
c
c     balls in unit cells
c
60    so     3.0
61    s      3.6119940    3.6119940    3.6119940   3.0
62    s      3.6119940    3.6119940   -3.6119940   3.0
63    s      3.6119940   -3.6119940   -3.6119940   3.0
64    s      3.6119940   -3.6119940    3.6119940   3.0
65    s     -3.6119940    3.6119940    3.6119940   3.0
66    s     -3.6119940    3.6119940   -3.6119940   3.0
67    s     -3.6119940   -3.6119940   -3.6119940   3.0
68    s     -3.6119940   -3.6119940    3.6119940   3.0
c
c     inside fuel pebble
c
85    so     2.5                                              $ fueled region
c
c     unit cell for CFP lattice
c
87    px     0.0955071
88    px    -0.0955071
89    py     0.0955071
90    py    -0.0955071
91    pz     0.0955071
92    pz    -0.0955071
c
c     coated fuel particle
95    so     0.02510                                          $ UO2 kernel
96    so     0.03425                                          $ buffer
97    so     0.03824                                          $ inner PyC
98    so     0.04177                                          $ SiC
99    so     0.04577                                          $ outer PyC
c     ---------------------------------------------------------------------

c      RUN PARAMETERS
c
c      problem type
c
mode  n
kcode 5000 1.0 10 110
ksrc  0  0  81.611994    0  0  88.835982    0  0  96.059970
      0  0 103.283958    0  0 110.507946    0  0 117.731934
      0  0 124.955922    0  0 132.179910    0  0 139.403898
      0  0 146.627886
totnu
print
dbcn  9j  300
```

```
prdmp j   -60  1  2
c
c     neutron importance
c
imp:n 0                                                    $ outside world
      1 14r                                                $ reactor structure
      1 4r                                                 $ core cavity
      1                                                    $ u=1: lattice
      1 9r                                                 $ u=2: unit cell
      1 1                                                  $ u=3: fuel pebble
      1                                                    $ u=4: CFP lattice
      1 5r                                                 $ u=5: CFP
c
c     transformations
c
tr1   0.0         0.0        81.6119940
c
c     material specifications
c
c     axial reflector
m1     6000.60c 8.61e-02     5011.60c 3.60e-08     5010.60c 9.00e-09
mt1   grph.01t
c
c     radial reflector
m2     6000.60c 8.84e-02     5011.60c 3.70e-08     5010.60c 9.20e-09
mt2   grph.01t
c
m3    13027.60c 1                                          $ aluminum
c
c     humid air
m4     1001.60c 5.79913e-07  1002.60c 8.7e-11      7014.60c 3.98536e-05
       7015.60c 1.46400e-07   8016.60c 1.0e-05
c
c     pebble graphite shell
m6     5010.60c 2.47855e-08  5011.60c 1.00394e-07  6000.60c 8.64563e-02
mt6   grph.01t
c
c     moderator pebble (N = 8.38303e-02)
m8     5010.60c 2.40326e-08  5011.60c 9.73442e-08  6000.60c 8.38302e-02
mt8   grph.01t
c
c     fuel kernel (N = 7.292359e-02)
m10   92235.60c 4.11729e-03 92238.60c 2.01906e-02  8016.60c 4.86157e-02
c
c     buffer
m11   6000.60c  5.51511e-02  5011.60c 6.40418e-08  5010.60c 1.58108e-08
mt11  grph.01t
c
c     PyC
m12   6000.60c  9.52609e-02  5011.60c 1.10617e-07  5010.60c 2.73095e-08
mt12  grph.01t
c
c     SiC
m13  14000.60c  4.80603e-02  6000.60c 4.80603e-02  5011.60c 5.58080e-08
      5010.60c  1.37780e-08
mt13  grph.01t
```

APPENDIX A.2: MCNP4B Model of HTR-PROTEUS Core 4.2

```
HTR-PROTEUS EXPERIMENT 4.2 -- IRREGULAR CORE
c
c    MCNP4B model of critical experiment 4.2 in the PROTEUS facility
c    using the detailed geometry specification from the calculational
c    benchmark. The random packing is modeled using a loose BCC, with
c    F/M ratio of one, and a detailed model of coated fuel particles.
c    Uses a 1.5 cm exclusion zone and a detailed top reflector.
c
c    J.R. Lebenhaft, MIT, January 2001
c    ------------------------------------------------------------------
c    CELL CARDS
c
1    0                    -1: 11: 22           $ outside world
c
c    reactor structure
c
2    1    8.61e-02         1  -2 -20           $ bottom axial reflector
3    3    6.18e-02         5  -6  16 -21       $ Al ring
4    2    8.84e-02         1 -10  20 -22  #3   $ radial reflector
5    4    5.058e-05       10 -11  20 -22       $ air above rad reflector
6    4    5.058e-05        6 -11  19 -20       $ air between Al and ref
7    3    6.18e-02         6 -11  18 -19       $ outer Al cylinder
8    3    6.18e-02         6 -11  12 -13       $ inner Al cylinder
9    3    6.18e-02         6  -7  13 -18       $ lower Al plate
10   3    6.18e-02         8  -9  13 -18       $ upper Al plate - outer
11   3    6.18e-02         8  -9 -12           $ upper Al plate - inner
12   3    6.18e-02         7  -8  14 -15       $ middle Al cylinder
13   4    5.058e-05        7  -8  13 -14       $ inner air cavity
14   4    5.058e-05        7  -8  15 -18       $ outer air cavity
15   1    8.61e-02         9 -11 -12           $ inner axial reflector
16   1    8.61e-02         9 -11  13 -18       $ outer axial reflector
c
c    core cavity
c
20   4    5.058e-05        4  -8 -12           $ air above core center
21   4    5.058e-05        4  -6  12 -20  #3   $ rest of air above core
22   4    5.058e-05        2  -4  17 -20       $ radial exclusion zone
23   4    5.058e-05        2  -3 -17           $ bottom exclusion zone
24   0                     3  -4 -17
     fill=1(1)                                 $ pebble bed
c
c    universe 1: BCC lattice of pebbles
c
31   0                  -51  52 -53  54 -55  56
     lat=1   fill=2
     u=1
c
c    universe 2: contents of unit cell
c
32   0                  -60              fill=3  u=2  $ [ 0  0  0]
33   8  8.61659e-02     -61                      u=2  $ [ 1  1  1]
34   8  8.61659e-02     -62                      u=2  $ [ 1  1 -1]
35   8  8.61659e-02     -63                      u=2  $ [ 1 -1 -1]
36   8  8.61659e-02     -64                      u=2  $ [ 1 -1  1]
```

```
37    8  8.61659e-02      -65                          u=2  $ [-1  1  1]
38    8  8.61659e-02      -66                          u=2  $ [-1  1 -1]
39    8  8.61659e-02      -67                          u=2  $ [-1 -1 -1]
40    8  8.61659e-02      -68                          u=2  $ [-1 -1  1]
41    4  5.058e-05         60  61  62  63  64
                          65  66  67  68               u=2  $ air between
pebbles
c
c     universe 3: contents of fuel pebble
c
45    6   8.64564e-02      85                          u=3  $ graphite shell
46    0                   -85              fill=4      u=3  $ fueled region
c
c     universe 4: embedded coated fuel particles
c
50    0                   -87  88 -89  90 -91  92
      lat=1  fill=5
      u=4
c
c     universe 5: coated fuel particle
c
51    10 -10.88           -95                          u=5  $ UO2 kernel
52    11  -1.1             95 -96                      u=5  $ PyC layer 1
53    12  -1.9             96 -97                      u=5  $ PyC layer 2
54    13  -3.2             97 -98                      u=5  $ SiC layer
55    12  -1.89            98 -99                      u=5  $ PyC layer 3
56    6    8.64564e-02     99                          u=5  $ graphite matrix
c
c     ---------------------------------------------------

c     SURFACE CARDS
c
c     reactor structure surfaces
c
1     pz     0.0                    $ bottom of reactor
2     pz    78.0                    $ bottom of pebble bed
3     pz    79.5                    $ bottom exclusion zone
4     pz   228.5                    $ top of pebble bed
5     pz   251.0                    $ lower surface of Al ring
6     pz   252.0                    $ upper surface of Al ring
7     pz   252.4                    $ upper surface of bottom Al plate
8     pz   267.0                    $ lower surface of top Al plate
9     pz   267.2                    $ upper surface of top Al plate
10    pz   330.0                    $ top of radial reflector
11    pz   345.3                    $ top of reactor
12    cz    19.88                   $ inside of inner Al cylinder
13    cz    20.38                   $ outside of inner Al cylinder
14    cz    43.15                   $ inside of middle Al cylinder
15    cz    43.55                   $ outside of middle Al cylinder
16    cz    60.0                    $ inner surface of Al ring
17    cz    61.0                    $ radial exclusion zone
18    cz    61.95                   $ inner surface of outer Al cylinder
19    cz    62.25                   $ outer surface of outer Al cylinder
20    cz    62.5                    $ inner surface of radial reflector
21    cz    70.0                    $ outer surface of Al ring
22    cz   166.1                    $ outer surface of radial reflector
c
```

```
c    pebble bed surfaces
c
c   Unit cell in core
c
51   px    3.5823865                                        $ [-1  0  0]
52   px   -3.5823865                                        $ [ 1  0  0]
53   py    3.5823865                                        $ [ 0  1  0]
54   py   -3.5823865                                        $ [ 0 -1  0]
55   pz    3.5823865                                        $ [ 0  0  1]
56   pz   -3.5823865                                        $ [ 0  0 -1]
c
c   Balls in unit cells
c
60   so    3.0
61   s     3.5823865   3.5823865   3.5823865  3.0
62   s     3.5823865   3.5823865  -3.5823865  3.0
63   s     3.5823865  -3.5823865  -3.5823865  3.0
64   s     3.5823865  -3.5823865   3.5823865  3.0
65   s    -3.5823865   3.5823865   3.5823865  3.0
66   s    -3.5823865   3.5823865  -3.5823865  3.0
67   s    -3.5823865  -3.5823865  -3.5823865  3.0
68   s    -3.5823865  -3.5823865   3.5823865  3.0
c
c    inside fuel pebble
c
85   so    2.5                                              $ fueled region
c
c    unit cell for CFP lattice
c
87   px    0.0955071
88   px   -0.0955071
89   py    0.0955071
90   py   -0.0955071
91   pz    0.0955071
92   pz   -0.0955071
c
c    coated fuel particle
95   so    0.02510                                          $ UO2 kernel
96   so    0.03425                                          $ buffer
97   so    0.03824                                          $ inner PyC
98   so    0.04177                                          $ SiC
99   so    0.04577                                          $ outer PyC
c    ---------------------------------------------------------------------

c     RUN PARAMETERS
c
c     problem type
c
mode  n
kcode 5000 1.0 10 110
ksrc  0  0  81.5823865  0  0  88.7471595  0  0  95.9119325
      0  0 103.0767055  0  0 110.2414785  0  0 117.4062515
      0  0 124.5710245  0  0 131.7357975  0  0 138.9005705
      0  0 146.0653435
totnu
print
dbcn  9j  300
```

```
prdmp j   -60  1  2
c
c     neutron importance
c
imp:n 0                                                $ outside world
      1 14r                                            $ reactor structure
      1 4r                                             $ core cavity
      1                                                $ u=1: lattice
      1 9r                                             $ u=2: unit cell
      1 1                                              $ u=3: fuel pebble
      1                                                $ u=4: CFP lattice
      1 5r                                             $ u=5: CFP
c
c     transformations
c
tr1   0.0        0.0       81.5823865
c
c     material specifications
c
c     axial reflector
m1     6000.60c 8.61e-02     5011.60c 3.60e-08     5010.60c 9.00e-09
mt1   grph.01t
c
c     radial reflector
m2     6000.60c 8.84e-02     5011.60c 3.70e-08     5010.60c 9.20e-09
mt2   grph.01t
c
m3    13027.60c 1                                  $ aluminum
c
c     humid air
m4     1001.60c 5.79913e-07  1002.60c 8.7e-11      7014.60c 3.98536e-05
       7015.60c 1.46400e-07   8016.60c 1.0e-05
c
c     pebble graphite shell
m6     5010.60c 2.47855e-08  5011.60c 1.00394e-07  6000.60c 8.64563e-02
mt6   grph.01t
c
c     moderator pebble (N = 8.38303e-02)
m8     5010.60c 2.40326e-08  5011.60c 9.73442e-08  6000.60c 8.38302e-02
mt8   grph.01t
c
c     fuel kernel (N = 6.958395e-02)
m10   92235.60c 4.11729e-03 92238.60c 2.01906e-02  8016.60c 4.86157e-02
c
c     buffer
m11   6000.60c  5.51511e-02  5011.60c 6.40418e-08  5010.60c 1.58108e-08
mt11  grph.01t
c
c     PyC
m12   6000.60c  9.52609e-02  5011.60c 1.10617e-07  5010.60c 2.73095e-08
mt12  grph.01t
c
c     SiC
m13  14000.60c  4.80603e-02  6000.60c 4.80603e-02  5011.60c 5.58080e-08
      5010.60c  1.37780e-08
mt13  grph.01t
```

APPENDIX A.3: MCNP4B Model of HTR-PROTEUS Core 4.3

```
HTR-PROTEUS EXPERIMENT 4.3 -- IRREGULAR CORE
c
c    MCNP4B model of critical experiment 4.3 in the PROTEUS facility
c    using the detailed geometry specification from the calculational
c    benchmark. The random packing is modeled using a loose BCC, with
c    F/M ratio of one, and a detailed model of coated fuel particles.
c    Uses a 1.5 cm exclusion zone to account for partial pebbles at
c    core edge, and a detailed representation of the top reflector.
c
c    J.R. Lebenhaft, MIT, January 2001
c    ------------------------------------------------------------------
c    CELL CARDS
c
c
1    0                    -1: 11: 22           $ outside world
c
c    reactor structure
c
2    1   8.61e-02          1  -2 -20           $ bottom axial reflector
3    3   6.18e-02          5  -6  16 -21       $ Al ring
4    2   8.84e-02          1 -10  20 -22  #3    $ radial reflector
5    4   5.058e-05        10 -11  20 -22       $ air above rad reflector
6    4   5.058e-05         6 -11  19 -20       $ air between Al and ref
7    3   6.18e-02          6 -11  18 -19       $ outer Al cylinder
8    3   6.18e-02          6 -11  12 -13       $ inner Al cylinder
9    3   6.18e-02          6  -7  13 -18       $ lower Al plate
10   3   6.18e-02          8  -9  13 -18       $ upper Al plate - outer
11   3   6.18e-02          8  -9 -12           $ upper Al plate - inner
12   3   6.18e-02          7  -8  14 -15       $ middle Al cylinder
13   4   5.058e-05         7  -8  13 -14       $ inner air cavity
14   4   5.058e-05         7  -8  15 -18       $ outer air cavity
15   1   8.61e-02          9 -11 -12           $ inner axial reflector
16   1   8.61e-02          9 -11  13 -18       $ outer axial reflector
c
c    core cavity
c
20   4   5.058e-05         4  -8 -12           $ air above core center
21   4   5.058e-05         4  -6  12 -20  #3    $ rest of air above core
22   4   5.058e-05         2  -4  17 -20       $ radial exclusion zone
23   4   5.058e-05         2  -3 -17           $ bottom exclusion zone
24   0                     3  -4 -17
     fill=1(1)                                 $ pebble bed
c
c    universe 1: BCC lattice of pebbles
c
31   0                  -51  52 -53  54 -55  56
     lat=1   fill=2
     u=1
c
c    universe 2: contents of unit cell
c
32   0                  -60              fill=3  u=2  $ [ 0  0  0]
33   8  8.61659e-02     -61                      u=2  $ [ 1  1  1]
34   8  8.61659e-02     -62                      u=2  $ [ 1  1 -1]
```

```
35   8  8.61659e-02     -63                          u=2  $ [ 1 -1 -1]
36   8  8.61659e-02     -64                          u=2  $ [ 1 -1  1]
37   8  8.61659e-02     -65                          u=2  $ [-1  1  1]
38   8  8.61659e-02     -66                          u=2  $ [-1  1 -1]
39   8  8.61659e-02     -67                          u=2  $ [-1 -1 -1]
40   8  8.61659e-02     -68                          u=2  $ [-1 -1  1]
41   4  5.058e-05        60  61  62  63  64
                        65  66  67  68                u=2  $ air bet pebbles
c
c    universe 3: contents of fuel pebble
c
45   6   8.64564e-02     85                          u=3  $ graphite shell
46   0                  -85              fill=4      u=3  $ fueled region
c
c    universe 4: embedded coated fuel particles
c
50   0                  -87  88 -89  90 -91  92
     lat=1  fill=5
     u=4
c
c    universe 5: coated fuel particle
c
51   10 -10.88          -95                          u=5  $ UO2 kernel
52   11  -1.1            95 -96                      u=5  $ PyC layer 1
53   12  -1.9            96 -97                      u=5  $ PyC layer 2
54   13  -3.2            97 -98                      u=5  $ SiC layer
55   12  -1.89           98 -99                      u=5  $ PyC layer 3
56   6    8.64564e-02    99                          u=5  $ graphite matrix
c
c    ---------------------------------------------

c    SURFACE CARDS
c
c    reactor structure surfaces
c
1    pz    0.0                    $ bottom of reactor
2    pz   78.0                    $ bottom of pebble bed
3    pz   79.5                    $ bottom exclusion zone
4    pz  226.5                    $ top of pebble bed minus exclusion
5    pz  251.0                    $ lower surface of Al ring
6    pz  252.0                    $ upper surface of Al ring
7    pz  252.4                    $ upper surface of bottom Al plate
8    pz  267.0                    $ lower surface of top Al plate
9    pz  267.2                    $ upper surface of top Al plate
10   pz  330.0                    $ top of radial reflector
11   pz  345.3                    $ top of reactor
12   cz   19.88                   $ inside of inner Al cylinder
13   cz   20.38                   $ outside of inner Al cylinder
14   cz   43.15                   $ inside of middle Al cylinder
15   cz   43.55                   $ outside of middle Al cylinder
16   cz   60.0                    $ inner surface of Al ring
17   cz   61.0                    $ radial exclusion zone
18   cz   61.95                   $ inner surface of outer Al cylinder
19   cz   62.25                   $ outer surface of outer Al cylinder
20   cz   62.5                    $ inner surface of radial reflector
21   cz   70.0                    $ outer surface of Al ring
22   cz  166.1                    $ outer surface of radial reflector
```

```
c
c    pebble bed surfaces
c
c   Unit cell in core
c
51    px     3.576580                                    $ [-1   0   0]
52    px    -3.576580                                    $ [ 1   0   0]
53    py     3.576580                                    $ [ 0   1   0]
54    py    -3.576580                                    $ [ 0  -1   0]
55    pz     3.576580                                    $ [ 0   0   1]
56    pz    -3.576580                                    $ [ 0   0  -1]
c
c   Balls in unit cells
c
60    so     3.0
61    s      3.576580     3.576580     3.576580    3.0
62    s      3.576580     3.576580    -3.576580    3.0
63    s      3.576580    -3.576580    -3.576580    3.0
64    s      3.576580    -3.576580     3.576580    3.0
65    s     -3.576580     3.576580     3.576580    3.0
66    s     -3.576580     3.576580    -3.576580    3.0
67    s     -3.576580    -3.576580    -3.576580    3.0
68    s     -3.576580    -3.576580     3.576580    3.0
c
c    inside fuel pebble
c
85    so     2.5                                         $ fueled region
c
c    unit cell for CFP lattice
c
87    px     0.0955071
88    px    -0.0955071
89    py     0.0955071
90    py    -0.0955071
91    pz     0.0955071
92    pz    -0.0955071
c
c    coated fuel particle
95    so     0.02510                                     $ UO2 kernel
96    so     0.03425                                     $ buffer
97    so     0.03824                                     $ inner PyC
98    so     0.04177                                     $ SiC
99    so     0.04577                                     $ outer PyC
c    ------------------------------------------------------------------------

c     RUN PARAMETERS
c
c     problem type
c
mode  n
kcode 5000 1.0 10 110
ksrc  0  0  81.576580   0  0  88.729740   0  0  95.882900
      0  0 103.036060   0  0 110.189220   0  0 117.342380
      0  0 124.495540   0  0 131.648700   0  0 138.801860
      0  0 145.955020
totnu
print
```

```
dbcn  9j  300
prdmp j   -60  1  2
c
c     neutron importance
c
imp:n 0                                              $ outside world
      1 14r                                          $ reactor structure
      1 4r                                           $ core cavity
      1                                              $ u=1: lattice
      1 9r                                           $ u=2: unit cell
      1 1                                            $ u=3: fuel pebble
      1                                              $ u=4: CFP lattice
      1 5r                                           $ u=5: CFP
c
c     transformations
c
tr1   0.0        0.0       81.576580
c
c     material specifications
c
c     axial reflector
m1     6000.60c 8.61e-02     5011.60c 3.60e-08     5010.60c 9.00e-09
mt1   grph.01t
c
c     radial reflector
m2     6000.60c 8.84e-02     5011.60c 3.70e-08     5010.60c 9.20e-09
mt2   grph.01t
c
m3    13027.60c 1                                  $ aluminum
c
c     humid air
m4     1001.60c 5.79913e-07  1002.60c 8.7e-11      7014.60c 3.98536e-05
       7015.60c 1.46400e-07  8016.60c 1.0e-05
c
c     pebble graphite shell
m6     5010.60c 2.47855e-08  5011.60c 1.00394e-07  6000.60c 8.64563e-02
mt6   grph.01t
c
c     moderator pebble (N = 8.38303e-02)
m8     5010.60c 2.40326e-08  5011.60c 9.73442e-08  6000.60c 8.38302e-02
mt8   grph.01t
c
c     fuel kernel (N = 6.958395e-02)
m10   92235.60c 4.11729e-03 92238.60c 2.01906e-02  8016.60c 4.86157e-02
c
c     buffer
m11   6000.60c  5.51511e-02  5011.60c 6.40418e-08  5010.60c 1.58108e-08
mt11  grph.01t
c
c     PyC
m12   6000.60c  9.52609e-02  5011.60c 1.10617e-07  5010.60c 2.73095e-08
mt12  grph.01t
c
c     SiC
m13  14000.60c  4.80603e-02  6000.60c 4.80603e-02  5011.60c 5.58080e-08
      5010.60c  1.37780e-08
mt13  grph.01t
```

APPENDIX B. MCNP4B Models of HTR-10

This Appendix contains the MCNP4B input files with models of the HTR-10 reactor. The model of the initial critical core for benchmark problem B1, which uses the standard ENDF/B-VI cross-section libraries, appears in Appendix B.1. The model of the reactor for benchmark problem B2.1, with a full core and using the University of Texas at Austin libraries, appears in Appendix B.2. Details of the HTR-10 reactor appear in Chapter 5.

APPENDIX B-1: MCNP4B Model of HTR-10 Benchmark Problem B1

```
HTR-10 PEBBLE-BED REACTOR
c
c   MCNP4B model of the HTR-10 initial core, based on IAEA benchmark
c   problem CRP-5 specification. Benchmark problem B1.
c
c   Modeling assumptions:
c
c   A BCC lattice of spheres in core with 0.61 packing fraction and a
c   1:1 mix of fuel and moderator pebbles in cylindrical portion of
c   core, but adjusted with moderator pebble size reduced to
c   approximate a 57:43 fuel-to-moderator ratio. The control,
c   irradiation, KLAK and He channels were modeled explicitly.  A 1.71
c   cm radial exclusion zone corrects for core-edge fuel pebbles.
c
c   Prepared by J.R. Lebenhaft (MIT) December 2000
c
c   ---------------------------------------------------------------
c   Revision history:
c
c   January 2001, J. Lebenhaft - detailed model of control rods
c
=========================================================================
c    CELL CARDS
c
1    0                    1: -17:  29                    $ outside world
c
c    Graphite reactor structure
c
2    2   0.0762391      -1    2  -23                     $ zone 1
3    3   0.0851467      -2    3  -23                     $ zone 2
4    4   0.0145351      -3    4  -23                     $ zone 3
5    5   0.0802920      -4    6  -23                     $ zone 4
6    1   0.0851052      30    9  -23                     $ zone 0
7    7   0.0538278      -9   14  -20                     $ zone 6
8    7   0.0538278     -14   16  -20                     $ zone 7
9    18  0.0797184     -16   17  -20                     $ zone 81
10   8   0.0781412      -9   10   20  -23                $ zone 8
11   9   0.0823755     -10   11   20  -23                $ zone 9
12   10  0.0846632     -11   12   20  -21                $ zone 10
13   11  0.0818665     -11   12   21  -23                $ zone 11
14   12  0.0852881     -12   15   20  -21                $ zone 12
15   13  0.0819526     -12   13   21  -23                $ zone 13
16   14  0.0541695     -13   14   21  -22                $ zone 14
17   15  0.0332112     -13   14   22  -23                $ zone 15
18   16  0.0882170     -14   15   21  -23                $ zone 16
19   17  0.0800619     -15   16   20  -24                $ zone 17
20   18  0.0797184     -16   17   20  -24                $ zone 18
21   19  0.0795574      -1    2   23  -24                $ zone 19
22   20  0.0878379      -2    3   23  -24                $ zone 20
23   21  0.0579699      -3    4   23  -24                $ zone 21
24   22  0.0882423      -4    9   23  -24                $ zone 22
25   22  0.0882423      -9   11   23  -24                $ zone 23
26   23  0.0881225     -11   12   23  -24                $ zone 24
```

```
27   22  0.0882423      -12   13   23  -24                $ zone 25
28   24  0.0846759      -13   14   23  -24                $ zone 26
29   22  0.0882423      -14   15   23  -24                $ zone 80
30   25  8.55939e-02     -1    2   24  -25                $ zone 27
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316  314))
                        340  341  342
31   26  9.43585e-02     -2    3   24  -25                $ zone 28
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
                        340  341  342
32   27  5.61302e-02     -3    4   24  -25                $ zone 29
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
                        340  341  342
33   26  9.43585e-02     -4    5   24  -25                $ zone 82
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
                        340  341  342
34   28  9.43396e-02     -5    6   24  -25                $ zone 30
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
```

```
                          340   341   342
35    29   8.81642e-02     -6     9    24   -25                  $ zones 31-40
                          260   261   262   263    264
                          265   266   267   268    269
                         (275:-276:(277   279):(280 -278))
                         (281:-282:(283   285):(286 -284))
                         (287:-288:(289   291):(292 -290))
                         (293:-294:(295   297):(298 -296))
                         (299:-300:(301   303):(304 -302))
                         (305:-306:(307   309):(310 -308))
                         (311:-312:(313   315):(316 -314))
                          340   341   342
76    45   9.43396e-02     -9    18    24   -25                  $ zone 41a -
260   261   262   263   264    265                               $ at bottom
                          266   267   268   269                  $ of CR
                         (275:-276:(277   279):(280 -278))
                         (281:-282:(283   285):(286 -284))
                         (287:-288:(289   291):(292 -290))
                         (293:-294:(295   297):(298 -296))
                         (299:-300:(301   303):(304 -302))
                         (305:-306:(307   309):(310 -308))
                         (311:-312:(313   315):(316 -314))
36    28   0.0678903      -18    11    24   -25                  $ zone 41b
37    30   0.0678011      -11    12    24   -25                  $ zone 42
38    31   0.0861481      -12    13    24   -25                  $ zone 43
39    32   0.0829070      -13    14    24   -25                  $ zone 44
40    31   0.0861481      -14    15    24   -25                  $ zone 45
41    33   0.0781618      -15    16    24   -25                  $ zone 46
42    18   0.0778265      -16    17    24   -25                  $ zone 47
43    17   0.0800619       -1     2    25   -28                  $ zone 74
44    22   0.0882423       -2     3    25   -27                  $ zone 66a
45    22   0.0882423       -2     9    27   -28                  $ zone 66b
46    35   0.0582702       -3     4    25   -26                  $ zone 48
47    22   0.0882423       -4     9    25   -26                  $ zone 49
48    22   0.0882423       -9    11    25   -26                  $ zone 50
49    23   0.0881225      -11    12    25   -26                  $ zone 51
50    22   0.0882423      -12    13    25   -26                  $ zone 52
51    36   0.0855865      -13    14    25   -26                  $ zone 53
52    22   0.0882423      -14    15    25   -26                  $ zone 54
53    17   0.0800619      -15    16    25   -26                  $ zone 55
54    18   0.0797184      -16    17    25   -26                  $ zone 56
55    37   0.0728266       -3     4    26   -27                  $ zone 57
56    38   0.0760372       -4     9    26   -27                  $ zone 58
                          320   321   322   323   324
                          325   326   327   328   329
                          330   331   332   333   334
                          335   336   337   338   339
57    38   0.0760372       -9    11    26   -27                  $ zone 59
58    39   0.0759340      -11    12    26   -27                  $ zone 60
59    38   0.0760372      -12    13    26   -27                  $ zone 61
60    40   0.0737488      -13    14    26   -27                  $ zone 62
61    38   0.0760372      -14    15    26   -27                  $ zone 63
62    41   0.0689883      -15    16    26   -27                  $ zone 64
63    18   0.0686924      -16    17    26   -27                  $ zone 65
64    22   0.0882423       -9    11    27   -28                  $ zone 67
65    23   0.0881225      -11    12    27   -28                  $ zone 68
66    22   0.0882423      -12    13    27   -28                  $ zone 69
```

```
67   43  0.0861505     -13   14   27  -28                $ zone 70
68   22  0.0882423     -14   15   27  -28                $ zone 71
69   17  0.0800619     -15   16   27  -28                $ zone 72
70   18  0.0797184     -16   17   27  -28                $ zone 73
71   17  0.0800619      -1    2   28  -29                $ zone 75
72   17  0.0800619      -2   13   28  -29                $ zone 76
73   44  0.0783836     -13   14   28  -29                $ zone 77
74   17  0.0800619     -14   16   28  -29                $ zone 78
75   17  0.0800619     -16   17   28  -29                $ zone 79
c
c    Cavity above core
c
80   50  5.058e-05      -6    7  -23                     $ air
c
c    ---------------------------------------------------------------
c    Cylindrical Region of Core
c
84   50  5.058e-05     -7   8  19 -23                    $ radial gap
85   0                 -7   8 -19          fill=10(1)    $ pebble bed
c
c    Universe 10: BCC lattice of fuel and dummy spheres
c
86   0                45 -46 -47  48 -49  50
     lat=1  fill=11
     u=10
c
c    Universe 11: unit cell
c
87   0                 -51             fill=12  u=11  $ fuel [ 0  0  0]
88   64  9.225716e-02  -52                      u=11  $ mod  [ 1  1  1]
89   64  9.225716e-02  -53                      u=11  $ mod  [ 1  1 -1]
90   64  9.225716e-02  -54                      u=11  $ mod  [ 1 -1 -1]
91   64  9.225716e-02  -55                      u=11  $ mod  [ 1 -1  1]
92   64  9.225716e-02  -56                      u=11  $ mod  [-1  1  1]
93   64  9.225716e-02  -57                      u=11  $ mod  [-1  1 -1]
94   64  9.225716e-02  -58                      u=11  $ mod  [-1 -1 -1]
95   64  9.225716e-02  -59                      u=11  $ mod  [-1 -1  1]
96   50  5.058e-05       51  52  53  54  55
                         56  57  58  59          u=11  $ air in between
c
c    Universe 12: details of fuel element
c
97   65  8.674180e-02   41                      u=12  $ graphite shell
98   0                 -41             fill=13  u=12  $ fuel region
c
c    Universe 13: embedded coated fuel particles
c
99   0               -250  251 -252  253 -254  255
     lat=1  fill=14
     u=13
c
c    Universe 14:  coated fuel particle
c
100  61  6.970994e-02 -245                      u=14  $ UO2 kernel
101  62 -1.1           245 -246                 u=14  $ PyC layer 1
102  62 -1.9           246 -247                 u=14  $ PyC layer 2
103  63 -3.18          247 -248                 u=14  $ SiC layer
```

```
104  62 -1.9           248 -249                  u=14  $ PyC layer 3
105  65  8.674180e-02  249                       u=14  $ graphite matrix
c
c    ---------------------------------------------------------------
c    Conus Region of Core (dummy balls)
c
110  0                  -8   9 -30      fill=20(2)
c
c    Universe 20: BCC lattice of dummy spheres
c
111  0                  45 -46 -47  48 -49  50
     lat=1  fill=21
     u=20
c
c    Universe 21: unit cell
c
112  64  9.225716e-02  -51                       u=21  $ mod [ 0  0  0]
113  64  9.225716e-02  -52                       u=21  $ mod [ 1  1  1]
114  64  9.225716e-02  -53                       u=21  $ mod [ 1  1 -1]
115  64  9.225716e-02  -54                       u=21  $ mod [ 1 -1 -1]
116  64  9.225716e-02  -55                       u=21  $ mod [ 1 -1  1]
117  64  9.225716e-02  -56                       u=21  $ mod [-1  1  1]
118  64  9.225716e-02  -57                       u=21  $ mod [-1  1 -1]
119  64  9.225716e-02  -58                       u=21  $ mod [-1 -1 -1]
120  64  9.225716e-02  -59                       u=21  $ mod [-1 -1  1]
121  50  5.058e-05      51  52  53  54  55
                        56  57  58  59           u=21  $ air in between
c
c    ---------------------------------------------------------------
c    Control rod sites
c
130  0                -1  18 -260     fill=25(15)     $  CR1
131  0                -1  18 -261     fill=25(16)     $  CR2
132  0                -1  18 -262     fill=25(17)     $  CR3
133  0                -1  18 -263     fill=25(18)     $  CR4
134  0                -1  18 -264     fill=25(19)     $  CR5
135  0                -1  18 -265     fill=25(20)     $  CR6
136  0                -1  18 -266     fill=25(21)     $  CR7
137  0                -1  18 -267     fill=25(22)     $  CR8
138  0                -1  18 -268     fill=25(23)     $  CR9
139  0                -1  18 -269     fill=25(24)     $  CR10
c
c    Universe 25: contents of CR guide tubes
c
145  50  5.058e-05   367                          u=25  $ air around CR
146  50  5.058e-05  -367 -350                     u=25  $ air below CR
147  0              -367  350         fill=26     u=25  $ CR
c
c    Universe 26: control rod
c
148  51 -7.9        -351  362                     u=26  $ lower end
c
c    segment 1
c
149  51 -7.9         351 -352  362 -363           u=26  $ inner sleeve
150  50  5.058e-05   351 -352  363 -364           u=26  $ gap
151  52 -1.7         351 -352  364 -365           u=26  $ B4C
```

```
152  50  5.058e-05   351 -352  365 -366          u=26  $ gap
153  51 -7.9         351 -352  366               u=26  $ outer sleeve
c
154  51 -7.9         352 -353  362               u=26  $ joint 1
c
c    segment 2
c
155  51 -7.9         353 -354  362 -363          u=26  $ inner sleeve
156  50  5.058e-05   353 -354  363 -364          u=26  $ gap
157  52 -1.7         353 -354  364 -365          u=26  $ B4C
158  50  5.058e-05   353 -354  365 -366          u=26  $ gap
159  51 -7.9         353 -354  366               u=26  $ outer sleeve
c
160  51 -7.9         354 -355  362               u=26  $ joint 2
c
c    segment 3
c
161  51 -7.9         355 -356  362 -363          u=26  $ inner sleeve
162  50  5.058e-05   355 -356  363 -364          u=26  $ gap
163  52 -1.7         355 -356  364 -365          u=26  $ B4C
164  50  5.058e-05   355 -356  365 -366          u=26  $ gap
165  51 -7.9         355 -356  366               u=26  $ outer sleeve
c
166  51 -7.9         356 -357  362               u=26  $ joint 3
c
c    segment 4
c
167  51 -7.9         357 -358  362 -363          u=26  $ inner sleeve
168  50  5.058e-05   357 -358  363 -364          u=26  $ gap
169  52 -1.7         357 -358  364 -365          u=26  $ B4C
170  50  5.058e-05   357 -358  365 -366          u=26  $ gap
171  51 -7.9         357 -358  366               u=26  $ outer sleeve
c
172  51 -7.9         358 -359  362               u=26  $ joint 4
c
c    segment 5
c
173  51 -7.9         359 -360  362 -363          u=26  $ inner sleeve
174  50  5.058e-05   359 -360  363 -364          u=26  $ gap
175  52 -1.7         359 -360  364 -365          u=26  $ B4C
176  50  5.058e-05   359 -360  365 -366          u=26  $ gap
177  51 -7.9         359 -360  366               u=26  $ outer sleeve
c
178  51 -7.9         360 -361  362               u=26  $ upper end
179  50  5.058e-05  -361 -362                    u=26  $ centre channel
180  50  5.058e-05   361                         u=26  $ above rod
c
c    ------------------------------------------------------------------
c    Absorber ball KLAK sites
c
190  50  5.058e-05    -1  18 -275  276 (-277:-279) (278:-280)     $ KL1
191  50  5.058e-05    -1  18 -281  282 (-283:-285) (284:-286)     $ KL2
192  50  5.058e-05    -1  18 -287  288 (-289:-291) (290:-292)     $ KL3
193  50  5.058e-05    -1  18 -293  294 (-295:-297) (296:-298)     $ KL4
194  50  5.058e-05    -1  18 -299  300 (-301:-303) (302:-304)     $ KL5
195  50  5.058e-05    -1  18 -305  306 (-307:-309) (308:-310)     $ KL6
196  50  5.058e-05    -1  18 -311  312 (-313:-315) (314:-316)     $ KL7
```

```
c
c    ------------------------------------------------------------------
c    Helium flow channels
c
200   50   5.058e-05     -4    9 -320                        $ HE1
201   50   5.058e-05     -4    9 -321                        $ HE2
202   50   5.058e-05     -4    9 -322                        $ HE3
203   50   5.058e-05     -4    9 -323                        $ HE4
204   50   5.058e-05     -4    9 -324                        $ HE5
205   50   5.058e-05     -4    9 -325                        $ HE6
206   50   5.058e-05     -4    9 -326                        $ HE7
207   50   5.058e-05     -4    9 -327                        $ HE8
208   50   5.058e-05     -4    9 -328                        $ HE9
209   50   5.058e-05     -4    9 -329                        $ HE10
210   50   5.058e-05     -4    9 -330                        $ HE11
211   50   5.058e-05     -4    9 -331                        $ HE12
212   50   5.058e-05     -4    9 -332                        $ HE13
213   50   5.058e-05     -4    9 -333                        $ HE14
214   50   5.058e-05     -4    9 -334                        $ HE15
215   50   5.058e-05     -4    9 -335                        $ HE16
216   50   5.058e-05     -4    9 -336                        $ HE17
217   50   5.058e-05     -4    9 -337                        $ HE18
218   50   5.058e-05     -4    9 -338                        $ HE19
219   50   5.058e-05     -4    9 -339                        $ HE20
c
c    ------------------------------------------------------------------
c    Irradiation channels
c
230   50   5.058e-05     -1    9 -340                        $ IR1
231   50   5.058e-05     -1    9 -341                        $ IR2
232   50   5.058e-05     -1    9 -342                        $ IR3
c
======================================================================

c  SURFACE CARDS
c
1    pz       0.0              $ Top of borated C bricks at reactor top
2    pz     -40.0              $ Bottom of borated C bricks @ reactor top
3    pz     -95.0              $ Upper surface of cold He chamber
4    pz    -105.0              $ Lower surface of cold He chamber
5    pz    -114.7              $ Surface between axial regions 30 and 82
6    pz    -130.0              $ Lower surface of top reflector
c    7    pz    -171.698           $ Top of fueled region (full core)
7    pz    -224.318            $ Top of fueled region (initial critical)
8    pz    -351.818            $ Upper surface of cone region
9    pz    -388.764            $ Lower surface of cone region
10   pz    -402.0              $ Surface between axial regions 8 and 9
11   pz    -430.0              $ Surface between axial regions 9 and 10
12   pz    -450.0              $ Surface between axial regions 10 and 12
13   pz    -465.0              $ Surface between axial regions 13 and 14
14   pz    -495.0              $ Surface between axial regions 6 and 7
15   pz    -510.0              $ Surface between axial regions 16 and 17
16   pz    -540.0              $ Surface between axia regions 7 and 81
17   pz    -610.0              $ Bottom of reactor
18   pz    -394.2              $ Bottom of CR guide hole
c
19   cz      88.29             $ radial fuel exclusion zone
```

```
20  cz      25.0
21  cz      41.75
22  cz      70.75
23  cz      90.0                $ Inner surface of radial reflector
24  cz      95.6                $ Inner surface of control rod region
25  cz     108.6                $ Outer surface of control rod region
26  cz     140.6                $ Inner surface of He flow region
27  cz     148.6                $ Outer surface of He flow region
28  cz     167.793              $ Outer surface of side graphite reflector
29  cz     190.0                $ Outside of radial borated C bricks
c
30  kz    -402.974 3.09522 1    $ Outer surface of bottom cone
c
c   Fuel element
c
41  so      2.5                                          $ fuel region
c
c   Unit cell in core
c
45  px     -3.4386                                       $ [-1  0  0]
46  px      3.4386                                       $ [ 1  0  0]
47  py      3.4386                                       $ [ 0  1  0]
48  py     -3.4386                                       $ [ 0 -1  0]
49  pz      3.4386                                       $ [ 0  0  1]
50  pz     -3.4386                                       $ [ 0  0 -1]
c
c   Pebbles in unit BCC cells
c
51  so      3.0                                          $ centre fuel
52  s       3.4386  3.4386  3.4386  2.731               $
53  s       3.4386  3.4386 -3.4386  2.731               $
54  s       3.4386 -3.4386 -3.4386  2.731               $
55  s       3.4386 -3.4386  3.4386  2.731               $ reduced
56  s      -3.4386  3.4386  3.4386  2.731               $ radius
57  s      -3.4386  3.4386 -3.4386  2.731               $ moderator
58  s      -3.4386 -3.4386 -3.4386  2.731               $ spheres
59  s      -3.4386 -3.4386  3.4386  2.731               $
c
c   Coated Fuel Particles
c
245 so      0.025                                        $ kernel
246 so      0.034                                        $ 1st PyC layer
247 so      0.038                                        $ 2nd PyC layer
248 so      0.0415                                       $ SiC layer
249 so      0.0455                                       $ 3rd PyC layer
c
c   Unit cell for CFP lattice in graphite matrix
c
250 px      0.09938918
251 px     -0.09938918
252 py      0.09938918
253 py     -0.09938918
254 pz      0.09938918
255 pz     -0.09938918
c
c   Control rod channels
c
```

```
260 c/z    90.972   46.352  6.49   $ CR1
261 c/z    46.352   90.972  6.49   $ CR2
262 c/z   -15.972  100.843  6.49   $ CR3
263 c/z   -72.196   72.196  6.49   $ CR4
264 c/z  -100.843   15.972  6.49   $ CR5
265 c/z   -90.972  -46.352  6.49   $ CR6
266 c/z   -46.352  -90.972  6.49   $ CR7
267 c/z    15.972 -100.843  6.49   $ CR8
268 c/z    72.196  -72.196  6.49   $ CR9
269 c/z   100.843  -15.972  6.49   $ CR10
c
c   Small absorber ball channels
c
c   .. KL1
275 5   px     3.0
276 5   px    -3.0
277 5   py     5.0
278 5   py    -5.0
279 5   c/z    0.0  5.0  3.0
280 5   c/z    0.0 -5.0  3.0
c
c   .. KL2
281 6   px     3.0
282 6   px    -3.0
283 6   py     5.0
284 6   py    -5.0
285 6   c/z    0.0  5.0  3.0
286 6   c/z    0.0 -5.0  3.0
c
c   .. KL3
287 7   px     3.0
288 7   px    -3.0
289 7   py     5.0
290 7   py    -5.0
291 7   c/z    0.0  5.0  3.0
292 7   c/z    0.0 -5.0  3.0
c
c   .. KL4
293 8   px     3.0
294 8   px    -3.0
295 8   py     5.0
296 8   py    -5.0
297 8   c/z    0.0  5.0  3.0
298 8   c/z    0.0 -5.0  3.0
c
c   .. KL5
299 9   px     3.0
300 9   px    -3.0
301 9   py     5.0
302 9   py    -5.0
303 9   c/z    0.0  5.0  3.0
304 9   c/z    0.0 -5.0  3.0
c
c   .. KL6
305 10  px     3.0
306 10  px    -3.0
307 10  py     5.0
```

```
308 10  py     -5.0
309 10  c/z     0.0  5.0  3.0
310 10  c/z     0.0 -5.0  3.0
c
c    .. KL7
311 11  px      3.0
312 11  px     -3.0
313 11  py      5.0
314 11  py     -5.0
315 11  c/z     0.0  5.0  3.0
316 11  c/z     0.0 -5.0  3.0
c
c    Helium flow channels
c
320 c/z  142.820   22.620  3.99                    $ HE1
321 c/z  128.840   65.647  3.99                    $ HE2
322 c/z  102.248  102.248  3.99                    $ HE3
323 c/z   65.647  128.840  3.99                    $ HE4
324 c/z   22.620  142.820  3.99                    $ HE5
325 c/z  -22.620  142.820  3.99                    $ HE6
326 c/z  -65.647  128.840  3.99                    $ HE7
327 c/z -102.248  102.248  3.99                    $ HE8
328 c/z -128.840   65.647  3.99                    $ HE9
329 c/z -142.82    22.620  3.99                    $ HE10
330 c/z -142.82   -22.620  3.99                    $ HE11
331 c/z -128.84   -65.647  3.99                    $ HE12
332 c/z -102.248 -102.248  3.99                    $ HE13
333 c/z  -65.647 -128.840  3.99                    $ HE14
334 c/z  -22.620 -142.820  3.99                    $ HE15
335 c/z   22.620 -142.820  3.99                    $ HE16
336 c/z   65.647 -128.840  3.99                    $ HE17
337 c/z  102.248 -102.248  3.99                    $ HE18
338 c/z  128.840  -65.647  3.99                    $ HE19
339 c/z  142.820  -22.620  3.99                    $ HE20
c
c    Irradiation Channels
c
340 c/z  100.843   15.972  6.49                    $ IR1
341 c/z -100.843  -15.972  6.49                    $ IR2
342 c/z  -15.972 -100.843  6.49                    $ IR3
c
c    Control Rods
c
350 25  pz      0.001                    $ bottom of contro
rod
351 25  pz      4.501                    $ segment 1 -
bottom
352 25  pz     53.201                    $ segment 1 - top
353 25  pz     56.801                    $ segment 2 -
bottom
354 25  pz    105.501                    $ segment 2 - top
355 25  pz    109.101                    $ segment 3 -
bottom
356 25  pz    157.801                    $ segment 3 - top
357 25  pz    161.401                   $ segment 4 - bottom
358 25  pz    210.101                   $ segment 4 - top
359 25  pz    213.701                   $ segment 5 - bot
```

```
360 25  pz   262.401                                    $ segment 5 - top
361 25  pz   264.701                                    $ top of rod
362     cz     2.751                                    $ inner sleeve - in
363     cz     2.951                                    $ inner sleeve - out
364     cz     3.001                                    $ absorber - inside
365     cz     5.251                                    $ absorber - outside
366     cz     5.301                                    $ outer sleeve - in
367     cz     5.501                                    $ outer sleeve - out
c
=======================================================================

c     RUN PARAMETERS
c
c     NEUTRON IMPORTANCES
imp:n
      0                                          $ outside world
      1 74r                                      $ graphite structure
      1 1                                        $ helium cavity
      1 20r                                      $ fuel region
      1 9r                                       $ control rod sites
      1 2r                                       $ control rod guide tubes
      1 32r                                      $ control rod
      1 11r                                      $ conus
      1 6r                                       $ KLAK sites
      1 19r                                      $ Helium flow channels
      1 2r                                       $ Irradiation sites
c
c     TRANSFORMATIONS
c
c     Center positions of unit cells in fill zones
tr1   0.0  0.0  -348.3794                                $ fuel sphere
tr2   0.0  0.0  -355.2566                                $ mod sphere
c
c     Small absorber ball channels (centered on r = 98.61 cm)
*tr5   69.728   69.728  0.0     45  45 90  135  45 90   90 90 0  $ KL1
*tr6   15.426   97.396  0.0     81   9 90  171  81 90   90 90 0  $ KL2
*tr7  -44.768   87.862  0.0    117  27 90  153 117 90   90 90 0  $ KL3
*tr8  -87.862   44.768  0.0    153  63 90  117 153 90   90 90 0  $ KL4
*tr9  -69.728  -69.728  0.0    135 135 90   45 135 90   90 90 0  $ KL5
*tr10  44.768  -87.862  0.0     63 153 90   27  63 90   90 90 0  $ KL6
*tr11  87.862  -44.768  0.0     27 117 90   63  27 90   90 90 0  $ KL7
c
c     Control rod radial positions
c
tr15   90.972   46.352  0.0                               $ CR1
tr16   46.352   90.972  0.0                               $ CR2
tr17  -15.972  100.843  0.0                               $ CR3
tr18  -72.196   72.196  0.0                               $ CR4
tr19 -100.843   15.972  0.0                               $ CR5
tr20  -90.972  -46.352  0.0                               $ CR6
tr21  -46.352  -90.972  0.0                               $ CR7
tr22   15.972 -100.843  0.0                               $ CR8
tr23   72.196  -72.196  0.0                               $ CR9
tr24  100.843  -15.972  0.0                               $ CR10
c
c     Control rod insertion (length = 264.7 cm)
c
```

```
tr25    0.0       0.0    -119.2                              $ fully out
c     tr25    0.0       0.0    -394.2                        $ fully in
c
c     MATERIAL SPECIFICATIONS
c     Graphite Structure
c
m1    6000.60c   8.51047e-02  5010.60c  9.09283e-08
      5011.60c   3.65998e-07
mt1   grph.01t
c
m2    6000.60c   7.29410e-02  5010.60c  6.56324e-04
      5011.60c   2.64179e-03
mt2   grph.01t
c
m3    6000.60c   8.51462e-02  5010.60c  9.09725e-08
      5011.60c   3.66176e-07
mt3   grph.01t
c
m4    6000.60c   1.45350e-02  5010.60c  1.55296e-08
      5011.60c   6.25088e-08
mt4   grph.01t
c
m5    6000.60c   8.02916e-02  5010.60c  8.57857e-08
      5011.60c   3.45298e-07
mt5   grph.01t
c
m7    6000.60c   5.38275e-02  5010.60c  5.75108e-08
      5011.60c   2.31488e-07
mt7   grph.01t
c
m8    6000.60c   7.81408e-02  5010.60c  8.34879e-08
      5011.60c   3.36049e-07
mt8   grph.01t
c
m9    6000.60c   8.23751e-02  5010.60c  8.80119e-08
      5011.60c   3.54259e-07
mt9   grph.01t
c
m10   6000.60c   8.43647e-02  5010.60c  5.94023e-05
      5011.60c   2.39102e-04
mt10  grph.01t
c
m11   6000.60c   8.17101e-02  5010.60c  3.11268e-05
      5011.60c   1.25289e-04
mt11  grph.01t
c
m12   6000.60c   8.50790e-02  5010.60c  4.16093e-05
      5011.60c   1.67483e-04
mt12  grph.01t
c
m13   6000.60c   8.19167e-02  5010.60c  7.13473e-06
      5011.60c   2.87182e-05
mt13  grph.01t
c
m14   6000.60c   5.41118e-02  5010.60c  1.14914e-05
      5011.60c   4.62542e-05
mt14  grph.01t
```

```
c
m15    6000.60c   3.32110e-02  5010.60c  3.54835e-08
       5011.60c   1.42826e-07
mt15   grph.01t
c
m16    6000.60c   8.81811e-02  5010.60c  7.14143e-06
       5011.60c   2.87452e-05
mt16   grph.01t
c
m17    6000.60c   7.65948e-02  5010.60c  6.89235e-04
       5011.60c   2.77426e-03
mt17   grph.01t
c
m18    6000.60c   1
mt18   grph.01t
c
m19    6000.60c   7.61157e-02  5010.60c  6.84890e-04
       5011.60c   2.75677e-03
mt19   grph.01t
c
m20    6000.60c   8.78374e-02  5010.60c  9.38478e-08
       5011.60c   3.77749e-07
mt20   grph.01t
c
m21    6000.60c   5.79696e-02  5010.60c  6.19364e-08
       5011.60c   2.49302e-07
mt21   grph.01t
c
m22    6000.60c   8.82418e-02  5010.60c  9.42800e-08
       5011.60c   3.79489e-07
mt22   grph.01t
c
m23    6000.60c   8.79541e-02  5010.60c  3.35054e-05
       5011.60c   1.34864e-04
mt23   grph.01t
c
m24    6000.60c   8.46754e-02  5010.60c  9.04696e-08
       5011.60c   3.64151e-07
mt24   grph.01t
c
m25    6000.60c   8.18911e-02  5010.60c  7.36859e-04
       5011.60c   2.96595e-03
mt25   grph.01t
c
m26    6000.60c   9.43390e-02  5010.60c  3.87139e-06
       5011.60c   1.55828e-05
mt26   grph.01t
c
m27    6000.60c   5.61108e-02  5010.60c  3.87139e-06
       5011.60c   1.55828e-05
mt27   grph.01t
c
m28    6000.60c   9.43390e-02  5010.60c  1.00795e-07
       5011.60c   4.05711e-07
mt28   grph.01t
c
m29    6000.60c   8.81637e-02  5010.60c  9.41966e-08
```

```
      5011.60c   3.79153e-07
mt29  grph.01t
c
m30   6000.60c   6.76758e-02  5010.60c  2.49409e-05
      5011.60c   1.00390e-04
mt30  grph.01t
c
m31   6000.60c   8.61476e-02  5010.60c  9.20425e-08
      5011.60c   3.70483e-07
mt31  grph.01t
c
m32   6000.60c   8.29066e-02  5010.60c  8.85797e-08
      5011.60c   3.56544e-07
mt32  grph.01t
c
m33   6000.60c   7.47805e-02  5010.60c  6.72877e-04
      5011.60c   2.70841e-03
mt33  grph.01t
c
m35   6000.60c   5.82699e-02  5010.60c  6.22572e-08
      5011.60c   2.50593e-07
mt35  grph.01t
c
m36   6000.60c   8.55860e-02  5010.60c  9.14425e-08
      5011.60c   3.68068e-07
mt36  grph.01t
c
m37   6000.60c   7.28262e-02  5010.60c  7.78096e-08
      5011.60c   3.13193e-07
mt37  grph.01t
c
m38   6000.60c   7.60368e-02  5010.60c  8.12398e-08
      5011.60c   3.27000e-07
mt38  grph.01t
c
m39   6000.60c   7.57889e-02  5010.60c  2.88713e-05
      5011.60c   1.16211e-04
mt39  grph.01t
c
m40   6000.60c   7.37484e-02  5010.60c  7.87948e-08
      5011.60c   3.17159e-07
mt40  grph.01t
c
m41   6000.60c   6.60039e-02  5010.60c  5.93904e-04
      5011.60c   2.39054e-03
mt41  grph.01t
c
m43   6000.60c   8.61500e-02  5010.60c  9.20451e-08
      5011.60c   3.70493e-07
mt43  grph.01t
c
m44   6000.60c   7.49927e-02  5010.60c  6.74785e-04
      5011.60c   2.71609e-03
mt44  grph.01t
c
m45   6000.60c   9.43390e-02  5010.60c  1.00795e-07
      5011.60c   4.05711e-07
```

```
mt45  grph.01t
c
c     Humid air
c
m50    1001.60c    5.79913e-07  1002.60c    8.7e-11
       7014.60c    3.98536e-05  7015.60c    1.46400e-07
       8016.60c    1.0e-05
c
c     Control rod
c
m51   24000.50c   -0.18      26000.50c -0.681     28000.50c -0.1
      14000.60c   -0.01      25055.60c -0.02      6000.60c -0.001
      22000.60c   -0.008
c
m52    6000.60c   0.2             5010.60c  0.1584
       5011.60c   0.6416                                    $ B4C
c
c     Fuel element
c
c     .. fuel kernel (N = 6.970994e-02)
m61   92235.60c   3.992067e-03    92238.60c  1.924449e-02
       8016.60c   4.647329e-02     5011.60c  7.445022e-08
       5010.60c   1.849637e-08
c
c     .. graphite layers of CFP
m62    6000.60c   1
c
c     .. SiC layer of CFP
m63   14000.60c   0.5              6000.60c  0.5
c
c     .. moderator graphite (N = 9.225716e-02)
m64    6000.60c   9.225714e-02     5011.60c  9.248780e-09
       5010.60c   2.283365e-09
mt64   grph.01t
c
c     .. graphite matrix in fuel pebble (N = 8.674180e-02)
m65    6000.60c   8.674169e-02     5011.60c  9.032424e-08
       5010.60c   2.244010e-08
mt65   grph.01t
c
c      PROBLEM TYPE
c
mode   n
totnu
kcode 5000   1.0   10   210
c
sdef   pos=0 0 -351.818 axs=0 0 1 rad=d1 ext=d2
si1    0 88.29
sp1    0 1
si2    0 127.5
sp2    0 1
c
c     Printing and cutoff cards
c
print
dbcn   9j 300
prdmp j   -60   1   2
```

APPENDIX B-2: MCNP4B Model of HTR-10 Benchmark Problem B2.1

```
HTR-10 PEBBLE-BED REACTOR (CASE B21 UTX)
c
c
=======================================================================
c
c   MCNP4B model of the HTR-10 initial core, based on IAEA benchmark
c   problem CRP-5 specification. Benchmark problem B21.
c
c   Modeling assumptions:
c
c   A BCC lattice of spheres in core with 0.61 packing fraction and a
c   1:1 mix of fuel and moderator balls in cylindrical portion of core,
c   but with a reduced moderator pebble size to approximate a 57/43 f/m
c   pebble ratio. The control, irradiation, KLAK and He channels are
c   modeled explicitly. Pressurized helium atmosphere.
c
c   Benchmark problem B2.1, calculated using the U of Texas cross
c   sections at 300K.
c
c   Prepared by J.R. Lebenhaft (MIT) May 2001.
c
c   ---------------------------------------------------------------
c   Revision history:
c
c   January 2001, J. Lebenhaft - detailed model of control rod; radial
c   core exclusion zone to correct for partial pebbles at boundary.
c
c   May 2001, J. Lebenhaft - revised moderator density and boron
c   content; reduced fueled region in fuel spheres; corrected size of
c   CFP unit cell.
c
=======================================================================
c    CELL CARDS
c
1    0                    1: -17:  29                    $ outside world
c
c    Graphite reactor structure
c
2    2   0.0762391      -1    2  -23                     $ zone 1
3    3   0.0851467      -2    3  -23                     $ zone 2
4    4   0.0145351      -3    4  -23                     $ zone 3
5    5   0.0802920      -4    6  -23                     $ zone 4
6    1   0.0851052      30    9  -23                     $ zone 0
7    7   0.0538278      -9   14  -20                     $ zone 6
8    7   0.0538278     -14   16  -20                     $ zone 7
9    18  0.0797184     -16   17  -20                     $ zone 81
10   8   0.0781412      -9   10   20  -23                $ zone 8
11   9   0.0823755     -10   11   20  -23                $ zone 9
12   10  0.0846632     -11   12   20  -21                $ zone 10
13   11  0.0818665     -11   12   21  -23                $ zone 11
14   12  0.0852881     -12   15   20  -21                $ zone 12
15   13  0.0819526     -12   13   21  -23                $ zone 13
16   14  0.0541695     -13   14   21  -22                $ zone 14
17   15  0.0332112     -13   14   22  -23                $ zone 15
```

```
18   16  0.0882170     -14   15   21  -23                $ zone 16
19   17  0.0800619     -15   16   20  -24                $ zone 17
20   18  0.0797184     -16   17   20  -24                $ zone 18
21   19  0.0795574      -1    2   23  -24                $ zone 19
22   20  0.0878379      -2    3   23  -24                $ zone 20
23   21  0.0579699      -3    4   23  -24                $ zone 21
24   22  0.0882423      -4    9   23  -24                $ zone 22
25   22  0.0882423      -9   11   23  -24                $ zone 23
26   23  0.0881225     -11   12   23  -24                $ zone 24
27   22  0.0882423     -12   13   23  -24                $ zone 25
28   24  0.0846759     -13   14   23  -24                $ zone 26
29   22  0.0882423     -14   15   23  -24                $ zone 80
30   25  8.55939e-02    -1    2   24  -25                $ zone 27
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
                        340  341  342
31   26  9.43585e-02    -2    3   24  -25                $ zone 28
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
                        340  341  342
32   27  5.61302e-02    -3    4   24  -25                $ zone 29
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
                        340  341  342
33   26  9.43585e-02    -4    5   24  -25                $ zone 82
                        260  261  262  263   264  265
                        266  267  268  269
                       (275:-276:(277  279):(280 -278))
                       (281:-282:(283  285):(286 -284))
                       (287:-288:(289  291):(292 -290))
                       (293:-294:(295  297):(298 -296))
                       (299:-300:(301  303):(304 -302))
                       (305:-306:(307  309):(310 -308))
                       (311:-312:(313  315):(316 -314))
                        340  341  342
34   28  9.43396e-02    -5    6   24  -25                $ zone 30
```

```
                          260  261  262  263   264  265
                          266  267  268  269
                         (275:-276:(277  279):(280 -278))
                         (281:-282:(283  285):(286 -284))
                         (287:-288:(289  291):(292 -290))
                         (293:-294:(295  297):(298 -296))
                         (299:-300:(301  303):(304 -302))
                         (305:-306:(307  309):(310 -308))
                         (311:-312:(313  315):(316 -314))
                          340  341  342
35   29  8.81642e-02       -6    9   24  -25                $ zones 31 to
40
                          260  261  262  263   264
                          265  266  267  268   269
                         (275:-276:(277  279):(280 -278))
                         (281:-282:(283  285):(286 -284))
                         (287:-288:(289  291):(292 -290))
                         (293:-294:(295  297):(298 -296))
                         (299:-300:(301  303):(304 -302))
                         (305:-306:(307  309):(310 -308))
                         (311:-312:(313  315):(316 -314))
                          340  341  342
76   45  9.43396e-02       -9   18   24  -25                $ zone 41a -
                          260  261  262  263   264   265    $ CR bottom
                          266  267  268  269
                         (275:-276:(277  279):(280 -278))
                         (281:-282:(283  285):(286 -284))
                         (287:-288:(289  291):(292 -290))
                         (293:-294:(295  297):(298 -296))
                         (299:-300:(301  303):(304 -302))
                         (305:-306:(307  309):(310 -308))
                         (311:-312:(313  315):(316 -314))
36   28  0.0678903       -18   11   24  -25                $ zone 41b
37   30  0.0678011       -11   12   24  -25                $ zone 42
38   31  0.0861481       -12   13   24  -25                $ zone 43
39   32  0.0829070       -13   14   24  -25                $ zone 44
40   31  0.0861481       -14   15   24  -25                $ zone 45
41   33  0.0781618       -15   16   24  -25                $ zone 46
42   18  0.0778265       -16   17   24  -25                $ zone 47
43   17  0.0800619        -1    2   25  -28                $ zone 74
44   22  0.0882423        -2    3   25  -27                $ zone 66a
45   22  0.0882423        -2    9   27  -28                $ zone 66b
46   35  0.0582702        -3    4   25  -26                $ zone 48
47   22  0.0882423        -4    9   25  -26                $ zone 49
48   22  0.0882423        -9   11   25  -26                $ zone 50
49   23  0.0881225       -11   12   25  -26                $ zone 51
50   22  0.0882423       -12   13   25  -26                $ zone 52
51   36  0.0855865       -13   14   25  -26                $ zone 53
52   22  0.0882423       -14   15   25  -26                $ zone 54
53   17  0.0800619       -15   16   25  -26                $ zone 55
54   18  0.0797184       -16   17   25  -26                $ zone 56
55   37  0.0728266        -3    4   26  -27                $ zone 57
56   38  0.0760372        -4    9   26  -27                $ zone 58
                          320  321  322  323  324
                          325  326  327  328  329
                          330  331  332  333  334
                          335  336  337  338  339
```

```
57   38  0.0760372      -9   11   26  -27                $ zone 59
58   39  0.0759340     -11   12   26  -27                $ zone 60
59   38  0.0760372     -12   13   26  -27                $ zone 61
60   40  0.0737488     -13   14   26  -27                $ zone 62
61   38  0.0760372     -14   15   26  -27                $ zone 63
62   41  0.0689883     -15   16   26  -27                $ zone 64
63   18  0.0686924     -16   17   26  -27                $ zone 65
64   22  0.0882423      -9   11   27  -28                $ zone 67
65   23  0.0881225     -11   12   27  -28                $ zone 68
66   22  0.0882423     -12   13   27  -28                $ zone 69
67   43  0.0861505     -13   14   27  -28                $ zone 70
68   22  0.0882423     -14   15   27  -28                $ zone 71
69   17  0.0800619     -15   16   27  -28                $ zone 72
70   18  0.0797184     -16   17   27  -28                $ zone 73
71   17  0.0800619      -1    2   28  -29                $ zone 75
72   17  0.0800619      -2   13   28  -29                $ zone 76
73   44  0.0783836     -13   14   28  -29                $ zone 77
74   17  0.0800619     -14   16   28  -29                $ zone 78
75   17  0.0800619     -16   17   28  -29                $ zone 79
c
c    Cavity above core
c
80   50 -4.814e-03      -6    7  -23
c
c    ---------------------------------------------------------------
c    Cylindrical Region of Core
c
84   50 -4.814e-03    -7   8  19 -23                     $ radial gap
85   0                -7   8 -19          fill=10(1)     $ pebble bed
c
c    Universe 10: BCC lattice of fuel and dummy spheres
c
86   0                45 -46 -47  48 -49  50
     lat=1  fill=11
     u=10
c
c    Universe 11: unit cell
c
87   0                 -51            fill=12  u=11  $ fuel [ 0  0  0]
88   64  9.225716e-02  -52                     u=11  $ mod  [ 1  1  1]
89   64  9.225716e-02  -53                     u=11  $ mod  [ 1  1 -1]
90   64  9.225716e-02  -54                     u=11  $ mod  [ 1 -1 -1]
91   64  9.225716e-02  -55                     u=11  $ mod  [ 1 -1  1]
92   64  9.225716e-02  -56                     u=11  $ mod  [-1  1  1]
93   64  9.225716e-02  -57                     u=11  $ mod  [-1  1 -1]
94   64  9.225716e-02  -58                     u=11  $ mod  [-1 -1 -1]
95   64  9.225716e-02  -59                     u=11  $ mod  [-1 -1  1]
96   50 -4.814e-03      51  52  53  54  55
                        56  57  58  59         u=11  $ helium between
c
c    Universe 12: details of fuel element
c
97   65  8.674180e-02   41                     u=12  $ graphite shell
98   0                 -41            fill=13  u=12  $ fuel region
c
c    Universe 13: embedded coated fuel particles
c
```

```
99   0                -250  251 -252  253 -254  255
     lat=1  fill=14
     u=13
c
c    Universe 14:  coated fuel particle
c
100  61  6.970994e-02 -245                      u=14  $ UO2 kernel
101  62 -1.1           245 -246                 u=14  $ PyC layer 1
102  62 -1.9           246 -247                 u=14  $ PyC layer 2
103  63 -3.18          247 -248                 u=14  $ SiC layer
104  62 -1.9           248 -249                 u=14  $ PyC layer 3
105  65  8.674180e-02  249                      u=14  $ graphite matrix
c
c    ---------------------------------------------------------------
c    Conus Region of Core (dummy balls)
c
110  0                  -8   9 -30      fill=20(2)
c
c    Universe 20: BCC lattice of moderator spheres
c
111  0                  45 -46 -47  48 -49  50
     lat=1  fill=21
     u=20
c
c    Universe 21: unit cell
c
112  64  9.225716e-02  -51                      u=21  $ mod [ 0  0  0]
113  64  9.225716e-02  -52                      u=21  $ mod [ 1  1  1]
114  64  9.225716e-02  -53                      u=21  $ mod [ 1  1 -1]
115  64  9.225716e-02  -54                      u=21  $ mod [ 1 -1 -1]
116  64  9.225716e-02  -55                      u=21  $ mod [ 1 -1  1]
117  64  9.225716e-02  -56                      u=21  $ mod [-1  1  1]
118  64  9.225716e-02  -57                      u=21  $ mod [-1  1 -1]
119  64  9.225716e-02  -58                      u=21  $ mod [-1 -1 -1]
120  64  9.225716e-02  -59                      u=21  $ mod [-1 -1  1]
121  50 -4.814e-03      51  52  53  54  55
                        56  57  58  59          u=21  $ helium between
c
c    ---------------------------------------------------------------
c    Control rod sites
c
130  0                -1  18 -260     fill=25(15)     $  CR1
131  0                -1  18 -261     fill=25(16)     $  CR2
132  0                -1  18 -262     fill=25(17)     $  CR3
133  0                -1  18 -263     fill=25(18)     $  CR4
134  0                -1  18 -264     fill=25(19)     $  CR5
135  0                -1  18 -265     fill=25(20)     $  CR6
136  0                -1  18 -266     fill=25(21)     $  CR7
137  0                -1  18 -267     fill=25(22)     $  CR8
138  0                -1  18 -268     fill=25(23)     $  CR9
139  0                -1  18 -269     fill=25(24)     $  CR10
c
c    Universe 25: contents of CR guide tubes
c
145  50 -4.814e-03   367                          u=25  $ He around CR
146  50 -4.814e-03  -367 -350                     u=25  $ He below CR
147  0              -367  350         fill=26     u=25  $ CR
```

```
c
c    Universe 26: control rod
c
148  51 -5.0         -351  362                    u=26  $ lower end
c
c    segment 1
c
149  51 -5.0          351 -352  362 -363          u=26  $ inner sleeve
150  50 -4.814e-03    351 -352  363 -364          u=26  $ gap
151  52 -1.7          351 -352  364 -365          u=26  $ B4C
152  50 -4.814e-03    351 -352  365 -366          u=26  $ gap
153  51 -5.0          351 -352  366               u=26  $ outer sleeve
c
154  51 -5.0          352 -353  362               u=26  $ joint 1
c
c    segment 2
c
155  51 -5.0          353 -354  362 -363          u=26  $ inner sleeve
156  50 -4.814e-03    353 -354  363 -364          u=26  $ gap
157  52 -1.7          353 -354  364 -365          u=26  $ B4C
158  50 -4.814e-03    353 -354  365 -366          u=26  $ gap
159  51 -5.0          353 -354  366               u=26  $ outer sleeve
c
160  51 -5.0          354 -355  362               u=26  $ joint 2
c
c    segment 3
c
161  51 -5.0          355 -356  362 -363          u=26  $ inner sleeve
162  50 -4.814e-03    355 -356  363 -364          u=26  $ gap
163  52 -1.7          355 -356  364 -365          u=26  $ B4C
164  50 -4.814e-03    355 -356  365 -366          u=26  $ gap
165  51 -5.0          355 -356  366               u=26  $ outer sleeve
c
166  51 -5.0          356 -357  362               u=26  $ joint 3
c
c    segment 4
c
167  51 -5.0          357 -358  362 -363          u=26  $ inner sleeve
168  50 -4.814e-03    357 -358  363 -364          u=26  $ gap
169  52 -1.7          357 -358  364 -365          u=26  $ B4C
170  50 -4.814e-03    357 -358  365 -366          u=26  $ gap
171  51 -5.0          357 -358  366               u=26  $ outer sleeve
c
172  51 -5.0          358 -359  362               u=26  $ joint 4
c
c    segment 5
c
173  51 -5.0          359 -360  362 -363          u=26  $ inner sleeve
174  50 -4.814e-03    359 -360  363 -364          u=26  $ gap
175  52 -1.7          359 -360  364 -365          u=26  $ B4C
176  50 -4.814e-03    359 -360  365 -366          u=26  $ gap
177  51 -5.0          359 -360  366               u=26  $ outer sleeve
c
178  51 -5.0          360 -361  362               u=26  $ upper end
179  50 -4.814e-03   -361 -362                    u=26  $ centre channel
180  50 -4.814e-03    361                         u=26  $ above rod
c
```

```
c    ------------------------------------------------------------------
c    Absorber ball KLAK sites
c
190  50 -4.814e-03    -1  18 -275  276 (-277:-279) (278:-280)     $ KL1
191  50 -4.814e-03    -1  18 -281  282 (-283:-285) (284:-286)     $ KL2
192  50 -4.814e-03    -1  18 -287  288 (-289:-291) (290:-292)     $ KL3
193  50 -4.814e-03    -1  18 -293  294 (-295:-297) (296:-298)     $ KL4
194  50 -4.814e-03    -1  18 -299  300 (-301:-303) (302:-304)     $ KL5
195  50 -4.814e-03    -1  18 -305  306 (-307:-309) (308:-310)     $ KL6
196  50 -4.814e-03    -1  18 -311  312 (-313:-315) (314:-316)     $ KL7
c
c    ------------------------------------------------------------------
c    Helium flow channels
c
200  50 -4.814e-03    -4   9 -320                      $ HE1
201  50 -4.814e-03    -4   9 -321                      $ HE2
202  50 -4.814e-03    -4   9 -322                      $ HE3
203  50 -4.814e-03    -4   9 -323                      $ HE4
204  50 -4.814e-03    -4   9 -324                      $ HE5
205  50 -4.814e-03    -4   9 -325                      $ HE6
206  50 -4.814e-03    -4   9 -326                      $ HE7
207  50 -4.814e-03    -4   9 -327                      $ HE8
208  50 -4.814e-03    -4   9 -328                      $ HE9
209  50 -4.814e-03    -4   9 -329                      $ HE10
210  50 -4.814e-03    -4   9 -330                      $ HE11
211  50 -4.814e-03    -4   9 -331                      $ HE12
212  50 -4.814e-03    -4   9 -332                      $ HE13
213  50 -4.814e-03    -4   9 -333                      $ HE14
214  50 -4.814e-03    -4   9 -334                      $ HE15
215  50 -4.814e-03    -4   9 -335                      $ HE16
216  50 -4.814e-03    -4   9 -336                      $ HE17
217  50 -4.814e-03    -4   9 -337                      $ HE18
218  50 -4.814e-03    -4   9 -338                      $ HE19
219  50 -4.814e-03    -4   9 -339                      $ HE20
c
c    ------------------------------------------------------------------
c    Irradiation channels
c
230  50 -4.814e-03    -1   9 -340                      $ IR1
231  50 -4.814e-03    -1   9 -341                      $ IR2
232  50 -4.814e-03    -1   9 -342                      $ IR3
c
=======================================================================

c  SURFACE CARDS
c
1   pz      0.0              $ Top of borated C bricks at reactor top
2   pz    -40.0              $ Bottom of borated C bricks @ reactor top
3   pz    -95.0              $ Upper surface of cold He chamber
4   pz   -105.0              $ Lower surface of cold He chamber
5   pz   -114.7              $ Surface between axial regions 30 and 82
6   pz   -130.0              $ Lower surface of top reflector
7   pz   -173.408            $ Top of fueled region minus 1.71 cm
8   pz   -351.818            $ Upper surface of cone region
9   pz   -388.764            $ Lower surface of cone region
10  pz   -402.0              $ Surface between axial regions 8 and 9
11  pz   -430.0              $ Surface between axial regions 9 and 10
```

```
12  pz    -450.0                $ Surface between axial regions 10 and 12
13  pz    -465.0                $ Surface between axial regions 13 and 14
14  pz    -495.0                $ Surface between axial regions 6 and 7
15  pz    -510.0                $ Surface between axial regions 16 and 17
16  pz    -540.0                $ Surface between axia regions 7 and 81
17  pz    -610.0                $ Bottom of reactor
18  pz    -394.2                $ Bottom of CR guide hole
c
19  cz      88.29               $ radial fuel exclusion zone
20  cz      25.0
21  cz      41.75
22  cz      70.75
23  cz      90.0                $ Outer radius of fueled region
24  cz      95.6                $ Inner surface of control rod region
25  cz     108.6                $ Outer surface of control rod region
26  cz     140.6                $ Inner surface of He flow region
27  cz     148.6                $ Outer surface of He flow region
28  cz     167.793              $ Outer surface of side graphite reflector
29  cz     190.0                $ Outside of radial borated C bricks
c
30  kz    -402.974 3.09522 1    $ Outer surface of cone at bottom of core
c
c   Fuel element
c
41  so      2.5                       $ fuel region
c
c   Unit cell in core
c
45  px     -3.4386                    $ [-1  0  0]
46  px      3.4386                    $ [ 1  0  0]
47  py      3.4386                    $ [ 0  1  0]
48  py     -3.4386                    $ [ 0 -1  0]
49  pz      3.4386                    $ [ 0  0  1]
50  pz     -3.4386                    $ [ 0  0 -1]
c
c   Balls in unit cells
c
51  so      3.0
52  s       3.4386  3.4386  3.4386  2.731
53  s       3.4386  3.4386 -3.4386  2.731
54  s       3.4386 -3.4386 -3.4386  2.731
55  s       3.4386 -3.4386  3.4386  2.731
56  s      -3.4386  3.4386  3.4386  2.731
57  s      -3.4386  3.4386 -3.4386  2.731
58  s      -3.4386 -3.4386 -3.4386  2.731
59  s      -3.4386 -3.4386  3.4386  2.731
c
c   Coated Fuel Particles
c
245 so      0.025                     $ kernel
246 so      0.034                     $ 1st PyC layer
247 so      0.038                     $ 2nd PyC layer
248 so      0.0415                    $ SiC layer
249 so      0.0455                    $ 3rd PyC layer
c
c   Unit cell for CFP lattice in graphite matrix
c
```

```
250 px      0.09938918
251 px     -0.09938918
252 py      0.09938918
253 py     -0.09938918
254 pz      0.09938918
255 pz     -0.09938918
c
c   Control rod channels
c
260 c/z    90.972   46.352  6.49   $ CR1
261 c/z    46.352   90.972  6.49   $ CR2
262 c/z   -15.972  100.843  6.49   $ CR3
263 c/z   -72.196   72.196  6.49   $ CR4
264 c/z  -100.843   15.972  6.49   $ CR5
265 c/z   -90.972  -46.352  6.49   $ CR6
266 c/z   -46.352  -90.972  6.49   $ CR7
267 c/z    15.972 -100.843  6.49   $ CR8
268 c/z    72.196  -72.196  6.49   $ CR9
269 c/z   100.843  -15.972  6.49   $ CR10
c
C   Small absorber ball channels
C
C   .. KL1
275 5   px     3.0
276 5   px    -3.0
277 5   py     5.0
278 5   py    -5.0
279 5   c/z    0.0  5.0  3.0
280 5   c/z    0.0 -5.0  3.0
C
C   .. KL2
281 6   px     3.0
282 6   px    -3.0
283 6   py     5.0
284 6   py    -5.0
285 6   c/z    0.0  5.0  3.0
286 6   c/z    0.0 -5.0  3.0
C
C   .. KL3
287 7   px     3.0
288 7   px    -3.0
289 7   py     5.0
290 7   py    -5.0
291 7   c/z    0.0  5.0  3.0
292 7   c/z    0.0 -5.0  3.0
C
C   .. KL4
293 8   px     3.0
294 8   px    -3.0
295 8   py     5.0
296 8   py    -5.0
297 8   c/z    0.0  5.0  3.0
298 8   c/z    0.0 -5.0  3.0
C
C   .. KL5
299 9   px     3.0
300 9   px    -3.0
```

```
301 9   py     5.0
302 9   py    -5.0
303 9   c/z    0.0  5.0  3.0
304 9   c/z    0.0 -5.0  3.0
C
C   .. KL6
305 10  px     3.0
306 10  px    -3.0
307 10  py     5.0
308 10  py    -5.0
309 10  c/z    0.0  5.0  3.0
310 10  c/z    0.0 -5.0  3.0
C
C   .. KL7
311 11  px     3.0
312 11  px    -3.0
313 11  py     5.0
314 11  py    -5.0
315 11  c/z    0.0  5.0  3.0
316 11  c/z    0.0 -5.0  3.0
C
C   Helium flow channels
C
320 c/z  142.820   22.620  3.99                    $ HE1
321 c/z  128.840   65.647  3.99                    $ HE2
322 c/z  102.248  102.248  3.99                    $ HE3
323 c/z   65.647  128.840  3.99                    $ HE4
324 c/z   22.620  142.820  3.99                    $ HE5
325 c/z  -22.620  142.820  3.99                    $ HE6
326 c/z  -65.647  128.840  3.99                    $ HE7
327 c/z -102.248  102.248  3.99                    $ HE8
328 c/z -128.840   65.647  3.99                    $ HE9
329 c/z -142.82    22.620  3.99                    $ HE10
330 c/z -142.82   -22.620  3.99                    $ HE11
331 c/z -128.84   -65.647  3.99                    $ HE12
332 c/z -102.248 -102.248  3.99                    $ HE13
333 c/z  -65.647 -128.840  3.99                    $ HE14
334 c/z  -22.620 -142.820  3.99                    $ HE15
335 c/z   22.620 -142.820  3.99                    $ HE16
336 c/z   65.647 -128.840  3.99                    $ HE17
337 c/z  102.248 -102.248  3.99                    $ HE18
338 c/z  128.840  -65.647  3.99                    $ HE19
339 c/z  142.820  -22.620  3.99                    $ HE20
C
C   Irradiation Channels
C
340 c/z  100.843   15.972  6.49                    $ IR1
341 c/z -100.843  -15.972  6.49                    $ IR2
342 c/z  -15.972 -100.843  6.49                    $ IR3
c
c   Control Rods
c
350 25  pz     0.001                               $ bottom of CR
351 25  pz     4.501                               $ segment 1 - bottom
352 25  pz    53.201                               $ segment 1 - top
353 25  pz    56.801                               $ segment 2 - bottom
354 25  pz   105.501                               $ segment 2 - top
```

```
355 25  pz    109.101                                  $ segment 3 - bottom
356 25  pz    157.801                                  $ segment 3 - top
357 25  pz    161.401                                  $ segment 4 - bottom
358 25  pz    210.101                                  $ segment 4 - top
359 25  pz    213.701                                  $ segment 5 - bottom
360 25  pz    262.401                                  $ segment 5 - top
361 25  pz    264.701                                  $ top of rod
362     cz      2.751                                  $ inner sleeve - in
363     cz      2.951                                  $ inner sleeve - out
364     cz      3.001                                  $ absorber - inside
365     cz      5.251                                  $ absorber - outside
366     cz      5.301                                  $ outer sleeve - in
367     cz      5.501                                  $ outer sleeve - out
c
c ===========================================================================

c     RUN PARAMETERS
c
c     NEUTRON IMPORTANCES
imp:n
      0                                  $ outside world
      1 74r                              $ graphite structure
      1                                  $ helium cavity
      1 21r                              $ fuel region
      1 11r                              $ conus
      1 9r                               $ control rod sites
      1 2r                               $ control rod guide tubes
      1 32r                              $ control rod
      1 6r                               $ KLAK sites
      1 19r                              $ Helium flow channels
      1 2r                               $ Irradiation sites
c
c     TRANSFORMATIONS
c
c     Center positions of unit cells in fill zones
c
tr1   0.0  0.0  -348.3794                      $ fuel ball region
tr2   0.0  0.0  -355.2566                      $ dummy ball region
c
c     Small absorber ball channels (centered on r = 98.61 cm)
c
*tr5   69.728   69.728  0.0    45  45 90  135  45 90  90 90 0   $ KL1
*tr6   15.426   97.396  0.0    81   9 90  171  81 90  90 90 0   $ KL2
*tr7  -44.768   87.862  0.0   117  27 90  153 117 90  90 90 0   $ KL3
*tr8  -87.862   44.768  0.0   153  63 90  117 153 90  90 90 0   $ KL4
*tr9  -69.728  -69.728  0.0   135 135 90   45 135 90  90 90 0   $ KL5
*tr10  44.768  -87.862  0.0    63 153 90   27  63 90  90 90 0   $ KL6
*tr11  87.862  -44.768  0.0    27 117 90   63  27 90  90 90 0   $ KL7
c
c     Control rod radial positions
c
tr15   90.972   46.352  0.0                              $ CR1
tr16   46.352   90.972  0.0                              $ CR2
tr17  -15.972  100.843  0.0                              $ CR3
tr18  -72.196   72.196  0.0                              $ CR4
tr19 -100.843   15.972  0.0                              $ CR5
tr20  -90.972  -46.352  0.0                              $ CR6
```

```
tr21  -46.352  -90.972  0.0                                    $ CR7
tr22   15.972 -100.843  0.0                                    $ CR8
tr23   72.196  -72.196  0.0                                    $ CR9
tr24  100.843  -15.972  0.0                                    $ CR10
c
c     Control rod insertion (length = 264.7 cm)
c
tr25    0.0      0.0   -119.2                                  $ fully out
c     tr25    0.0      0.0   -394.2                           $ fully in
c
c     MATERIAL SPECIFICATIONS
c
c     Graphite Structure
c
m1    6000.62c  8.51047e-02  5010.62c  9.09283e-08
      5011.62c  3.65998e-07
mt1   grph.01t
c
m2    6000.62c  7.29410e-02  5010.62c  6.56324e-04
      5011.62c  2.64179e-03
mt2   grph.01t
c
m3    6000.62c  8.51462e-02  5010.62c  9.09725e-08
      5011.62c  3.66176e-07
mt3   grph.01t
c
m4    6000.62c  1.45350e-02  5010.62c  1.55296e-08
      5011.62c  6.25088e-08
mt4   grph.01t
c
m5    6000.62c  8.02916e-02  5010.62c  8.57857e-08
      5011.62c  3.45298e-07
mt5   grph.01t
c
m7    6000.62c  5.38275e-02  5010.62c  5.75108e-08
      5011.62c  2.31488e-07
mt7   grph.01t
c
m8    6000.62c  7.81408e-02  5010.62c  8.34879e-08
      5011.62c  3.36049e-07
mt8   grph.01t
c
m9    6000.62c  8.23751e-02  5010.62c  8.80119e-08
      5011.62c  3.54259e-07
mt9   grph.01t
c
m10   6000.62c  8.43647e-02  5010.62c  5.94023e-05
      5011.62c  2.39102e-04
mt10  grph.01t
c
m11   6000.62c  8.17101e-02  5010.62c  3.11268e-05
      5011.62c  1.25289e-04
mt11  grph.01t
c
m12   6000.62c  8.50790e-02  5010.62c  4.16093e-05
      5011.62c  1.67483e-04
mt12  grph.01t
```

```
c
m13    6000.62c  8.19167e-02  5010.62c  7.13473e-06
       5011.62c  2.87182e-05
mt13   grph.01t
c
m14    6000.62c  5.41118e-02  5010.62c  1.14914e-05
       5011.62c  4.62542e-05
mt14   grph.01t
c
m15    6000.62c  3.32110e-02  5010.62c  3.54835e-08
       5011.62c  1.42826e-07
mt15   grph.01t
c
m16    6000.62c  8.81811e-02  5010.62c  7.14143e-06
       5011.62c  2.87452e-05
mt16   grph.01t
c
m17    6000.62c  7.65948e-02  5010.62c  6.89235e-04
       5011.62c  2.77426e-03
mt17   grph.01t
c
m18    6000.62c  1
mt18   grph.01t
c
m19    6000.62c  7.61157e-02  5010.62c  6.84890e-04
       5011.62c  2.75677e-03
mt19   grph.01t
c
m20    6000.62c  8.78374e-02  5010.62c  9.38478e-08
       5011.62c  3.77749e-07
mt20   grph.01t
c
m21    6000.62c  5.79696e-02  5010.62c  6.19364e-08
       5011.62c  2.49302e-07
mt21   grph.01t
c
m22    6000.62c  8.82418e-02  5010.62c  9.42800e-08
       5011.62c  3.79489e-07
mt22   grph.01t
c
m23    6000.62c  8.79541e-02  5010.62c  3.35054e-05
       5011.62c  1.34864e-04
mt23   grph.01t
c
m24    6000.62c  8.46754e-02  5010.62c  9.04696e-08
       5011.62c  3.64151e-07
mt24   grph.01t
c
m25    6000.62c  8.18911e-02  5010.62c  7.36859e-04
       5011.62c  2.96595e-03
mt25   grph.01t
c
m26    6000.62c  9.43390e-02  5010.62c  3.87139e-06
       5011.62c  1.55828e-05
mt26   grph.01t
c
m27    6000.62c  5.61108e-02  5010.62c  3.87139e-06
```

```
5011.62c  1.55828e-05
mt27  grph.01t
c
m28   6000.62c  9.43390e-02  5010.62c  1.00795e-07
      5011.62c  4.05711e-07
mt28  grph.01t
c
m29   6000.62c  8.81637e-02  5010.62c  9.41966e-08
      5011.62c  3.79153e-07
mt29  grph.01t
c
m30   6000.62c  6.76758e-02  5010.62c  2.49409e-05
      5011.62c  1.00390e-04
mt30  grph.01t
c
m31   6000.62c  8.61476e-02  5010.62c  9.20425e-08
      5011.62c  3.70483e-07
mt31  grph.01t
c
m32   6000.62c  8.29066e-02  5010.62c  8.85797e-08
      5011.62c  3.56544e-07
mt32  grph.01t
c
m33   6000.62c  7.47805e-02  5010.62c  6.72877e-04
      5011.62c  2.70841e-03
mt33  grph.01t
c
m35   6000.62c  5.82699e-02  5010.62c  6.22572e-08
      5011.62c  2.50593e-07
mt35  grph.01t
c
m36   6000.62c  8.55860e-02  5010.62c  9.14425e-08
      5011.62c  3.68068e-07
mt36  grph.01t
c
m37   6000.62c  7.28262e-02  5010.62c  7.78096e-08
      5011.62c  3.13193e-07
mt37  grph.01t
c
m38   6000.62c   7.60368e-02  5010.62c  8.12398e-08
      5011.62c  3.27000e-07
mt38  grph.01t
c
m39   6000.62c   7.57889e-02  5010.62c  2.88713e-05
      5011.62c  1.16211e-04
mt39  grph.01t
c
m40   6000.62c   7.37484e-02  5010.62c  7.87948e-08
      5011.62c  3.17159e-07
mt40  grph.01t
c
m41   6000.62c   6.60039e-02  5010.62c  5.93904e-04
      5011.62c  2.39054e-03
mt41  grph.01t
c
m43   6000.62c   8.61500e-02  5010.62c  9.20451e-08
      5011.62c  3.70493e-07
```

```
mt43  grph.01t
c
m44   6000.62c  7.49927e-02  5010.62c  6.74785e-04
      5011.62c  2.71609e-03
mt44  grph.01t
c
m45   6000.62c  9.43390e-02  5010.62c  1.00795e-07
      5011.62c  4.05711e-07
mt45  grph.01t
c
c    Helium coolant (4.814e-3 g/cc at 300K)
c
m50   2003.62c  0.00000137   2004.62c  0.99999863
c
c    Control-rod metallic structure
c    (iron at a reduced density of 5 g/cm3)
c
m51  26054.62c  0.05845     26056.62c  0.91754     26057.62c  0.02119
     26058.62c  0.00282
c
c    Control-rod B4C absorber
c
m52   6000.62c  0.2          5010.62c  0.1584       5011.62c  0.6416
c
c    Fuel element
c
c    .. fuel kernel (N = 6.970994e-02)
m61  92235.62c  3.992067e-03   92238.62c  1.924449e-02
      8016.62c  4.647329e-02    5011.62c  7.445022e-08
      5010.62c  1.849637e-08
c
c    .. graphite layers of CFP
m62   6000.62c  1
c
c    .. SiC layer of CFP
m63  14000.60c  0.5             6000.62c  0.5
c
c    .. graphite matrix in fuel pebble (N = 9.225716e-02)
m64   6000.62c  9.225714e-02    5011.62c  9.248780e-09
      5010.62c  2.283365e-09
mt64  grph.01t
c
c    .. graphite matrix in fuel pebble (N = 8.674180e-02)
m65   6000.62c  8.674169e-02    5011.62c  9.032424e-08
      5010.62c  2.244010e-08
mt65  grph.01t
c
c    define U of Texas cross-section libraries at 300K
c
xs1   2003.62c 2.989032 he3.300 0 1 1 2841 0 0 2.585E-08       $ He-3
xs2   2004.62c 4.001500 he4.300 0 1 1 2761 0 0 2.585E-08       $ He-4
xs3   5010.62c 9.926921 b10.300 0 1 1 29335 0 0 2.585E-08      $ B-10
xs4   5011.62c 10.914700 b11.300 0 1 1 107576 0 0 2.585E-08    $ B-11
xs5   6000.62c 11.898000 cnat.300 0 1 1 25106 0 0 2.585E-08    $ C-nat
xs6   8016.62c 15.853160 o16.300 0 1 1 60016 0 0 2.585E-08     $ O-16
xs7   26054.62c 53.476002 fe54.300 0 1 1 190627 0 0 2.585E-08  $ Fe-54
xs8   26056.62c 55.453999 fe56.300 0 1 1 338423 0 0 2.585E-08  $ Fe-56
```

```
xs9   26057.62c 56.445999 fe57.300 0 1 1 167418 0 0 2.585E-08  $ Fe-57
xs10  26058.62c 57.436001 fe58.300 0 1 1 109347 0 0 2.585E-08  $ Fe-58
xs11  92235.62c 233.025000 u235.300 0 1 1 452322 0 0 2.585E-08 $ U-235
xs12  92238.62c 236.006000 u238.300 0 1 1 491254 0 0 2.585E-08 $ U-238
c
c     PROBLEM TYPE
c
mode  n
totnu
kcode 5000  1.0  10  210
c
sdef  pos=0 0 -351.818 axs=0 0 1 rad=d1 ext=d2
si1   0 88.29
sp1   0 1
si2   0 178.41
sp2   0 1
c
c    Printing and cutoff cards
c
print
dbcn  9j 300
prdmp j  -60  1  2
```

APPENDIX C. MCNP4B Models of ASTRA Facility

Appendix C collects the MCNP4B input files for the models of the ASTRA facility. Appendix C.1 contains the model with an exact 'super' cell core representation. Appendix C.2 contains the model of an infinite lattice with the exact 'super' cell representation of the fuelled region of the ASTRA core. In Appendix C.3, the same infinite lattice is approximated by a primitive BCC unit cell with borated fuel spheres. This approximate core representation is applied to the ASTRA core in Appendix C.4. Details on the ASTRA facility may be found in Chapter 6.

APPENDIX C.1: MCNP4B model of ASTRA, supercell core representation

```
ASTRA - PBMR CRITICAL EXPERIMENT
c
c    MCNP4B model of the PBMR mockup in ASTRA facility at the Kurchatov
c    Institute, Moscow.
c
c    Control/shutoff rod positions:
c
c              SD rods fully withdrawn                h = 395.3  cm
c              CR2 in position 1                      h = 382.7  cm
c              all other CRs in position 1            h = 382.7  cm
c              MR1 at reference critical height       h = 366.5  cm
c
c    No top reflector
c    Packing fraction = 0.625
c    BCC lattice
c    No exclusion zones
c
c    J.R. Lebenhaft, MIT, July 2001
c    ------------------------------------------------------------------------
c    CELLS
c
1    0                -8: 26: 32                              $ outside world
c
c    reactor structure
c
2    9   -1.65         8  -9 -32                              $ bottom reflector
c    3    9   -1.65        25 -26
c                     -35  36 -37  38  -39 -40  41  42
c                      28 183 184 185  186 187                $ top reflector
4    0                 9 -26 -32
                      (35:-36: 37:-38:  39: 40:-41:-42)
     fill=1(5)                                               $ radial reflector
c
c    radial reflector lattice
c
5    0               -55  56 -57  58
     lat=1  u=1
     fill=-12:4 -8:8 0:0
c
     0 0 0 0  0      0  0      5  5      5  0      0      0       0 0 0 0
     0 0 0 0  5      5  5      6  6      6  5      5      5       0 0 0 0
     0 0 0 5  6      6  6      6  6      6  6      6      6       5 0 0 0
     0 0 5 6  6      6  7      7  7      7  7      6      6       6 5 0 0
     0 5 6 6  6      7  33(53) 6  25(45) 6  37(57) 7      6       6 6 5 0
     0 5 6 6  7      6  5      0  0      0  5      24(44) 7       6 6 5 0
     0 5 6 7  31(51) 5  0      0  0      0  0      5      36(56)  7 6 5 0
     5 6 6 7  6      0  0      0  0      0  0      0      6       7 7 6 5
     5 8 8 9  21(41) 0  0      0  0      0  0      0      26(46)  7 6 6 5
     5 6 6 7  6      0  0      0  0      0  0      0      35(55)  7 6 6 5
     0 5 6 7  32(52) 5  0      0  0      0  0      5      23(43)  7 6 5 0
     0 5 6 6  7      6  5      0  0      0  5      6      7       6 6 5 0
     0 5 6 6  6      7  38(58) 6  22(42) 6  34(54) 7      6       6 6 5 0
     0 0 5 6  6      7  7      7  7      7  7      6      6       6 5 0 0
```

```
     0 0 0 0  0       0  0       5  5       5  0       0       0        0 0 0 0
c
c    ---------------------------------------------------------------------
c
c    universe 5: solid graphite block
c
10   9   -1.65        -68                                    u=5
c
c    universe 6: graphite block with empty center hole
c
15   9   -1.65         54                                    u=6   $ graphite
16   11   5.058e-05  -54                                    u=6   $ air
c
c    universe 7: graphite block with filled center hole
c
20   9   -1.65         54                                    u=7   $ graphite
21   11   5.058e-05  -54    53                              u=7   $ air gap
22   9   -1.65        -53                                    u=7   $ graphite plug
c
c    universe 8: graphite block with small experimental channel
c                and empty center hole
c
25   9   -1.65         54 (199:-200:-198)                    u=8   $ graphite
26   11   5.058e-05  198 -199  200                          u=8   $ channel
27   11   5.058e-05  -54                                    u=8   $ hole
c
c    universe 9: graphite block with small experimental channel
c                and plug in center hole
c
30   9   -1.65         54 (199:-200:-198)                    u=9   $ graphite
31   11   5.058e-05  198 -199  200                          u=9   $ channel
32   11   5.058e-05  -54   53                               u=9   $ air gap
33   9   -1.65        -53                                    u=9   $ plug
c
c    ---------------------------------------------------------------------
c
c    universe 11: control-rod spider
c
35   7   -7.9         203                                   u=11  $ outer ring
36   7   -7.9        -202                                   u=11  $ center
37   7   -7.9         202 -203 -205  206                    u=11  $ x-tie
38   7   -7.9         202 -203 -207  208                    u=11  $ y-tie
39   11   5.058e-05  202 -203  205  207                    u=11  $ gap - top right
40   11   5.058e-05  202 -203 -206  207                    u=11  $ gap - top left
41   11   5.058e-05  202 -203  205 -208                    u=11  $ gap - bot right
42   11   5.058e-05  202 -203 -206 -208                    u=11  $ gap - bot left
c
c    ---------------------------------------------------------------------
c
c    universe 12: control rod end-plate
c
920  7   -7.9         203  521  522  523  524  525
                      526  527  528  529  530  531
                      532  533  534  535                   u=12  $ outer ring
c
921  11   5.058e-05 -521                                   u=12  $ pin 1 holder
922  11   5.058e-05 -522                                   u=12  $ pin 2 holder
```

```
923  11   5.058e-05 -523                                  u=12  $ pin 3 holder
924  11   5.058e-05 -524                                  u=12  $ pin 4 holder
925  11   5.058e-05 -525                                  u=12  $ pin 5 holder
926  11   5.058e-05 -526                                  u=12  $ pin 6 holder
927  11   5.058e-05 -527                                  u=12  $ pin 7 holder
928  11   5.058e-05 -528                                  u=12  $ pin 8 holder
929  11   5.058e-05 -529                                  u=12  $ pin 9 holder
930  11   5.058e-05 -530                                  u=12  $ pin 10 holder
931  11   5.058e-05 -531                                  u=12  $ pin 11 holder
932  11   5.058e-05 -532                                  u=12  $ pin 12 holder
933  11   5.058e-05 -533                                  u=12  $ pin 13 holder
934  11   5.058e-05 -534                                  u=12  $ pin 14 holder
935  11   5.058e-05 -535                                  u=12  $ pin 15 holder
c
936  7   -7.9        -202                                 u=12  $ center
937  7   -7.9         202 -203 -205  206                  u=12  $ x-tie
938  7   -7.9         202 -203 -207  208                  u=12  $ y-tie
939  11   5.058e-05  202 -203  205  207                   u=12  $ gap - top right
940  11   5.058e-05  202 -203 -206  207                   u=12  $ gap - top left
941  11   5.058e-05  202 -203  205 -208                   u=12  $ gap - bot right
942  11   5.058e-05  202 -203 -206 -208                   u=12  $ gap - bot left
c
c    ---------------------------------------------------------------------
c
c    universe 15: control/shutdown pin assembly
c
45   0               -95                  fill=16(21)  u=15  $ pin 1
46   0               -96                  fill=16(22)  u=15  $ pin 2
47   0               -97                  fill=16(23)  u=15  $ pin 3
48   0               -98                  fill=16(24)  u=15  $ pin 4
49   0               -99                  fill=16(25)  u=15  $ pin 5
50   0              -100                  fill=16(26)  u=15  $ pin 6
51   0              -101                  fill=16(27)  u=15  $ pin 7
52   0              -102                  fill=16(28)  u=15  $ pin 8
53   0              -103                  fill=16(29)  u=15  $ pin 9
54   0              -104                  fill=16(30)  u=15  $ pin 10
55   0              -105                  fill=16(31)  u=15  $ pin 11
56   0              -106                  fill=16(32)  u=15  $ pin 12
57   0              -107                  fill=16(33)  u=15  $ pin 13
58   0              -108                  fill=16(34)  u=15  $ pin 14
59   0              -109                  fill=16(35)  u=15  $ pin 15
c
60   11   5.058e-05   95   96   97   98   99  100
                      101  102  103  104  105  106
                      107  108  109                    u=15  $ air
c
c    universe 16: contents of absorber pin
c
61   7   -7.9         110                              u=16  $ s/s clad
62   5   -1.53       -110                              u=16  $ B4C
c
c    ---------------------------------------------------------------
c
c    universe 17: air-filled portion of control/shutdown pins
c
64   0               -95                  fill=18(21)  u=17  $ pin 1
65   0               -96                  fill=18(22)  u=17  $ pin 2
```

```
66   0               -97                  fill=18(23)  u=17  $ pin 3
67   0               -98                  fill=18(24)  u=17  $ pin 4
68   0               -99                  fill=18(25)  u=17  $ pin 5
69   0              -100                  fill=18(26)  u=17  $ pin 6
70   0              -101                  fill=18(27)  u=17  $ pin 7
71   0              -102                  fill=18(28)  u=17  $ pin 8
72   0              -103                  fill=18(29)  u=17  $ pin 9
73   0              -104                  fill=18(30)  u=17  $ pin 10
74   0              -105                  fill=18(31)  u=17  $ pin 11
75   0              -106                  fill=18(32)  u=17  $ pin 12
76   0              -107                  fill=18(33)  u=17  $ pin 13
77   0              -108                  fill=18(34)  u=17  $ pin 14
78   0              -109                  fill=18(35)  u=17  $ pin 15
79   11   5.058e-05   95   96   97   98   99  100
                      101  102  103  104  105  106
                      107  108  109                  u=17  $ air
c
c    universe 18: contents of absorber pin
c
80   7   -7.9         110                            u=18  $ s/s clad
81   11   5.058e-05 -110                            u=18  $ air
c
c    ---------------------------------------------------------------------
c
c    universe 19: upper pin holder
c
82   0              -501                  fill=20(21)  u=19  $ pin 1
83   0              -502                  fill=20(22)  u=19  $ pin 2
84   0              -503                  fill=20(23)  u=19  $ pin 3
85   0              -504                  fill=20(24)  u=19  $ pin 4
86   0              -505                  fill=20(25)  u=19  $ pin 5
87   0              -506                  fill=20(26)  u=19  $ pin 6
88   0              -507                  fill=20(27)  u=19  $ pin 7
89   0              -508                  fill=20(28)  u=19  $ pin 8
90   0              -509                  fill=20(29)  u=19  $ pin 9
91   0              -510                  fill=20(30)  u=19  $ pin 10
92   0              -511                  fill=20(31)  u=19  $ pin 11
93   0              -512                  fill=20(32)  u=19  $ pin 12
94   0              -513                  fill=20(33)  u=19  $ pin 13
95   0              -514                  fill=20(34)  u=19  $ pin 14
96   0              -515                  fill=20(35)  u=19  $ pin 15
97   11   5.058e-05  501  502  503  504  505  506
                      507  508  509  510  511  512
                      513  514  515                  u=19  $ air
c
c    universe 20: hollow interior
c
98   7   -7.9         201                            u=20  $ s/s holder
99   11   5.058e-05 -201                            u=20  $ air
c
c    ---------------------------------------------------------------------
c
c    universe 21: control rod CR1 (with small experiment channel)
c
100  9   -1.65         54 (199:-200:-198)            u=21  $ graphite
101  11   5.058e-05  198 -199  200                   u=21  $ expt. channel
102  11   5.058e-05  -54  204                        u=21  $ surrounding air
```

```
103  11   5.058e-05 -204 -215                          u=21  $ air below rod
104  0              -204  215              fill=210    u=21  $ rod
c
c    universe 22: control rod CR2
c
105  9   -1.65        54                               u=22  $ graphite
106  11   5.058e-05  -54  204                          u=22  $ surrounding air
107  11   5.058e-05 -204 -215                          u=22  $ air below rod
108  0              -204  215              fill=210    u=22  $ rod
c
c
c    universe 23: control rod CR3
c
110  9   -1.65        54                               u=23  $ graphite
111  11   5.058e-05  -54  204                          u=23  $ surrounding air
112  11   5.058e-05 -204 -215                          u=23  $ air below rod
113  0              -204  215              fill=210    u=23  $ rod
c
c
c    universe 24: control rod CR4
c
115  9   -1.65        54                               u=24  $ graphite
116  11   5.058e-05  -54  204                          u=24  $ surrounding air
117  11   5.058e-05 -204 -215                          u=24  $ air below rod
118  0              -204  215              fill=210    u=24  $ rod
c
c
c    universe 25: control rod CR5
c
120  9   -1.65        54                               u=25  $ graphite
121  11   5.058e-05  -54  204                          u=25  $ surrounding air
122  11   5.058e-05 -204 -215                          u=25  $ air below rod
123  0              -204  215              fill=210    u=25  $ rod
c
c
c    ---------------------------------------------------------------------
c
c    universe 26: manual rod MR1
c
125  9   -1.65        54                               u=26  $ graphite
126  11   5.058e-05  -54  213                          u=26  $ surrounding air
127  11   5.058e-05 -213 -315                          u=26  $ air below rod
128  0              -213  315              fill=220    u=26  $ rod
c
c    ---------------------------------------------------------------------
c
c    universe 31: control rod SR1
c
130  9   -1.65        54                               u=31  $ graphite
131  11   5.058e-05  -54  204                          u=31  $ surrounding air
132  11   5.058e-05 -204 -215                          u=31  $ air below rod
133  0              -204  215              fill=210    u=31  $ rod
c
c
c    universe 32: control rod SR2
c
135  9   -1.65        54                               u=32  $ graphite
```

```
136  11   5.058e-05  -54  204                          u=32  $ surrounding air
137  11   5.058e-05 -204 -215                         u=32  $ air below rod
138  0              -204  215              fill=210    u=32  $ rod
c
c
c    universe 33: control rod SR3
c
140  9   -1.65        54                              u=33  $ graphite
141  11   5.058e-05  -54  204                         u=33  $ surrounding air
142  11   5.058e-05 -204 -215                         u=33  $ air below rod
143  0              -204  215              fill=210    u=33  $ rod
c
c
c    universe 34: control rod SR4
c
145  9   -1.65        54                              u=34  $ graphite
146  11   5.058e-05  -54  204                         u=34  $ surrounding air
147  11   5.058e-05 -204 -215                         u=34  $ air below rod
148  0              -204  215              fill=210    u=34  $ rod
c
c
c    universe 35: control rod SR5
c
150  9   -1.65        54                              u=35  $ graphite
151  11   5.058e-05  -54  204                         u=35  $ surrounding air
152  11   5.058e-05 -204 -215                         u=35  $ air below rod
153  0              -204  215              fill=210    u=35  $ rod
c
c
c    universe 36: control rod SR6
c
155  9   -1.65        54                              u=36  $ graphite
156  11   5.058e-05  -54  204                         u=36  $ surrounding air
157  11   5.058e-05 -204 -215                         u=36  $ air below rod
158  0              -204  215              fill=210    u=36  $ rod
c
c
c    universe 37: control rod SR7
c
160  9   -1.65        54                              u=37  $ graphite
161  11   5.058e-05  -54  204                         u=37  $ surrounding air
162  11   5.058e-05 -204 -215                         u=37  $ air below rod
163  0              -204  215              fill=210    u=37  $ rod
c
c
c    universe 38: control rod SR8
c
165  9   -1.65        54                              u=38  $ graphite
166  11   5.058e-05  -54  204                         u=38  $ surrounding air
167  11   5.058e-05 -204 -215                         u=38  $ air below rod
168  0              -204  215              fill=210    u=38  $ rod
c
c    ------------------------------------------------------
c
c    universe 210: details of control/shutoff rod
c
170  7   -7.9        -216                             u=210 $ lower endplate
```

```
171  0              216 -217                    fill=12   u=210 $ lower pin holder
172  0              217 -218                    fill=17   u=210 $ empty pin zone
173  0              218 -219                    fill=15   u=210 $ absorber
174  0              219 -220                    fill=17   u=210 $ empty pin zone
175  0              220 -221                    fill=19   u=210 $ upper pin holder
176  0              221 -222                    fill=11   u=210 $ spider
177  11   5.058e-05 222 -223  202                         u=210 $ middle gap
178  7    -7.9      222 -223 -202                         u=210 $ middle joint
179  7    -7.9      223 -224                              u=210 $ lower endplate
180  0              224 -225                    fill=12   u=210 $ lower pin holder
181  0              225 -226                    fill=17   u=210 $ empty pin zone
182  0              226 -227                    fill=15   u=210 $ absorber region
183  0              227 -228                    fill=17   u=210 $ empty pin zone
184  0              228 -229                    fill=19   u=210 $ upper pin holder
185  0              229 -230                    fill=11   u=210 $ spider
186  11   5.058e-05 230                                   u=210 $ air above rod
c
c    universe 220: details of manual rod
c
190  12  -2.69     -316  210                              u=220 $ solid bottom
191  12  -7.69      316 -317  210 -211                    u=220 $ inner wall
192  11   5.058e-05 316 -317  211 -212                    u=220 $ air gap
193  12  -2.69      316 -317  212                         u=220 $ outer wall
194  12  -2.69      317 -318  210                         u=220 $ solid top
195  11   5.058e-05 -318 -210                            u=220 $ center gap
196  12  -2.69      318 -319                              u=220 $ upper mid plate
c
c    ---------------------------------------------------------------------------
-
c
c    core cavity
c
510  11   5.058e-05   17  -26   31  -35   36  -37  38
                      -39  -40   41   42  186  187       $ above fuel zone
511  11   5.058e-05   18  -26   30  -31  185              $ above mixed zone
512  11   5.058e-05   19  -26   28  -30  183  184         $ above inner reflect
c
c    core regions
c
529  0                 9  -19   28  -30  184
     fill=50(2)                                          $ inner reflector
530  0                 9  -18   30  -31  185
     fill=52(3)                                          $ mixed zone
531  0                 9  -17   31  -35   36  -37
                       38  -39  -40   41   42  186
                      187
     fill=54(4)                                          $ fuel outer zone
c
c    experimental channels
c
532  0                 9  -26  -28            fill=68   $ central channel
533  0                 9  -26 -183            fill=70   $ E1
534  0                 9  -26 -184            fill=75   $ E2
535  0                 9  -26 -185            fill=80   $ E3
536  0                 9  -26 -186            fill=85   $ E4
537  0                 9  -26 -187            fill=90   $ E5
c
```

```
c    ------------------------------------------------------------
c
c    universe 50: inner reflector
c
540  0                -70   69  -72   71  -74   73
     lat=1  fill=51(7)
     u=50
541  0              -170  169 -172  171 -174  173
     lat=1  u=51
     fill=0:1 0:1 -2:2
       56 56 56 56
       56 56 56 56
       56 56 56 56
       56 56 56 56
       56 56 56 56
c
c    ------------------------------------------------------------
c
c    universe 52: mixed fuel/moderator/absorber zone
c
542  0                -70   69  -72   71  -74   73
     lat=1  fill=53(7)
     u=52
543  0              -170  169 -172  171 -174  173
     lat=1  u=53
     fill=0:1 0:1 -2:2
       57 57 57 57
       57 57 57 57
       57 57 58 57
       57 57 57 57
       57 57 57 57
c
c    ------------------------------------------------------------
c
c    universe 54: outer fuel zone
c
544  0                -70  69  -72   71  -74   73
     lat=1  fill=55(7)
     u=54
545  0              -170 169 -172  171 -174  173
     lat=1  u=55
     fill=0:1 0:1 -2:2
       59 59 59 59
       59 60 59 59
       59 59 59 59
       59 59 60 59
       59 59 59 59
c
c    ------------------------------------------------------
c
c    Universe 56: bcc unit cell (moderator)
c
550  4  -1.68        -641                                  u=56
551  4  -1.68        -642                                  u=56
552  4  -1.68        -643                                  u=56
553  4  -1.68        -644                                  u=56
554  4  -1.68        -645                                  u=56
```

```
555  4  -1.68        -646                                    u=56
556  4  -1.68        -647                                    u=56
557  4  -1.68        -648                                    u=56
558  4  -1.68        -649                                    u=56
c
c     air between spheres
c
559  11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=56
c
c    ------------------------------------------------------
c
c    Universe 57: bcc unit cell (moderator + 1 fuel sphere)
c
565  4  -1.68        -641                                    u=57
566  4  -1.68        -642                                    u=57
567  4  -1.68        -643                                    u=57
568  4  -1.68        -644                                    u=57
569  0               -645                 fill=62(645)       u=57
570  4  -1.68        -646                                    u=57
571  4  -1.68        -647                                    u=57
572  4  -1.68        -648                                    u=57
573  4  -1.68        -649                                    u=57
c
c    air between spheres
c
574  11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=57
c
c    ------------------------------------------------------
c
c    Universe 58: bcc unit cell (moderator + 1 absorber sphere)
c
580  4  -1.68        -641                                    u=58
581  4  -1.68        -642                                    u=58
582  4  -1.68        -643                                    u=58
583  4  -1.68        -644                                    u=58
584  0               -645                 fill=65(645)       u=58
585  4  -1.68        -646                                    u=58
586  4  -1.68        -647                                    u=58
587  4  -1.68        -648                                    u=58
588  4  -1.68        -649                                    u=58
c
c    air between spheres
c
589  11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=58
c
c    ------------------------------------------------------
c
c    Universe 59: bcc unit cell (fuel)
c
595  0               -641                 fill=62(641)       u=59
596  0               -642                 fill=62(642)       u=59
```

```
597  0              -643                    fill=62(643)  u=59
598  0              -644                    fill=62(644)  u=59
599  0              -645                    fill=62(645)  u=59
600  0              -646                    fill=62(646)  u=59
601  0              -647                    fill=62(647)  u=59
602  0              -648                    fill=62(648)  u=59
603  0              -649                    fill=62(649)  u=59
c
c    air between spheres
c
604  11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=59
c
c    ------------------------------------------------------
c
c    Universe 60: bcc unit cell (fuel + 1 absorber sphere)
c
610  0              -641                    fill=62(641)  u=60
611  0              -642                    fill=62(642)  u=60
612  0              -643                    fill=62(643)  u=60
613  0              -644                    fill=62(644)  u=60
614  0              -645                    fill=65(645)  u=60
615  0              -646                    fill=62(646)  u=60
616  0              -647                    fill=62(647)  u=60
617  0              -648                    fill=62(648)  u=60
618  0              -649                    fill=62(649)  u=60
c
c     air between spheres
c
619  11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=60
c
c    ------------------------------------------------------------
c
c    Universe 62: details of fuel sphere
c
625  4  -1.85          75                                  u=62  $ shell
626  0               -75                        fill=63    u=62  $ fuel region
c
c    Universe 63: embedded coated fuel particles
c
627  0               -76  77 -78  79 -80  81
     lat=1  fill=64
     u=63
c
c    Universe 64:  coated fuel particle
c
628  1  -10.1        -82                                   u=64  $ UO2 kernel
629  2   -1.1         82 -83                               u=64  $ PyC layer 1
630  2   -1.8         83 -84                               u=64  $ PyC layer 2
631  3   -3.2         84 -85                               u=64  $ SiC layer
632  2   -1.8         85 -86                               u=64  $ PyC layer 3
633  4   -1.85        86                                   u=64  $ graphite
c
c    ------------------------------------------------------------
```

```
c
c     universe 65: absorber sphere
c
640   4  -1.75          87                                    u=65  $ shell
641   0                -87                          fill=66   u=65  $ absorber
c
c     universe 66: absorber region
c
642   0                -88  89 -90  91 -92  93
      lat=1  fill=67
      u=66                                                         $ simple cubic
c
c     universe 67: absorber kernel
c
643   5  -2.4          -94                                   u=67  $ B4C
644   4  -1.75          94                                   u=67  $ graphite
c
c    ---------------------------------------------------------------
c
c    universe 68: central channel
c
650  10  -2.69         27                                    u=68  $ Al wall
651  11   5.058e-05   -27                                    u=68  $ air
c
c    ---------------------------------------------------------------
c
c    universe 70: experimental tube E1
c
655  10  -2.69        188                                    u=70  $ Al wall
656  11   5.058e-05  -188                                    u=70  $ air
c
c    universe 75: experimental tube E2
c
660  10  -2.69        189                                    u=75  $ Al wall
661  11   5.058e-05  -189                                    u=75  $ air
c
c    universe 80: experimental tube E3
c
670  10  -2.69        190                                    u=80  $ Al wall
671  11   5.058e-05  -190                                    u=80  $ air
c
c    universe 85: experimental tube E4
c
680  10  -2.69        191                                    u=85  $ Al wall
681  11   5.058e-05  -191                                    u=85  $ air
c
c    universe 90: experimental tube E5
c
690  10  -2.69        192                                    u=90  $ Al wall
691  11   5.058e-05  -192                                    u=90  $ air
c
c    ---------------------------------------------------------------------

c    SURFACES
c
8    pz     0.0                          $ bottom of reactor
9    pz    40.0                          $ bottom of core
```

```
c
c    core height
c
17   pz   308.9                                  $ top of outer fuel zone
18   pz   308.9                                  $ top of mixed fuel zone
19   pz   308.9                                  $ top of inner reflector
c
20   pz   360.8                                  $ bottom of Al structure
25   pz   399.5                                  $ bottom of upper reflector
26   pz   460.0                                  $ top of reactor
27   cz     5.0                                  $ center tube - inner surface
28   cz     5.25                                 $ center tube - outer surface
30   cz    34.75                                 $ inner reflector boundary
31   cz    51.25                                 $ mixed- zone boundary
32   cz   190.0                                  $ outer surface of reactor
c
c    core boundary (x-y plane)
c
35   px    87.5                                  $ right
36   px   -87.5                                  $ left
37   py    87.5                                  $ top
38   py   -87.5                                  $ bottom
39   p      1.0    1.0    0.0     125.0         $ top right
40   p     -1.0    1.0    0.0     125.0         $ top left
41   p      1.0    1.0    0.0    -125.0         $ bottom left
42   p     -1.0    1.0    0.0    -125.0         $ bottom right
c
c    reflector blocks (x-y plane)
c
53   cz     5.6                                  $ graphite plug
54   cz     5.7                                  $ hole in graphite block
55   px    12.5                                  $ right
56   px   -12.5                                  $ left
57   py    12.5                                  $ top
58   py   -12.5                                  $ bottom
c
68   cz    17.68                                    $ universe boundary
c
c    pebble-bed lattice
c
69   px    -7.126355                                $ -x
70   px     7.126355                                $ +x
71   py    -7.126355                                $ -y
72   py     7.126355                                $ +y
73   pz   -17.8158874                               $ bottom
74   pz    17.8158874                               $ top
c
c    inside fuel pebble
c
75   so     2.5                                     $ fueled region
c
c    unit cell for CFP lattice
c
76   px     0.124988
77   px    -0.124988
78   py     0.124988
79   py    -0.124988
```

```
 80   pz      0.124988
 81   pz     -0.124988
 c
 c    coated fuel particle
 c
 82   so      0.025                          $ UO2 kernel
 83   so      0.034                          $ buffer
 84   so      0.041                          $ inner PyC
 85   so      0.047                          $ SiC
 86   so      0.053                          $ outer PyC
 c
 c    inside absorber sphere
 c
 87   so      2.0                            $ radius of absorber region
 c
 c    unit absorber cell
 c
 88   px      0.02072235
 89   px     -0.02072235
 90   py      0.02072235
 91   py     -0.02072235
 92   pz      0.02072235
 93   pz     -0.02072235
 c
 94   so      0.003                          $ absorber kernel radius
 c
 c    absorber pins - outer surfaces
 c
 95   c/z     3.8       0.0       0.625
 96   c/z     3.47147   1.5456    0.625
 97   c/z     2.5427    2.82395   0.625
 98   c/z     1.17426   3.61401   0.625
 99   c/z    -0.39721   3.77918   0.625
100   c/z    -1.9       3.2909    0.625
101   c/z    -3.07426   2.23358   0.625
102   c/z    -3.71696   0.79006   0.625
103   c/z    -3.71696  -0.79006   0.625
104   c/z    -3.07426  -2.23358   0.625
105   c/z    -1.9      -3.2909    0.625
106   c/z    -0.39721  -3.77918   0.625
107   c/z     1.17426  -3.61401   0.625
108   c/z     2.5427   -2.82395   0.625
109   c/z     3.47147  -1.5456    0.625
 c
110   cz      0.505                            $ absorber outer surface
 c
 c    bcc unit cell
 c
169   px     -3.5631775                        $ -x
170   px      3.5631775                        $ +x
171   py     -3.5631775                        $ -y
172   py      3.5631775                        $ +y
173   pz     -3.5631775                        $ bottom
174   pz      3.5631775                        $ top
 c
 c    aluminum experiment tubes - outer surfaces
 c
```

```
183  c/z   -5.8501   0.0      0.6              $ E1
184  c/z  -25.0      0.0      0.6              $ E2
185  c/z  -45.0      0.0      0.6              $ E3
186  c/z  -65.0      0.0      0.6              $ E4
187  c/z  -80.0      0.0      0.6              $ E5
c
c    aluminum experiment tubes - inner surfaces
c
188  c/z   -5.8501   0.0      0.5              $ E1
189  c/z  -25.0      0.0      0.5              $ E2
190  c/z  -45.0      0.0      0.5              $ E3
191  c/z  -65.0      0.0      0.5              $ E4
192  c/z  -80.0      0.0      0.5              $ E5
c
c    small experiment channels
c
198  px    11.0
199  py     1.5
200  py    -1.5
c
c    control and shutoff rod surfaces
c
201  cz     0.3                                $ radius of pin end-region
202  cz     1.5                                $ joint
203  cz     3.1                                $ inside of pin holder
204  cz     4.5                                $ outside of pin holder
205  px     0.50                               $ pin support
206  px    -0.50                               $ pin support
207  py     0.50                               $ pin support
208  py    -0.50                               $ pin support
c
c   manual rod
210  cz     3.5                                $ inside of inner surface
211  cz     3.75                               $ outside of inner surface
212  cz     4.5                                $ inside of outer surface
213  cz     4.75                               $ outer surface of rod
c
c    CR1
c
215  pz     0.0                                $ bottom of lower endplate
216  pz     0.1                                $ bottom of lower pin holder
217  pz     1.0                                $ bottom of lower pins
218  pz     2.0                                $ bottom of B4C in lower pins
219  pz   189.5                                $ top of B4C in lower pins
220  pz   190.5                                $ bottom of lower pin holder
221  pz   191.2                                $ bottom of lower spider
222  pz   192.2                                $ bottom of middle gap
223  pz   192.7                                $ bottom of upper endplate
224  pz   192.8                                $ bottom of pin holder
225  pz   193.7                                $ bottom of upper pins
226  pz   194.7                                $ bottom of B4C in upper pins
227  pz   382.2                                $ top of B4C in upper pins
228  pz   383.2                                $ bottom of upper holder
229  pz   383.9                                $ bottom of upper spider
230  pz   384.9                                $ top of upper spider
c
c    MR1
```

```
c
315  45  pz    0.0                                  $ bottom of rod
316  45  pz    2.0                                  $ bottom of air gap
317  45  pz  383.5                                  $ top of air gap
318  45  pz  385.5                                  $ bottom of top plate
319  45  pz  388.5                                  $ top of rod
c
c    upper pin holder
c
501  c/z    3.8       0.0       0.7
502  c/z    3.47147   1.5456    0.7
503  c/z    2.5427    2.82395   0.7
504  c/z    1.17426   3.61401   0.7
505  c/z   -0.39721   3.77918   0.7
506  c/z   -1.9       3.2909    0.7
507  c/z   -3.07426   2.23358   0.7
508  c/z   -3.71696   0.79006   0.7
509  c/z   -3.71696  -0.79006   0.7
510  c/z   -3.07426  -2.23358   0.7
511  c/z   -1.9      -3.2909    0.7
512  c/z   -0.39721  -3.77918   0.7
513  c/z    1.17426  -3.61401   0.7
514  c/z    2.5427   -2.82395   0.7
515  c/z    3.47147  -1.5456    0.7
c
c    control rod end-plate
c
521  c/z    3.8       0.0       0.3
522  c/z    3.47147   1.5456    0.3
523  c/z    2.5427    2.82395   0.3
524  c/z    1.17426   3.61401   0.3
525  c/z   -0.39721   3.77918   0.3
526  c/z   -1.9       3.2909    0.3
527  c/z   -3.07426   2.23358   0.3
528  c/z   -3.71696   0.79006   0.3
529  c/z   -3.71696  -0.79006   0.3
530  c/z   -3.07426  -2.23358   0.3
531  c/z   -1.9      -3.2909    0.3
532  c/z   -0.39721  -3.77918   0.3
533  c/z    1.17426  -3.61401   0.3
534  c/z    2.5427   -2.82395   0.3
535  c/z    3.47147  -1.5456    0.3
c
c     spheres
c
641   s    -3.5631775  -3.5631775   -3.5631775     3.0     $  [-a/2 -a/2 -b/2]
642   s     3.5631775  -3.5631775   -3.5631775     3.0     $  [ a/2 -a/2 -b/2]
643   s    -3.5631775   3.5631775   -3.5631775     3.0     $  [-a/2  a/2 -b/2]
644   s     3.5631775   3.5631775   -3.5631775     3.0     $  [ a/2  a/2 -b/2]
645   so                                           3.0     $  [ 0    0    0  ]
646   s    -3.5631775  -3.5631775    3.5631775     3.0     $  [-a/2 -a/2  b/2]
647   s     3.5631775  -3.5631775    3.5631775     3.0     $  [ a/2 -a/2  b/2]
648   s    -3.5631775   3.5631775    3.5631775     3.0     $  [-a/2  a/2  b/2]
649   s     3.5631775   3.5631775    3.5631775     3.0     $  [ a/2  a/2  b/2]
c

c
```

```
c    RUN PARAMETERS
c
c     problem type
c
mode  n
kcode 5000 1.0 10 210
c
sdef  pos=0 0 40 axs=0 0 1 rad=d1 ext=d2
si1   5.25 90.5
sp1   0 1
si2   0 268.7
sp2   0 1
c
totnu
print
dbcn  9j  300
prdmp j   -60  1  2
c
c     neutron importance
c
imp:n 0                                    $ outside world
      1 1                                  $ reactor structure
      1                                    $ u=1: radial reflector lattice
      1                                    $ u=5: solid graphite block
      1 1                                  $ u=6: graphite block with hole
      1 2r                                 $ u=7: graphite block/plug
      1 2r                                 $ u=8: graphite block/hole/channel
      1 3r                                 $ u=9: graphite block/plug/channel
      1 7r                                 $ u=11: contro rod end-plate
      1 22r                                $ u=12: lower pin holder
      1 17r                                $ u=15 and 16: B4C pins
      1 17r                                $ u=17 and 18: gap in pins
      1 17r                                $ u=19 and 20: pin holder
      1 4r  1 3r  1 3r  1 3r  1 3r         $ u=21 to 25: CRs
      1 3r                                 $ u=26: MR1
      1 3r  1 3r  1 3r  1 3r  1 3r         $ u=31 to 38: SD rods
      1 3r  1 3r  1 3r
      1 16r                                $ u=210: details of CR
      1 6r                                 $ u=220: details of MR
      1 2r                                 $ cavity above core
      1 2r                                 $ core regions
      1 5r                                 $ experimental channels
      1 5r                                 $ u=50 to 55: unit cells
      1 9r                                 $ u=56: moderator
      1 9r                                 $ u=57: moderator + 1 fuel
      1 9r                                 $ u=58: moderator + 1 absorber
      1 9r                                 $ u=59: fuel
      1 9r                                 $ u=60: fuel + absorber
      1 8r                                 $ u=62 to 64: fuel sphere
      1 4r                                 $ u=65 to 67: absorber sphere
      1 1                                  $ u=65: center channel
      1 1                                  $ u=70: E1
      1 1                                  $ u=75: E2
      1 1                                  $ u=80: E3
      1 1                                  $ u=85: E4
      1 1                                  $ u=90: E5
c
```

```
c     transformations
c
tr2       0.0          21.3790649    57.8158874      $ inner reflector origin
tr3       0.0          42.7581298    57.8158874      $ mixed zone origin
tr4       0.0          71.2635496    57.8158874      $ fuel zone origin
tr5     100.0           0.0           0.0            $ reflector origin
tr7      -3.5631775    -3.5631775     0.0            $ origin of unit cell fill
c
c    absorber pins - inner surfaces
c
tr21     3.8       0.0        1.0
tr22     3.47147   1.5456     1.0
tr23     2.5427    2.82395    1.0
tr24     1.17426   3.61401    1.0
tr25    -0.39721   3.77918    1.0
tr26    -1.9       3.2909     1.0
tr27    -3.07426   2.23358    1.0
tr28    -3.71696   0.79006    1.0
tr29    -3.71696  -0.79006    1.0
tr30    -3.07426  -2.23358    1.0
tr31    -1.9      -3.2909     1.0
tr32    -0.39721  -3.77918    1.0
tr33     1.17426  -3.61401    1.0
tr34     2.5427   -2.82395    1.0
tr35     3.47147  -1.5456     1.0
c
c     control rod positions
c                                                                    position
tr41     0         0         382.7                    $ CR1          1
tr42     0         0         382.7                    $ CR2          1
tr43     0         0         382.7                    $ CR3          1
tr44     0         0         382.7                    $ CR4          1
tr45     0         0         382.7                    $ CR5          1
tr46     0         0         366.5                    $ MR1     (critical)
c
c     shutdown rod positions
c
tr51     0         0         395.3                    $ SD1        out
tr52     0         0         395.3                    $ SD2
tr53     0         0         395.3                    $ SD3
tr54     0         0         395.3                    $ SD4
tr55     0         0         395.3                    $ SD5
tr56     0         0         395.3                    $ SD6
tr57     0         0         395.3                    $ SD7
tr58     0         0         395.3                    $ SD8
c
c     sphere positions
c
tr641    -3.5631775   -3.5631775   -3.5631775
tr642     3.5631775   -3.5631775   -3.5631775
tr643    -3.5631775    3.5631775   -3.5631775
tr644     3.5631775    3.5631775   -3.5631775
tr645     0.0          0.0          0.0
tr646    -3.5631775   -3.5631775    3.5631775
tr647     3.5631775   -3.5631775    3.5631775
tr648    -3.5631775    3.5631775    3.5631775
tr649     3.5631775    3.5631775    3.5631775
```

```
c
c     material specifications
c
m1     92234.60c  0.0015        92235.60c  0.2066
       92236.60c  0.0009        92238.60c  0.7910
        8016.60c  2.0                                    $ UO2
c
m2      6000.60c  1                                      $ PyC
mt2     grph.01t
c
m3     14000.60c  0.5            6000.60c  0.5          $ SiC
mt3     grph.01t
c
m4      6000.60c -0.999999       5010.60c -0.198e-06
        5011.60c -0.802e-06                             $ graphite
mt4     grph.01t
c
m5      6000.60c  0.2            5010.60c  0.1584
        5011.60c  0.6416                                $ B4C
mt5     grph.01t
c
c     control and shutdown rods
c
m7     26000.50c -0.691          6000.60c -0.0012
       14000.60c -0.0008        25055.60c -0.02
       24000.50c -0.18          28000.50c -0.1
       22000.60c -0.007                                 $ s/steel
c
c     reflector graphite
c
m9      6000.60c -0.99999945     5010.60c -0.1089e-06
        5011.60c -0.4411e-06
mt9     grph.01t
c
c     aluminum experiment tubes
c
m10    13027.60c -0.9999986      5010.60c -0.0000014
c
c     humid air
c
m11     1001.60c  5.79913e-07    1002.60c  8.7e-11
        7014.60c  3.98536e-05    7015.60c  1.46400e-07
        8016.60c  1.0e-05
c
c     aluminum manual rod
c
m12    29000.50c -0.0035        25055.60c -0.0035
       26000.50c -0.0050        14000.60c -0.0085
       24000.50c -0.0025        13027.60c -0.9770
```

APPENDIX C.2: Infinite ASTRA lattice using exact supercell model

```
ASTRA SUPERCELL MODEL
c
c     MCNP4B supercell model with 40 fuel spheres with borated shells.
c     The CFPs are modeled explicitly. The boron and carbon in these
c     spheres reproduce the 95/5 fuel-to-absorber sphere ratio. The
c     repeating unit geometry is an enlarged BCC cell.
c
c     ------------------------------------------------------------------
c
c    CELLS
c
1    0                 60: -59:  62: -61                    $ outside world
2    0                -60   59  -62   61
     fill=1                                                 $ periodic BC
3    0                -70   69  -72   71  -74   73
     lat=1
     fill=2(7)
     u=1                                                    $ inside world
c
c    universe 1: super cell
c
4    0               -170  169 -172  171 -174  173
     lat=1  u=2
     fill=0:1 0:1 -2:2
       59 59 59 59
       59 60 59 59
       59 59 59 59
       59 59 60 59
       59 59 59 59
c
c    ------------------------------------------------------
c
c    Universe 59: bcc unit cell (fuel)
c
10   0                -641                  fill=62(641)  u=59
11   0                -642                  fill=62(642)  u=59
12   0                -643                  fill=62(643)  u=59
13   0                -644                  fill=62(644)  u=59
14   0                -645                  fill=62(645)  u=59
15   0                -646                  fill=62(646)  u=59
16   0                -647                  fill=62(647)  u=59
17   0                -648                  fill=62(648)  u=59
18   0                -649                  fill=62(649)  u=59
c
c    air between spheres
c
19   11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=59
c
c    ------------------------------------------------------
c
c    Universe 60: bct unit cell (fuel + 1 absorber sphere)
c
25   0               -641                   fill=62(641)  u=60
```

```
26   0               -642                    fill=62(642)  u=60
27   0               -643                    fill=62(643)  u=60
28   0               -644                    fill=62(644)  u=60
29   0               -645                    fill=65(645)  u=60
30   0               -646                    fill=62(646)  u=60
31   0               -647                    fill=62(647)  u=60
32   0               -648                    fill=62(648)  u=60
33   0               -649                    fill=62(649)  u=60
c
c     air between spheres
c
34   11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=60
c
c    ------------------------------------------------------------
c
c    Universe 62: details of fuel sphere
c
45   4  -1.85          75                                  u=62  $ shell
46   0                -75                        fill=63   u=62  $ fuel region
c
c    Universe 63: embedded coated fuel particles
c
47   0                -76  77 -78  79 -80  81
     lat=1  fill=64
     u=63
c
c    Universe 64:  coated fuel particle
c
48   1  -10.1         -82                                 u=64  $ UO2 kernel
49   2   -1.1          82 -83                             u=64  $ PyC layer 1
50   2   -1.8          83 -84                             u=64  $ PyC layer 2
51   3   -3.2          84 -85                             u=64  $ SiC layer
52   2   -1.8          85 -86                             u=64  $ PyC layer 3
53   4   -1.85         86                                 u=64  $ graphite
c
c    ------------------------------------------------------------
c
c     universe 65: absorber sphere
c
60    4  -1.75         87                                 u=65  $ shell
61    0               -87                        fill=66   u=65  $ absorber
c
c     universe 66: absorber region
c
62    0               -88  89 -90  91 -92  93
      lat=1  fill=67
      u=66                                                     $ simple cubic
c
c     universe 67: absorber kernel
c
63    5  -2.4         -94                                 u=67  $ B4C
64    4  -1.75         94                                 u=67  $ graphite
c

c    SURFACES
```

```
c
c    pebble-bed lattice
c
59   -60  px   -10.6895325                    $ -x
60   -59  px    10.6895325                    $ +x
61   -62  py   -10.6895325                    $ -y
62   -61  py    10.6895325                    $ +y
c
69   px    -7.126355                          $ -x
70   px     7.126355                          $ +x
71   py    -7.126355                          $ -y
72   py     7.126355                          $ +y
73   pz   -17.8158874                         $ bottom
74   pz    17.8158874                         $ top
c
c    inside fuel pebble
c
75   so     2.5                                $ fueled region
c
c    unit cell for CFP lattice
c
76   px     0.124988
77   px    -0.124988
78   py     0.124988
79   py    -0.124988
80   pz     0.124988
81   pz    -0.124988
c
c    coated fuel particle
c
82   so     0.025                          $ UO2 kernel
83   so     0.034                          $ buffer
84   so     0.041                          $ inner PyC
85   so     0.047                          $ SiC
86   so     0.053                          $ outer PyC
c
c    inside absorber sphere
c
87   so     2.0                            $ radius of absorber region
c
c    unit absorber cell
c
88   px     0.02072235
89   px    -0.02072235
90   py     0.02072235
91   py    -0.02072235
92   pz     0.02072235
93   pz    -0.02072235
c
94   so     0.003                          $ absorber kernel radius
c
c    bcc unit cell
c
169  px    -3.5631775                       $ -x
170  px     3.5631775                       $ +x
171  py    -3.5631775                       $ -y
172  py     3.5631775                       $ +y
```

```
173  pz    -3.5631775                          $ bottom
174  pz     3.5631775                          $ top
c
c     spheres
c
641   s    -3.5631775  -3.5631775   -3.5631775     3.0      $  [-a/2 -a/2 -b/2]
642   s     3.5631775  -3.5631775   -3.5631775     3.0      $  [ a/2 -a/2 -b/2]
643   s    -3.5631775   3.5631775   -3.5631775     3.0      $  [-a/2  a/2 -b/2]
644   s     3.5631775   3.5631775   -3.5631775     3.0      $  [ a/2  a/2 -b/2]
645   so                                          3.0      $  [ 0    0    0  ]
646   s    -3.5631775  -3.5631775    3.5631775     3.0      $  [-a/2 -a/2  b/2]
647   s     3.5631775  -3.5631775    3.5631775     3.0      $  [ a/2 -a/2  b/2]
648   s    -3.5631775   3.5631775    3.5631775     3.0      $  [-a/2  a/2  b/2]
649   s     3.5631775   3.5631775    3.5631775     3.0      $  [ a/2  a/2  b/2]
c

c     TRANSFORMATIONS
c
tr7        -3.5631775  -3.5631775    0.0       $ origin of unit cell fill
c
c     sphere positions
c
tr641      -3.5631775  -3.5631775   -3.5631775
tr642       3.5631775  -3.5631775   -3.5631775
tr643      -3.5631775   3.5631775   -3.5631775
tr644       3.5631775   3.5631775   -3.5631775
tr645       0.0         0.0          0.0
tr646      -3.5631775  -3.5631775    3.5631775
tr647       3.5631775  -3.5631775    3.5631775
tr648      -3.5631775   3.5631775    3.5631775
tr649       3.5631775   3.5631775    3.5631775
c
c     MATERIALS
c
m1    92234.60c  0.0015       92235.60c  0.2066
      92236.60c  0.0009       92238.60c  0.7910
       8016.60c  2.0                                    $ UO2
c
m2     6000.60c  1                                      $ PyC
mt2    grph.01t
c
m3    14000.60c  0.5           6000.60c  0.5            $ SiC
mt3    grph.01t
c
m4     6000.60c -0.999999      5010.60c -0.198e-06
       5011.60c -0.802e-06                              $ graphite
mt4    grph.01t
c
m5     6000.60c  0.2           5010.60c  0.1584
       5011.60c  0.6416                                 $ B4C
mt5    grph.01t
c
c     humid air
c
m11    1001.60c  5.79913e-07   1002.60c  8.7e-11
       7014.60c  3.98536e-05   7015.60c  1.46400e-07
       8016.60c  1.0e-05
```

```
c
c     RUN PARAMETERS
c
mode  n
kcode 5000 1.0 10 110
c
sdef  pos=0 0 -17.8158874 axs=0 0 1 rad=d1 ext=d2
si1   0 7.126355
sp1   0 1
si2   0 35.6317748
sp2   0 1
c
imp:n 0                                                $ outside world
      1                                                $ inside world
      1                                                $ u=1
      1                                                $ u=2: super cell
      1 9r                                             $ u=59
      1 9r                                             $ u=60
      1 8r                                             $ u=62 to u=64
      1 4r                                             $ u=65 to u=67
c
totnu
print
dbcn  9j  300
prdmp j   -60  1  2
```

APPENDIX C.3: Infinite ASTRA lattice using borated fuel shell

```
ASTRA SUPERCELL MODEL
c
c     MCNP4B model of an infinite BCC lattice of fuel spheres with
c     borated shells.
c
c     ------------------------------------------------------------------
c
c    CELLS
c
1    0                60: -59:  62: -61                      $ outside world
2    0               -60   59  -62   61
     fill=1                                                  $ periodic BC
3    0               -70   69  -72   71  -74   73
     fill=2  lat=1
     u=1                                                     $ lattice
c
c    Universe 2: bcc unit cell
c
25   0               -641                  fill=62(641)  u=2
26   0               -642                  fill=62(642)  u=2
27   0               -643                  fill=62(643)  u=2
28   0               -644                  fill=62(644)  u=2
29   0               -645                  fill=62(645)  u=2
30   0               -646                  fill=62(646)  u=2
31   0               -647                  fill=62(647)  u=2
32   0               -648                  fill=62(648)  u=2
33   0               -649                  fill=62(649)  u=2
c
c     air between spheres
c
34   11  5.058e-05    641  642  643  644  645  646
                      647  648  649
     u=2
c
c    ------------------------------------------------------------
c
c    Universe 62: details of fuel sphere
c
45   6  -1.850087      75                                  u=62  $ borated
shell
46   0               -75                       fill=63    u=62  $ fuel region
c
c    Universe 63: embedded coated fuel particles
c
47   0               -76  77 -78  79 -80  81
     lat=1  fill=64
     u=63
c
c    Universe 64:  coated fuel particle
c
48   1  -10.1        -82                                 u=64  $ UO2 kernel
49   2   -1.1         82 -83                             u=64  $ PyC layer 1
50   2   -1.8         83 -84                             u=64  $ PyC layer 2
51   3   -3.2         84 -85                             u=64  $ SiC layer
```

```
52   2   -1.8          85 -86                                  u=64  $ PyC layer 3
53   4   -1.85         86                                      u=64  $ graphite
c

c    SURFACES
c
c    pebble-bed lattice
c
59   -60  px    -5.34476625                    $ -x
60   -59  px     5.34476625                    $ +x
61   -62  py    -5.34476625                    $ -y
62   -61  py     5.34476625                    $ +y
c
c    bcc unit cell (packing fraction = 0.625)
c
69   px    -3.5631775                          $ -x
70   px     3.5631775                          $ +x
71   py    -3.5631775                          $ -y
72   py     3.5631775                          $ +y
73   pz    -3.5631775                          $ bottom
74   pz     3.5631775                          $ top
c
c    inside fuel pebble
c
75   so     2.5                                $ fueled region
c
c    unit cell for CFP lattice
c
76   px     0.124988
77   px    -0.124988
78   py     0.124988
79   py    -0.124988
80   pz     0.124988
81   pz    -0.124988
c
c    coated fuel particle
c
82   so     0.025                          $ UO2 kernel
83   so     0.034                          $ buffer
84   so     0.041                          $ inner PyC
85   so     0.047                          $ SiC
86   so     0.053                          $ outer PyC
c
c     spheres
c
641  s    -3.5631775  -3.5631775   -3.5631775     3.0     $  [-a/2 -a/2 -b/2]
642  s     3.5631775  -3.5631775   -3.5631775     3.0     $  [ a/2 -a/2 -b/2]
643  s    -3.5631775   3.5631775   -3.5631775     3.0     $  [-a/2  a/2 -b/2]
644  s     3.5631775   3.5631775   -3.5631775     3.0     $  [ a/2  a/2 -b/2]
645  so                                           3.0     $  [ 0    0    0  ]
646  s    -3.5631775  -3.5631775    3.5631775     3.0     $  [-a/2 -a/2  b/2]
647  s     3.5631775  -3.5631775    3.5631775     3.0     $  [ a/2 -a/2  b/2]
648  s    -3.5631775   3.5631775    3.5631775     3.0     $  [-a/2  a/2  b/2]
649  s     3.5631775   3.5631775    3.5631775     3.0     $  [ a/2  a/2  b/2]
c

c     TRANSFORMATIONS
```

```
c
c     sphere positions
c
tr641      -3.5631775  -3.5631775   -3.5631775
tr642       3.5631775  -3.5631775   -3.5631775
tr643      -3.5631775   3.5631775   -3.5631775
tr644       3.5631775   3.5631775   -3.5631775
tr645       0.0         0.0          0.0
tr646      -3.5631775  -3.5631775    3.5631775
tr647       3.5631775  -3.5631775    3.5631775
tr648      -3.5631775   3.5631775    3.5631775
tr649       3.5631775   3.5631775    3.5631775
c
c     MATERIALS
m1     92234.60c  0.0015       92235.60c  0.2066
       92236.60c  0.0009       92238.60c  0.7910
        8016.60c  2.0                                        $ UO2
c
m2      6000.60c  1                                          $ PyC
mt2     grph.01t
c
m3     14000.60c  0.5           6000.60c  0.5                $ SiC
mt3     grph.01t
c
m4      6000.60c -0.999999      5010.60c -0.198e-06
        5011.60c -0.802e-06                                  $ graphite
mt4     grph.01t
c
m6      6000.60c -0.9999521     5010.60c -9.485733e-06
        5011.60c -3.842201e-05                               $ borated shell
mt6     grph.01t
c
c     humid air
m11     1001.60c  5.79913e-07   1002.60c  8.7e-11
        7014.60c  3.98536e-05   7015.60c  1.46400e-07
        8016.60c  1.0e-05
c
c     RUN PARAMETERS
mode  n
kcode 5000 1.0 10 60
c
sdef  pos=0 0 -3.5631775 axs=0 0 1 rad=d1 ext=d2
si1   0 3.5631775
sp1   0 1
si2   0 7.126355
sp2   0 1
c
imp:n 0                                                  $ outside world
      1                                                  $ inside world
      1                                                  $ u=1
      1 9r                                               $ u=2: bcc unit
      1 8r                                               $ u=62 to u=64
c
totnu
print
dbcn  9j  300
prdmp j   -60  1  2
```

APPENDIX C.4: MCNP4B model of ASTRA using BCC core representation

```
ASTRA - PBMR EXPERIMENT
c
c    MCNP4B model of the PBMR mockup in ASTRA facility at the Kurchatov
c    Institute, Moscow.
c
c    Task 3:  Differential reactivity worth of control rods.
c
c             No top reflector
c             SD rods fully withdrawn                h = 395.3  cm
c             CR2 in position 1                      h = 382.7  cm
c             all other CRs in position 1            h = 382.7  cm
c             MR1 at reference critical height       h = 366.5  cm
c
c    Packing fraction = 0.625
c    Simple BCC lattice with borated fuel spheres
c    No exclusion zones
c
c    J.R. Lebenhaft, MIT, August 2001
c    ------------------------------------------------------------------------
c    CELLS
c
1    0                -8: 26: 32                              $ outside world
c
c    reactor structure
c
2    9   -1.65         8  -9 -32                              $ bottom reflector
c    3    9   -1.65        25 -26
c                     -35  36 -37  38  -39 -40  41  42
c                      28 183 184 185  186 187                $ top reflector
4    0                 9 -26 -32
                      (35:-36: 37:-38:  39: 40:-41:-42)
     fill=1(5)                                               $ radial reflector
c
c    radial reflector lattice
c
5    0               -55  56 -57  58
     lat=1  u=1
     fill=-12:4 -8:8 0:0
c
     0 0 0 0  0      0  0      5  5      5  0      0      0       0 0 0 0
     0 0 0 0  5      5  5      6  6      6  5      5      5       0 0 0 0
     0 0 0 5  6      6  6      6  6      6  6      6      6       5 0 0 0
     0 0 5 6  6      6  7      7  7      7  7      6      6       6 5 0 0
     0 5 6 6  6      7  33(53) 6  25(45) 6  37(57) 7      6       6 6 5 0
     0 5 6 6  7      6  5      0  0      0  5      24(44) 7       6 6 5 0
     0 5 6 7  31(51) 5  0      0  0      0  0      5      36(56)  7 6 5 0
     5 6 6 7  6      0  0      0  0      0  0      0      6       7 7 6 5
     5 8 8 9  21(41) 0  0      0  0      0  0      0      26(46)  7 6 6 5
     5 6 6 7  6      0  0      0  0      0  0      0      35(55)  7 6 6 5
     0 5 6 7  32(52) 5  0      0  0      0  0      5      23(43)  7 6 5 0
```

```
     0 5 6 6  7       6  5       0  0       0  5       6       7       6 6 5 0
     0 5 6 6  6       7  38(58)  6  22(42)  6  34(54)  7       6       6 6 5 0
     0 0 5 6  6       7  7       7  7       7  7       6       6       6 5 0 0
     0 0 0 5  6       6  6       6  6       6  6       6       6       5 0 0 0
     0 0 0 0  5       5  5       7  6       6  5       5       5       0 0 0 0
     0 0 0 0  0       0  0       5  5       5  0       0       0       0 0 0 0
c
c    ---------------------------------------------------------------------
c
c    universe 5: solid graphite block
c
10   9   -1.65        -68                                    u=5
c
c    universe 6: graphite block with empty center hole
c
15   9   -1.65         54                                    u=6   $ graphite
16   11   5.058e-05   -54                                    u=6   $ air
c
c    universe 7: graphite block with filled center hole
c
20   9   -1.65         54                                    u=7   $ graphite
21   11   5.058e-05   -54   53                               u=7   $ air gap
22   9   -1.65        -53                                    u=7   $ graphite plug
c
c    universe 8: graphite block with small experimental channel
c                and empty center hole
c
25   9   -1.65         54 (199:-200:-198)                    u=8   $ graphite
26   11   5.058e-05   198 -199  200                          u=8   $ channel
27   11   5.058e-05   -54                                    u=8   $ hole
c
c    universe 9: graphite block with small experimental channel
c                and plug in center hole
c
30   9   -1.65         54 (199:-200:-198)                    u=9   $ graphite
31   11   5.058e-05   198 -199  200                          u=9   $ channel
32   11   5.058e-05   -54   53                               u=9   $ air gap
33   9   -1.65        -53                                    u=9   $ plug
c
c    ---------------------------------------------------------------------
c
c    universe 11: control-rod spider
c
35   7   -7.9          203                                   u=11  $ outer ring
36   7   -7.9         -202                                   u=11  $ center
37   7   -7.9          202 -203 -205  206                    u=11  $ x-tie
38   7   -7.9          202 -203 -207  208                    u=11  $ y-tie
39   11   5.058e-05    202 -203  205  207                    u=11  $ gap - top right
40   11   5.058e-05    202 -203 -206  207                    u=11  $ gap - top left
41   11   5.058e-05    202 -203  205 -208                    u=11  $ gap - bot right
42   11   5.058e-05    202 -203 -206 -208                    u=11  $ gap - bot left
c
c    ---------------------------------------------------------------------
c
c    universe 12: control rod end-plate
c
920  7   -7.9          203  521  522  523  524  525
```

```
                    526  527  528  529  530  531
                    532  533  534  535                u=12  $ outer ring
c
921  11   5.058e-05 -521                               u=12  $ pin 1 holder
922  11   5.058e-05 -522                               u=12  $ pin 2 holder
923  11   5.058e-05 -523                               u=12  $ pin 3 holder
924  11   5.058e-05 -524                               u=12  $ pin 4 holder
925  11   5.058e-05 -525                               u=12  $ pin 5 holder
926  11   5.058e-05 -526                               u=12  $ pin 6 holder
927  11   5.058e-05 -527                               u=12  $ pin 7 holder
928  11   5.058e-05 -528                               u=12  $ pin 8 holder
929  11   5.058e-05 -529                               u=12  $ pin 9 holder
930  11   5.058e-05 -530                               u=12  $ pin 10 holder
931  11   5.058e-05 -531                               u=12  $ pin 11 holder
932  11   5.058e-05 -532                               u=12  $ pin 12 holder
933  11   5.058e-05 -533                               u=12  $ pin 13 holder
934  11   5.058e-05 -534                               u=12  $ pin 14 holder
935  11   5.058e-05 -535                               u=12  $ pin 15 holder
c
936  7    -7.9       -202                              u=12  $ center
937  7    -7.9        202 -203 -205  206                u=12  $ x-tie
938  7    -7.9        202 -203 -207  208                u=12  $ y-tie
939  11    5.058e-05  202 -203  205  207                u=12  $ gap - top right
940  11   5.058e-05  202 -203 -206  207                u=12  $ gap - top left
941  11   5.058e-05  202 -203  205 -208                u=12  $ gap - bot right
942  11   5.058e-05  202 -203 -206 -208                u=12  $ gap - bot left
c
c    ---------------------------------------------------------------------
c
c    universe 15: control/shutdown pin assembly
c
45   0               -95                  fill=16(21)  u=15  $ pin 1
46   0               -96                  fill=16(22)  u=15  $ pin 2
47   0               -97                  fill=16(23)  u=15  $ pin 3
48   0               -98                  fill=16(24)  u=15  $ pin 4
49   0               -99                  fill=16(25)  u=15  $ pin 5
50   0              -100                  fill=16(26)  u=15  $ pin 6
51   0              -101                  fill=16(27)  u=15  $ pin 7
52   0              -102                  fill=16(28)  u=15  $ pin 8
53   0              -103                  fill=16(29)  u=15  $ pin 9
54   0              -104                  fill=16(30)  u=15  $ pin 10
55   0              -105                  fill=16(31)  u=15  $ pin 11
56   0              -106                  fill=16(32)  u=15  $ pin 12
57   0              -107                  fill=16(33)  u=15  $ pin 13
58   0              -108                  fill=16(34)  u=15  $ pin 14
59   0              -109                  fill=16(35)  u=15  $ pin 15
c
60   11   5.058e-05   95   96   97   98   99  100
                     101  102  103  104  105  106
                     107  108  109                u=15  $ air
c
c    universe 16: contents of absorber pin
c
61   7    -7.9        110                          u=16  $ s/s clad
62   5    -1.53      -110                          u=16  $ B4C
c
c    ---------------------------------------------------------------------
```

```
c
c    universe 17: air-filled portion of control/shutdown pins
c
64   0              -95                  fill=18(21)  u=17  $ pin 1
65   0              -96                  fill=18(22)  u=17  $ pin 2
66   0              -97                  fill=18(23)  u=17  $ pin 3
67   0              -98                  fill=18(24)  u=17  $ pin 4
68   0              -99                  fill=18(25)  u=17  $ pin 5
69   0             -100                  fill=18(26)  u=17  $ pin 6
70   0             -101                  fill=18(27)  u=17  $ pin 7
71   0             -102                  fill=18(28)  u=17  $ pin 8
72   0             -103                  fill=18(29)  u=17  $ pin 9
73   0             -104                  fill=18(30)  u=17  $ pin 10
74   0             -105                  fill=18(31)  u=17  $ pin 11
75   0             -106                  fill=18(32)  u=17  $ pin 12
76   0             -107                  fill=18(33)  u=17  $ pin 13
77   0             -108                  fill=18(34)  u=17  $ pin 14
78   0             -109                  fill=18(35)  u=17  $ pin 15
79   11   5.058e-05   95   96   97   98   99  100
                     101  102  103  104  105  106
                     107  108  109                    u=17  $ air
c
c    universe 18: contents of absorber pin
c
80   7   -7.9        110                              u=18  $ s/s clad
81   11   5.058e-05 -110                              u=18  $ air
c
c    ---------------------------------------------------------------------
c
c    universe 19: upper pin holder
c
82   0             -501                  fill=20(21)  u=19  $ pin 1
83   0             -502                  fill=20(22)  u=19  $ pin 2
84   0             -503                  fill=20(23)  u=19  $ pin 3
85   0             -504                  fill=20(24)  u=19  $ pin 4
86   0             -505                  fill=20(25)  u=19  $ pin 5
87   0             -506                  fill=20(26)  u=19  $ pin 6
88   0             -507                  fill=20(27)  u=19  $ pin 7
89   0             -508                  fill=20(28)  u=19  $ pin 8
90   0             -509                  fill=20(29)  u=19  $ pin 9
91   0             -510                  fill=20(30)  u=19  $ pin 10
92   0             -511                  fill=20(31)  u=19  $ pin 11
93   0             -512                  fill=20(32)  u=19  $ pin 12
94   0             -513                  fill=20(33)  u=19  $ pin 13
95   0             -514                  fill=20(34)  u=19  $ pin 14
96   0             -515                  fill=20(35)  u=19  $ pin 15
97   11   5.058e-05  501  502  503  504  505  506
                     507  508  509  510  511  512
                     513  514  515                    u=19  $ air
c
c    universe 20: hollow interior
c
98   7   -7.9        201                              u=20  $ s/s holder
99   11   5.058e-05 -201                              u=20  $ air
c
c    ---------------------------------------------------------------------
c
```

```
c    universe 21: control rod CR1 (with small experiment channel)
c
100  9   -1.65         54 (199:-200:-198)              u=21  $ graphite
101  11   5.058e-05   198 -199  200                    u=21  $ expt. channel
102  11   5.058e-05   -54  204                         u=21  $ surrounding air
103  11   5.058e-05  -204 -215                         u=21  $ air below rod
104  0               -204  215              fill=210    u=21  $ rod
c
c    universe 22: control rod CR2
c
105  9   -1.65         54                              u=22  $ graphite
106  11   5.058e-05   -54  204                         u=22  $ surrounding air
107  11   5.058e-05  -204 -215                         u=22  $ air below rod
108  0               -204  215              fill=210    u=22  $ rod
c
c
c    universe 23: control rod CR3
c
110  9   -1.65         54                              u=23  $ graphite
111  11   5.058e-05   -54  204                         u=23  $ surrounding air
112  11   5.058e-05  -204 -215                         u=23  $ air below rod
113  0               -204  215              fill=210    u=23  $ rod
c
c
c    universe 24: control rod CR4
c
115  9   -1.65         54                              u=24  $ graphite
116  11   5.058e-05   -54  204                         u=24  $ surrounding air
117  11   5.058e-05  -204 -215                         u=24  $ air below rod
118  0               -204  215              fill=210    u=24  $ rod
c
c
c    universe 25: control rod CR5
c
120  9   -1.65         54                              u=25  $ graphite
121  11   5.058e-05   -54  204                         u=25  $ surrounding air
122  11   5.058e-05  -204 -215                         u=25  $ air below rod
123  0               -204  215              fill=210    u=25  $ rod
c
c
c    ---------------------------------------------------------------------
c
c    universe 26: manual rod MR1
c
125  9   -1.65         54                              u=26  $ graphite
126  11   5.058e-05   -54  213                         u=26  $ surrounding air
127  11   5.058e-05  -213 -315                         u=26  $ air below rod
128  0               -213  315              fill=220    u=26  $ rod
c
c    ---------------------------------------------------------------------
c
c    universe 31: control rod SR1
c
130  9   -1.65         54                              u=31  $ graphite
131  11   5.058e-05   -54  204                         u=31  $ surrounding air
132  11   5.058e-05  -204 -215                         u=31  $ air below rod
133  0               -204  215              fill=210    u=31  $ rod
```

```
c
c
c    universe 32: control rod SR2
c
135  9   -1.65        54                                  u=32  $ graphite
136  11   5.058e-05  -54  204                            u=32  $ surrounding air
137  11   5.058e-05 -204 -215                            u=32  $ air below rod
138  0              -204  215              fill=210       u=32  $ rod
c
c
c    universe 33: control rod SR3
c
140  9   -1.65        54                                  u=33  $ graphite
141  11   5.058e-05  -54  204                            u=33  $ surrounding air
142  11   5.058e-05 -204 -215                            u=33  $ air below rod
143  0              -204  215              fill=210       u=33  $ rod
c
c
c    universe 34: control rod SR4
c
145  9   -1.65        54                                  u=34  $ graphite
146  11   5.058e-05  -54  204                            u=34  $ surrounding air
147  11   5.058e-05 -204 -215                            u=34  $ air below rod
148  0              -204  215              fill=210       u=34  $ rod
c
c
c    universe 35: control rod SR5
c
150  9   -1.65        54                                  u=35  $ graphite
151  11   5.058e-05  -54  204                            u=35  $ surrounding air
152  11   5.058e-05 -204 -215                            u=35  $ air below rod
153  0              -204  215              fill=210       u=35  $ rod
c
c
c    universe 36: control rod SR6
c
155  9   -1.65        54                                  u=36  $ graphite
156  11   5.058e-05  -54  204                            u=36  $ surrounding air
157  11   5.058e-05 -204 -215                            u=36  $ air below rod
158  0              -204  215              fill=210       u=36  $ rod
c
c
c    universe 37: control rod SR7
c
160  9   -1.65        54                                  u=37  $ graphite
161  11   5.058e-05  -54  204                            u=37  $ surrounding air
162  11   5.058e-05 -204 -215                            u=37  $ air below rod
163  0              -204  215              fill=210       u=37  $ rod
c
c
c    universe 38: control rod SR8
c
165  9   -1.65        54                                  u=38  $ graphite
166  11   5.058e-05  -54  204                            u=38  $ surrounding air
167  11   5.058e-05 -204 -215                            u=38  $ air below rod
168  0              -204  215              fill=210       u=38  $ rod
c
```

```
c    ------------------------------------------------------
c
c    universe 210: details of control/shutoff rod
c
170  7    -7.9        -216                                u=210 $ lower endplate
171  0                 216 -217              fill=12     u=210 $ lower pin holder
172  0                 217 -218              fill=17     u=210 $ empty pin zone
173  0                 218 -219              fill=15     u=210 $ absorber
174  0                 219 -220              fill=17     u=210 $ empty pin zone
175  0                 220 -221              fill=19     u=210 $ upper pin holder
176  0                 221 -222              fill=11     u=210 $ spider
177  11    5.058e-05   222 -223  202                     u=210 $ middle gap
178  7    -7.9         222 -223 -202                     u=210 $ middle joint
179  7    -7.9         223 -224                          u=210 $ lower endplate
180  0                 224 -225              fill=12     u=210 $ lower pin holder
181  0                 225 -226              fill=17     u=210 $ empty pin zone
182  0                 226 -227              fill=15     u=210 $ absorber region
183  0                 227 -228              fill=17     u=210 $ empty pin zone
184  0                 228 -229              fill=19     u=210 $ upper pin holder
185  0                 229 -230              fill=11     u=210 $ spider
186  11    5.058e-05   230                               u=210 $ air above rod
c
c    ------------------------------------------------------------------------
c
c    universe 220: details of manual rod
c
190  12   -2.69       -316  210                         u=220 $ solid bottom
191  12   -7.69        316 -317  210 -211                u=220 $ inner wall
192  11    5.058e-05   316 -317  211 -212                u=220 $ air gap
193  12   -2.69        316 -317  212                     u=220 $ outer wall
194  12   -2.69        317 -318  210                     u=220 $ solid top
195  11    5.058e-05  -318 -210                         u=220 $ center gap
196  12   -2.69        318 -319                          u=220 $ upper mid plate
c
c    ------------------------------------------------------------------------
c
c    core cavity
c
510  11    5.058e-05    17  -26    31  -35    36  -37  38
                       -39  -40    41   42   186  187       $ above outer fuel
zone
511  11    5.058e-05    18  -26    30  -31   185            $ above mixed zone
512  11    5.058e-05    19  -26    28  -30   183  184       $ above inner
reflector
c
c    core regions
c
529  0                   9  -19    28  -30   184
     fill=50(2)                                            $ inner reflector
530  0                   9  -18    30  -31   185
     fill=52(3)                                            $ mixed zone
531  0                   9  -17    31  -35    36  -37
                        38  -39   -40   41    42  186
                       187
     fill=54(4)                                            $ fuel outer zone
c
c    experimental channels
```

```
c
532  0                  9  -26  -28              fill=65  $ central channel
533  0                  9  -26 -183             fill=70  $ E1
534  0                  9  -26 -184             fill=75  $ E2
535  0                  9  -26 -185             fill=80  $ E3
536  0                  9  -26 -186             fill=85  $ E4
537  0                  9  -26 -187             fill=90  $ E5
c
c    ------------------------------------------------------------
c
c    universe 50: inner reflector
c
540  0                -70   69  -72   71  -74   73
     lat=1  fill=51
     u=50
c
c    Universe 51: bcc unit cell (moderator)
c
541  4  -1.68        -121                                  u=51
542  4  -1.68        -122                                  u=51
543  4  -1.68        -123                                  u=51
544  4  -1.68        -124                                  u=51
545  4  -1.68        -125                                  u=51
546  4  -1.68        -126                                  u=51
547  4  -1.68        -127                                  u=51
548  4  -1.68        -128                                  u=51
549  4  -1.68        -129                                  u=51
c
c     air between spheres
c
550  11  5.058e-05    121  122  123  124  125  126
                     127  128  129
     u=51
c
c    ------------------------------------------------------------
c
c    universe 52: mixed fuel/moderator/absorber zone
c
555  0                -70   69  -72   71  -74   73
     lat=1  fill=53
     u=52
c
c    Universe 53: BCC unit cell (moderator/borated fuel)
c
556  0                  -121               fill=60  u=53  $ [ 0  0  0]
557  4   -1.68          -122                        u=53  $ [ 1  1  1]
558  4   -1.68          -123                        u=53  $ [ 1  1 -1]
559  4   -1.68          -124                        u=53  $ [ 1 -1 -1]
560  4   -1.68          -125                        u=53  $ [ 1 -1  1]
561  4   -1.68          -126                        u=53  $ [-1  1  1]
562  4   -1.68          -127                        u=53  $ [-1  1 -1]
563  4   -1.68          -128                        u=53  $ [-1 -1 -1]
564  4   -1.68          -129                        u=53  $ [-1 -1  1]
c
565  11   5.058e-05      121 122 123 124 125
                        126 127 128 129            u=53  $ air
c
```

```
c    ------------------------------------------------------------
c
c    universe 54: outer borated fuel zone
c
570  0                -70  69  -72   71  -74   73
     lat=1  fill=55
     u=54
c
c    Universe 55: BCC unit cell
c
572  0                  -121          fill=60       u=55  $ [ 0  0  0]
573  0                  -122          fill=60(11)   u=55  $ [ 1  1  1]
574  0                  -123          fill=60(12)   u=55  $ [ 1  1 -1]
575  0                  -124          fill=60(13)   u=55  $ [ 1 -1 -1]
576  0                  -125          fill=60(14)   u=55  $ [ 1 -1  1]
577  0                  -126          fill=60(15)   u=55  $ [-1  1  1]
578  0                  -127          fill=60(16)   u=55  $ [-1  1 -1]
579  0                  -128          fill=60(17)   u=55  $ [-1 -1 -1]
580  0                  -129          fill=60(18)   u=55  $ [-1 -1  1]
c
581  11   5.058e-05      121 122 123 124 125
                        126 127 128 129            u=55  $ air
c
c    ------------------------------------------------------------------
c
c    Universe 60: details of fuel element
c
585  6   -1.850087        75                        u=60  $ borated shell
586  0                   -75              fill=61   u=60  $ fuel region
c
c    Universe 61: embedded coated fuel particles
c
590  0                -76  77 -78  79 -80  81
     lat=1  fill=62
     u=61
c
c    Universe 62:  coated fuel particle
c
591  1  -10.1         -82                                 u=62  $ UO2 kernel
592  2   -1.1          82 -83                             u=62  $ PyC layer 1
593  2   -1.8          83 -84                             u=62  $ PyC layer 2
594  3   -3.2          84 -85                             u=62  $ SiC layer
595  2   -1.8          85 -86                             u=62  $ PyC layer 3
596  4   -1.85         86                                 u=62  $ graphite
c
c    ------------------------------------------------------------
c
c    universe 65: central channel
c
650  10  -2.69        27                                  u=65  $ Al wall
651  11   5.058e-05  -27                                  u=65  $ air
c
c    ------------------------------------------------------------
c
c    universe 70: experimental tube E1
c
655  10  -2.69       188                                 u=70  $ Al wall
```

```
656  11   5.058e-05 -188                                        u=70  $ air
c
c    universe 75: experimental tube E2
c
660  10  -2.69       189                                       u=75  $ Al wall
661  11   5.058e-05 -189                                       u=75  $ air
c
c    universe 80: experimental tube E3
c
670  10  -2.69       190                                       u=80  $ Al wall
671  11   5.058e-05 -190                                       u=80  $ air
c
c    universe 85: experimental tube E4
c
680  10  -2.69       191                                       u=85  $ Al wall
681  11   5.058e-05 -191                                       u=85  $ air
c
c    universe 90: experimental tube E5
c
690  10  -2.69       192                                       u=90  $ Al wall
691  11   5.058e-05 -192                                       u=90  $ air
c
c    ------------------------------------------------------------------------

c    SURFACES
c
8    pz     0.0                                  $ bottom of reactor
9    pz    40.0                                  $ bottom of core
c
c    core height
c
17   pz   308.9                                  $ top of outer fuel zone
18   pz   308.9                                  $ top of mixed fuel zone
19   pz   308.9                                  $ top of inner reflector
c
c    20   pz   360.8                             $ bottom of Al structure
c    25   pz   399.5                             $ bottom of upper reflector
26   pz   460.0                                  $ top of reactor
27   cz     5.0                                  $ center tube - inner surface
28   cz     5.25                                 $ center tube - outer surface
30   cz    34.75                                 $ inner reflector boundary (36.25)
31   cz    51.25                                 $ mixed- zone boundary (52.75)
32   cz   190.0                                  $ outer surface of reactor
c
c    core boundary (x-y plane)
c
35   px    87.5                                  $ right
36   px   -87.5                                  $ left
37   py    87.5                                  $ top
38   py   -87.5                                  $ bottom
39   p      1.0    1.0    0.0    125.0          $ top right
40   p     -1.0    1.0    0.0    125.0          $ top left
41   p      1.0    1.0    0.0   -125.0          $ bottom left
42   p     -1.0    1.0    0.0   -125.0          $ bottom right
c
c    reflector blocks (x-y plane)
c
```

```
53   cz      5.6                                $ graphite plug
54   cz      5.7                                $ hole in graphite block
55   px     12.5                                $ right
56   px    -12.5                                $ left
57   py     12.5                                $ top
58   py    -12.5                                $ bottom
c
68   cz     17.68                                  $ universe boundary
c
c    pebble-bed lattice
c
69   px    -3.5631775                              $ -x
70   px     3.5631775                              $ +x
71   py    -3.5631775                              $ -y
72   py     3.5631775                              $ +y
73   pz    -3.5631775                              $ bottom
74   pz     3.5631775                              $ top
c
c    inside fuel pebble
c
75   so     2.5                                    $ fueled region
c
c    unit cell for CFP lattice
c
76   px     0.124988
77   px    -0.124988
78   py     0.124988
79   py    -0.124988
80   pz     0.124988
81   pz    -0.124988
c
c    coated fuel particle
c
82   so     0.025                              $ UO2 kernel
83   so     0.034                              $ buffer
84   so     0.041                              $ inner PyC
85   so     0.047                              $ SiC
86   so     0.053                              $ outer PyC
c
c    absorber pins - outer surfaces
c
95   c/z    3.8       0.0       0.625
96   c/z    3.47147   1.5456    0.625
97   c/z    2.5427    2.82395   0.625
98   c/z    1.17426   3.61401   0.625
99   c/z   -0.39721   3.77918   0.625
100  c/z   -1.9       3.2909    0.625
101  c/z   -3.07426   2.23358   0.625
102  c/z   -3.71696   0.79006   0.625
103  c/z   -3.71696  -0.79006   0.625
104  c/z   -3.07426  -2.23358   0.625
105  c/z   -1.9      -3.2909    0.625
106  c/z   -0.39721  -3.77918   0.625
107  c/z    1.17426  -3.61401   0.625
108  c/z    2.5427   -2.82395   0.625
109  c/z    3.47147  -1.5456    0.625
c
```

```
110  cz     0.505                                  $ absorber outer surface
c
c    spheres in unit cell
c
121  so     3.0
122  s      3.5631775   3.5631775   3.5631775  3.0
123  s      3.5631775   3.5631775  -3.5631775  3.0
124  s      3.5631775  -3.5631775  -3.5631775  3.0
125  s      3.5631775  -3.5631775   3.5631775  3.0
126  s     -3.5631775   3.5631775   3.5631775  3.0
127  s     -3.5631775   3.5631775  -3.5631775  3.0
128  s     -3.5631775  -3.5631775  -3.5631775  3.0
129  s     -3.5631775  -3.5631775   3.5631775  3.0
c
c    aluminum experiment tubes - outer surfaces
c
183  c/z   -5.8501   0.0      0.6              $ E1
184  c/z  -25.0      0.0      0.6              $ E2
185  c/z  -45.0      0.0      0.6              $ E3
186  c/z  -65.0      0.0      0.6              $ E4
187  c/z  -80.0      0.0      0.6              $ E5
c
c    aluminum experiment tubes - inner surfaces
c
188  c/z   -5.8501   0.0      0.5              $ E1
189  c/z  -25.0      0.0      0.5              $ E2
190  c/z  -45.0      0.0      0.5              $ E3
191  c/z  -65.0      0.0      0.5              $ E4
192  c/z  -80.0      0.0      0.5              $ E5
c
c    small experiment channels
c
198  px    11.0
199  py     1.5
200  py    -1.5
c
c    control and shutoff rod surfaces
c
201  cz     0.3                                  $ radius of pin end-region
202  cz     1.5                                  $ joint
203  cz     3.1                                  $ inside of pin holder
204  cz     4.5                                  $ outside of pin holder
205  px     0.50                                 $ pin support
206  px    -0.50                                 $ pin support
207  py     0.50                                 $ pin support
208  py    -0.50                                 $ pin support
c
c   manual rod
210  cz     3.5                                  $ inside of inner surface
211  cz     3.75                                 $ outside of inner surface
212  cz     4.5                                  $ inside of outer surface
213  cz     4.75                                 $ outer surface of rod
c
c    Control rod
c
215  pz     0.0                                  $ bottom of lower endplate
216  pz     0.1                                  $ bottom of lower pin holder
```

```
217  pz     1.0                          $ bottom of lower pins
218  pz     2.0                          $ bottom of B4C in lower pins
219  pz   189.5                          $ top of B4C in lower pins
220  pz   190.5                          $ bottom of lower pin holder
221  pz   191.2                          $ bottom of lower spider
222  pz   192.2                          $ bottom of middle gap
223  pz   192.7                          $ bottom of upper endplate
224  pz   192.8                          $ bottom of pin holder
225  pz   193.7                          $ bottom of upper pins
226  pz   194.7                          $ bottom of B4C in upper pins
227  pz   382.2                          $ top of B4C in upper pins
228  pz   383.2                          $ bottom of upper holder
229  pz   383.9                          $ bottom of upper spider
230  pz   384.9                          $ top of upper spider
c
c    Manual regulating rod
c
315  45  pz    0.0                       $ bottom of rod
316  45  pz    2.0                       $ bottom of air gap
317  45  pz  383.5                       $ top of air gap
318  45  pz  385.5                       $ bottom of top plate
319  45  pz  388.5                       $ top of rod
c
c    upper pin holder
c
501  c/z    3.8       0.0       0.7
502  c/z    3.47147   1.5456    0.7
503  c/z    2.5427    2.82395   0.7
504  c/z    1.17426   3.61401   0.7
505  c/z   -0.39721   3.77918   0.7
506  c/z   -1.9       3.2909    0.7
507  c/z   -3.07426   2.23358   0.7
508  c/z   -3.71696   0.79006   0.7
509  c/z   -3.71696  -0.79006   0.7
510  c/z   -3.07426  -2.23358   0.7
511  c/z   -1.9      -3.2909    0.7
512  c/z   -0.39721  -3.77918   0.7
513  c/z    1.17426  -3.61401   0.7
514  c/z    2.5427   -2.82395   0.7
515  c/z    3.47147  -1.5456    0.7
c
c    control rod end-plate
c
521  c/z    3.8       0.0       0.3
522  c/z    3.47147   1.5456    0.3
523  c/z    2.5427    2.82395   0.3
524  c/z    1.17426   3.61401   0.3
525  c/z   -0.39721   3.77918   0.3
526  c/z   -1.9       3.2909    0.3
527  c/z   -3.07426   2.23358   0.3
528  c/z   -3.71696   0.79006   0.3
529  c/z   -3.71696  -0.79006   0.3
530  c/z   -3.07426  -2.23358   0.3
531  c/z   -1.9      -3.2909    0.3
532  c/z   -0.39721  -3.77918   0.3
533  c/z    1.17426  -3.61401   0.3
534  c/z    2.5427   -2.82395   0.3
```

```
535  c/z    3.47147 -1.5456   0.3
c

c
c    RUN PARAMETERS
c
c     problem type
c
mode  n
kcode 5000 1.0 10 210
c
sdef  pos=0 0 40 axs=0 0 1 rad=d1 ext=d2
si1   5.25 90.5
sp1   0 1
si2   0 268.7
sp2   0 1
c
totnu
print
dbcn  9j  300
prdmp j   -60  1  2
c
c     neutron importance
c
imp:n 0                                    $ outside world
      1 1                                  $ reactor structure
      1                                    $ u=1: radial reflector lattice
      1                                    $ u=5: solid graphite block
      1 1                                  $ u=6: graphite block with hole
      1 2r                                 $ u=7: graphite block/plug
      1 2r                                 $ u=8: graphite block/hole/channel
      1 3r                                 $ u=9: graphite block/plug/channel
      1 7r                                 $ u=11: contro rod end-plate
      1 22r                                $ u=12: lower pin holder
      1 17r                                $ u=15 and 16: B4C pins
      1 17r                                $ u=17 and 18: gap in pins
      1 17r                                $ u=19 and 20: pin holder
      1 4r  1 3r  1 3r  1 3r  1 3r         $ u=21 to 25: CRs
      1 3r                                 $ u=26: MR1
      1 3r  1 3r  1 3r  1 3r  1 3r         $ u=31 to 38: SD rods
      1 3r  1 3r  1 3r
      1 16r                                $ u=210: details of CR
      1 6r                                 $ u=220: details of MR
      1 2r                                 $ cavity above core
      1 2r                                 $ core regions
      1 5r                                 $ experimental channels
      1 10r                                $ u=50 to 51: inner reflector
      1 10r                                $ u=52 to 53: mixed zone
      1 10r                                $ u=54 to 55: fuel zone
      1 8r                                 $ u=60 to 62: CFPs
      1 1                                  $ u=65: center channel
      1 1                                  $ u=70: E1
      1 1                                  $ u=75: E2
      1 1                                  $ u=80: E3
      1 1                                  $ u=85: E4
      1 1                                  $ u=90: E5
c
```

```
c     transformations
c
tr2     0.0      21.379065 43.5631775      $ inner reflector origin
tr3     0.0      42.758130 43.5631775      $ mixed zone origin
tr4     0.0      71.263550 43.5631775      $ fuel zone origin
tr5   100.0       0.0       0.0            $ reflector origin
c
c    unit cell positions
c
tr11    3.5631775   3.5631775   3.5631775
tr12    3.5631775   3.5631775  -3.5631775
tr13    3.5631775  -3.5631775  -3.5631775
tr14    3.5631775  -3.5631775   3.5631775
tr15   -3.5631775   3.5631775   3.5631775
tr16   -3.5631775   3.5631775  -3.5631775
tr17   -3.5631775  -3.5631775  -3.5631775
tr18   -3.5631775  -3.5631775   3.5631775
c
c    absorber pins - inner surfaces
c
tr21    3.8       0.0       1.0
tr22    3.47147   1.5456    1.0
tr23    2.5427    2.82395   1.0
tr24    1.17426   3.61401   1.0
tr25   -0.39721   3.77918   1.0
tr26   -1.9       3.2909    1.0
tr27   -3.07426   2.23358   1.0
tr28   -3.71696   0.79006   1.0
tr29   -3.71696  -0.79006   1.0
tr30   -3.07426  -2.23358   1.0
tr31   -1.9      -3.2909    1.0
tr32   -0.39721  -3.77918   1.0
tr33    1.17426  -3.61401   1.0
tr34    2.5427   -2.82395   1.0
tr35    3.47147  -1.5456    1.0
c
c     control rod positions
c                                                          position
tr41    0         0        382.7                 $ CR1        1
tr42    0         0        382.7                 $ CR2        1
tr43    0         0        382.7                 $ CR3        1
tr44    0         0        382.7                 $ CR4        1
tr45    0         0        382.7                 $ CR5        1
tr46    0         0        366.5                 $ MR1    (critical)
c
c     shutdown rod positions
c
tr51    0         0        395.3                 $ SD1      out
tr52    0         0        395.3                 $ SD2
tr53    0         0        395.3                 $ SD3
tr54    0         0        395.3                 $ SD4
tr55    0         0        395.3                 $ SD5
tr56    0         0        395.3                 $ SD6
tr57    0         0        395.3                 $ SD7
tr58    0         0        395.3                 $ SD8
c
c     material specifications
```

```
c
m1    92234.60c  0.0015       92235.60c  0.2066
      92236.60c  0.0009       92238.60c  0.7910
       8016.60c  2.0                                   $ UO2
c
m2     6000.60c  1                                     $ PyC
mt2    grph.01t
c
m3    14000.60c  0.5           6000.60c  0.5           $ SiC
mt3    grph.01t
c
m4     6000.60c -0.999999      5010.60c -1.98e-07
       5011.60c -8.02e-07                              $ graphite
mt4    grph.01t                                        $ matrix
c
m5     6000.60c  0.2           5010.60c  0.1584
       5011.60c  0.6416                                $ B4C
mt5    grph.01t
c
m6     6000.60c -0.9999521     5010.60c -9.485733e-06
       5011.60c -3.842201e-05                          $ borated shell
mt6    grph.01t
c
c     control and shutdown rods
c
m7    26000.50c -0.691          6000.60c -0.0012
      14000.60c -0.0008        25055.60c -0.02
      24000.50c -0.18          28000.50c -0.1
      22000.60c -0.007                                 $ s/steel
c
c     reflector graphite
c
m9     6000.60c -0.99999945    5010.60c -0.1089e-06
       5011.60c -0.4411e-06
mt9    grph.01t
c
c     aluminum experiment tubes
c
m10   13027.60c -0.9999986     5010.60c -0.0000014
c
c     humid air
c
m11    1001.60c  5.79913e-07   1002.60c  8.7e-11
       7014.60c  3.98536e-05   7015.60c  1.46400e-07
       8016.60c  1.0e-05
c
c     aluminum manual rod
c
m12   29000.50c -0.0035        25055.60c -0.0035
      26000.50c -0.0050        14000.60c -0.0085
      24000.50c -0.0025        13027.60c -0.9770
```

APPENDIX D. MCNP4B/VSOP94 Models of PBMR

This Appendix contains the key files used to model the PBMR core with burnup. The VSOP94 input file for the reference PBMR core is attached as Appendix D.1, while the corresponding MCNP4B model is in Appendix D.2. The modified VSOP94 subroutine VORSHU is included as Appendix D.3. Program MCARDS, which generates the MCNP4B material cards from the layer-averaged fuel compositions extracted from VSOP94, is in Appendix D.4. Details on the PBMR reactor, the VSOP94 and MCNP4B models and the link between these codes appear in Chapter 7.

APPENDIX D.1—VSOP94 input file for reference PBMR core

```
*1999 MS; 0.3%BE IN MS; 265 MW; 44 FISPRD; 9 G/K; 18 RODS + 16 KLAK          V  1
   07730    0  15  20    0  25    0   0                                      V  2
  65  42    0   4 350  45   9   3   0   3   0                              V  3
  44  44    0   0   0   1                                                  V  4
   1   3    1   1   2   2   0   0   0      0.0001          1.   0          V 10
 301   0    0   0   0   1                                              1 K1 V 11
   0   1    0   0   0   2                                             12    V 11
   0   1    0   0   0   3                                             23    V 11
   0   1    0   0   0   4                                             34    V 11
   0   1    0   0   0   5                                             45    V 11
   0   1    0   0   0   6                                             56    V 11
   0   1    0   0   0   7                                             67    V 11
   0   1    0   0   0   8                                             78    V 11
   0   1    0   0   0  10                                             89    V 11
   0   1    0   0   0   1                                            100 K2 V 11
   0   1    0   0   0   2                                            111    V 11
   0   1    0   0   0   3                                            122    V 11
   0   1    0   0   0   4                                            133    V 11
   0   1    0   0   0   5                                            144    V 11
   0   1    0   0   0   6                                            155    V 11
   0   1    0   0   0   7                                            166    V 11
   0   1    0   0   0   8                                            177    V 11
   0   1    0   0   0   9                                            188    V 11
   0   1    0   0   0  10                                            199    V 11
   0   1    0   0   0  26                                            210 K3 V 11
   0   1    0   0   0  27                                            221    V 11
   0   1    0   0   0  28                                            232    V 11
   0   1    0   0   0  29                                            243    V 11
   0   1    0   0   0  30                                            254    V 11
   0   1    0   0   0  31                                            265    V 11
   0   1    0   0   0  32                                            276    V 11
   0   1    0   0   0  33                                            287    V 11
   0   1    0   0   0  34                                            298    V 11
   0   1    0   0   0  35                                            309    V 11
   0   1    0   0   0   0                                            320    V 11
   0   1    0   0   0  26                                            331 K4 V 11
   0   1    0   0   0  27                                            342    V 11
   0   1    0   0   0  28                                            353    V 11
   0   1    0   0   0  29                                            364    V 11
   0   1    0   0   0  30                                            375    V 11
   0   1    0   0   0  31                                            386    V 11
   0   1    0   0   0  32                                            397    V 11
   0   1    0   0   0  33                                            408    V 11
   0   1    0   0   0  34                                            419    V 11
   0   1    0   0   0  35                                            430    V 11
   0   1    0   0   0   0                                            441    V 11
   0   1    0   0   0   0                                            452    V 11
   0   1    0   0   0  26                                            463 K5 V 11
   0   1    0   0   0  27                                            474    V 11
   0   1    0   0   0  28                                            485    V 11
   0   1    0   0   0  29                                            496    V 11
   0   1    0   0   0  30                                            507    V 11
   0   1    0   0   0  31                                            518    V 11
   0   1    0   0   0  32                                            529    V 11
   0   1    0   0   0  33                                            540    V 11
```

```
  0    1    0    0    0  34
  0    1    0    0    0  35
  0    1    0    0    0   0
  0    1    0    0    0   0
  0    1    0    0    0   0
  0    1    0    0    0   0
  0    1    0    0    0   0
  2    0    0    0    0  14
 63      2.30577 -02
 64      7.86962 -02
  4    0    0    0    0  11
 58      0.0     -04
 59      0.0     -03
 63      2.49736 -02
 64      8.52341 -02
  2    0    0    0    0
 63      2.48234 -02
 64      8.47225 -02
  2    0    0    0    0
 63      2.22115 -02
 64      7.58082 -02
  1    0    0    0    0  12
 64      9.02479 -04
  2    0    0    0    0  13
 63      1.55    -02
 64      5.28    -02
  2    0    0    0    0
 63      2.64423 -02
 64      9.02479 -02
  2    0    0    0    0  14
 63      2.45094 -02
 64      8.36508 -02
  2    0    0    0    0  15
 63      1.93792 -02
 64      6.61415 -02
  0    1    0    0    0
  2    0    0    0    0  16
 63      2.64423 -02
 64      9.02479 -02
  0   10    0    0    0  17
  0   10    0    0    0  18
  0   10    0    0    0  19
  0   10    0    0    0  20
  0   10    0    0    0  15
  3    0    0    0    0  16
 58      1.453   -06
 63      1.81923 -02
 64      6.20906 -02
  0   16    0    0    0
  0   16    0    0    0  17
  0   16    0    0    0
  3    0    0    0    0
 58      0.0     -06
 63      1.81923 -02
 64      6.20906 -02
  0   20    0    0    0  18
  0   20    0    0    0
```

```
551    V 11
562    V 11
573    V 11
584    V 11
595    V 11
606    V 11
617    V 11
628 KON V11
       V 12
       V 12
  1 B 1 V11
       V 12
       V 12
       V 12
       V 12
  2 B 2 V11
       V 12
       V 12
  3 B 3 V11
       V 12
       V 12
  4 B 4 V11
       V 12
  5 B 5 V11
       V 12
       V 12
  6 B 6 V11
       V 12
       V 12
  7 B 7 V11
       V 12
       V 12
  8 B 8 V11
       V 12
       V 12
  9 B 9 V11
 10 B10 V11
       V 12
       V 12
 11 B11 V11
 12 B12 V11
 13 B13 V11
 14 B14 V11
 15 B15 V11
 16 B16 V11
       V 12
       V 12
       V 12
 17 B17 V11
 18 B18 V11
 19 B19 V11
 20 B20 V11
       V 12
       V 12
       V 12
 21 B21 V11
 22 B22 V11
```

```
  0  20    0    0    0                                                  23 B23 V11
  0  20    0    0    0  19                                              24 B24 V11
  0  20    0    0    0  20                                              27 B27 V11
  0   1    0    0    0  21                                              28 B28 V11
  0   2    0    0    0                                                  29 B29 V11
  0  10    0    0    0                                                  30 B30 V11
  0  10    0    0    0  22                                              31 B31 V11
  0  10    0    0    0  23                                              32 B32 V11
  0  10    0    0    0  24                                              33 B33 V11
  0  10    0    0    0  25                                              34 B34 V11
  4   0    0    0    0  21                                              35 B35 V11
 58      0.0       -04                                                       V 12
 59      0.0       -03                                                       V 12
 63      2.49736 -02                                                         V 12
 64      8.52341 -02                                                         V 12
  0  35    0    0    0  22                                              36 B36 V11
  0  35    0    0    0  23                                              37 B37 V11
  0  35    0    0    0  24                                              38 B38 V11
  0  35    0    0    0  25                                              39 B39 V11
  4   0    0    0    0  21                                              40 B40 V11
 58      0.0       -04                                                       V 12
 59      0.0       -03                                                       V 12
 63      1.82734 -02                                                         V 12
 64      6.23664 -02                                                         V 12
  0  40    0    0    0  22                                              41 B41 V11
  0  40    0    0    0  23                                              42 B42 V11
  0  40    0    0    0  24                                              43 B43 V11
  4   0    0    0    0  37                                              44 B44 V11
 58      0.0       -04                                                       V 12
 59      0.0       -03                                                       V 12
 63      2.49736 -02                                                         V 12
 64      8.52341 -02                                                         V 12
  0  44    0    0    0  38                                              45 B45 V11
  0  44    0    0    0  39                                              46 B46 V11
  0  44    0    0    0  40                                              47 B47 V11
  0  44    0    0    0  41                                              48 B48 V11
  2   0    0    0    0  36                                              49 B49 V11
 60      4.08572 -02                                                         V 12
 64      9.02479 -04                                                         V 12
  4   0    0    0    0  42                                              50 B50 V11
 58      5.01175 -05                                                         V 12
 59      2.04286 -04                                                         V 12
 63      2.29165 -02                                                         V 12
 64      7.82771 -02                                                         V 12
  4   0    0    0    0  42                                              51 B51 V11
 58      5.40700 -05                                                         V 12
 59      2.20397 -04                                                         V 12
 63      2.47238 -02                                                         V 12
 64      8.44504 -02                                                         V 12
  0  10    0    0    0  11                                              52 B52 V11
  0  52    0    0    0  11                                              53 B53 V11
  0   1    0    0    0  15                                              54 B54 V11
  0  40    0    0    0  25                                             -55 B55 V11
    0.00347      265.+06          0.        0.700                           V 15
  2  10                                                                     V 16
  1   0    0    0 261   1                                                   V 21
  0                                                                        V 22
```

```
   1                                                                           V 23
 5015   180   515    30     3     3     5     0     0     0                    G  1
        575.          590.          612.          637.          663.          685.  G2/R19
        702.          712.          794.          647.            0.            0.  G2/R19
          0.            0.            0.            0.            0.            0.  G2/R19
          0.            0.            0.            0.            0.            0.  G2/R19
          0.          594.          629.          681.          738.          793.  G2/R19
        844.          887.          920.          944.          927.            0.  G2/R19
          0.            0.            0.            0.            0.            0.  G2
     1     1     1     1     1     1     1     1     1     1     3     3           G  3
     3     3     3     3     3     3     3     3     3     3     3     3           G  3
     3     2     2     2     2     2     2     2     2     2     2     3           G  3
     3     3     3     3     3     3                                             G  3
     1     0                                                                     G  4
     6   901   902   903   904   905   906                                       G  4
     1     0                                                                     G  4
     6   901   902   903   904   905   906                                       G  4
     1     0                                                                     G  4
     1     0                                                                     G  4
     100000.           29.          1.86                                         G  5
     2     3     2    11    -1     0                                             T  1
  1600  1601  1603  1604  1605  1606  1607  1608  1609  1610  1612               T  2
        573.          587.          608.          633.          658.          680.  T3/R20
        697.          708.          788.          644.          551.          566.  T3/R20
        751.          883.          745.          553.          602.          702.  T3/R20
        780.          836.          503.          534.          541.          546.  T3/R20
        589.          589.          622.          670.          725.          780.  T3/R20
        830.          874.          909.          934.          921.          200.  T3/R20
        503.          534.          541.          546.          589.          883.  T3
  1121  1122  1123  1124  1125                                                   T  2
        575.          590.          612.          637.          663.          685.  T3/R20
        702.          712.          794.          647.            0.            0.  T3/R20
          0.            0.            0.            0.            0.            0.  T3/R20
          0.            0.            0.            0.            0.            0.  T3/R20
          0.          594.          629.          681.          738.          793.  T3/R20
        844.          887.          920.          944.          927.          200.  T3/R20
          0.            0.            0.            0.            0.            0.  T3
         4.0     6    12    29                                                   T  4
     1     4     1     1     1     1     1     1     1     1     1     1           T  5
     3     3     3     3     3     3     3     3     3     3     3     3           T  5
     3     3     3     1     1     1     1     1     1     1     1     1           T  5
     1     3     3     3     3     3     3     3                                   T  5
         1.5          0.61           1.            1.           -1.            1.  T  6
11111111122220000000                                                             T  7
    4   01       0.0          1.          0.                                     T  9
    6   00      -1.0          0.          1.                                     T  9
   26   01       1.0          0.          0.                                     T  9
  130   01      -2.0         0.0          0.                                     T  9
  150   01      -2.0         0.0         0.0                                     T  9
-1001   01      -2.0         0.0         0.0                                     T  9
         1.5          0.61           0.            1.           -1.            1.  T  6
11111111122233333300 1 1          .025          .046        .14537        1.0694   T  7
         2.5           3.0         3.985                                         T  8
    4   01       0.0          1.          0.          0.                         T  9
    6   00       1.0          0.          1.          1.                         T  9
   26   01       1.0          0.          0.          0.                         T  9
  130   01       0.0         1.0          0.          0.                         T  9
```

```
  150   01    .24682    .17968    .57350        0.                          T  9
-1001   01    .24682    .17968    .57350        0.                          T  9
        1.5         1.0         0.0          1.          0.          0.     T  6
10000000000000000000                                                       T  7
        1.0                                                                T  8
   -4   00         1.                                                     T  9
        1.5         1.0         0.0          1.         -1.          1.     T  6
11112222220000000000 1 0         0.0         0.0         0.0         0.0    T  7
       0.375      1.0466                                                   T  8
    4   00         0.        1.                                           T  9
  130   01         1.        0.                                           T  9
  164   01         1.        0.                                           T  9
-1001   01   0.01445   0.98555                                            T  9
        0.61         0.0         2.5          3.0         0.6             T 11
120000                                                                     C0-1
 *7730* MEDUL H/R=805/175; CITA 2-Z                                        C0-2
 **KOPPLUNG: VSOP - CITATION**                                             C0-3
001                                                                        C1-1
  0  0  1  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  1  0  0  0  0 -1   C1-2
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0   C1-3
840  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  7  7  0  0  0  0   C1-4
          0.          0.          0.          0.          0.          0.   C1-5
003                                                                        C3-1
  0  0  0  0  7  0  0  0  0  0  1  0  0  0  0  0  0  1  0 -1  0  0  1  0   C3-2
      0.0001      0.0001          0.          0.          0.          0.   C3-3
       9999.          0.          0. 3.287800-11          1.          0.   C3-4
     1     1                                                               C7-1
   1 204 204                                                               C7-2
                                                                           C7-3
                                                                           C7-4
       175.         0.1         0.5                                       C7-5
    14    81    18     0                                                  CX-1
7730  33  75   3   0   0   0   0   0   0   $1000MILL                       K  1
        0.80        0.43         30.          1.                          K  2
        0.00        0.00        0.15         0.00        0.00        0.06 K  3
       0.002        0.00        1.00          0.0        0.00             K  4
       20.90         6.0         100.      0.0026        0.00        0.00 K  5
       10.00       -1.25         0.0                                      K  6
          6.        0.10          0.         890.        371.         TP1 K  7
         0.0         0.0         0.0          0.0                         K  8
          0.          0.          0.           0.          0.             K  9
          0.          0.          0.                                      K 10
          6.        0.10          0.         728.        371.         TP2 K  7
         0.0         0.0         0.0          0.0                         K  8
          0.          0.          0.           0.          0.             K  9
          0.          0.          0.                                      K 10
          6.        0.10          0.         890.        371.         TP3 K  7
         0.0         0.0         0.0          0.0                         K  8
          0.          0.          0.           0.          0.             K  9
          0.          0.          0.                                      K 10
         0.0         0.0        0.99         0.99        0.99        0.99 R  1
        0.99         0.0         0.0          0.0         0.0         0.0 R  1
         0.0         1.0         0.0          0.0         0.0         0.0 R  1
         0.0         0.0         0.0          0.0         0.0         0.0 R  1
         0.0         0.0         0.0          0.0         0.0         0.0 R  1
         0.0         0.0         0.0          0.0         0.0         0.0 R  1
         0.0         0.0         0.0          0.0         0.0         0.0 R  1
```

```
        0.0          0.0          0.0          0.0          0.0          0.0    R  1
        0.0          0.0          0.0          0.0          0.0          0.0    R  1
        0.0          0.0          0.0          1.0          1.0          1.0    R  1
        1.0          1.0          1.0          1.0                              R  1
         0.           0.         365.          0.8           0.           0.    R  2
 1   0   0   0                                                                  R  3
   1 0.636417E+6  -101            1.                                           R  5
   2 2.396666E+6  -201            2.                                           R  5
   3 0.636417E+6  -301            3.                                           R  5
1  3  2  1  2  0  0  0  1  1  0  3  0  0  1  1  1  1  0  0  0  0  0  0         R  9
2  0  0  0          0.5                                                        R 14
 1                                                                            R 16
 1                                                                            R 17
     554.5        571.1        595.1        622.8        651.0        676.3  G2/R19
     698.4        717.2        799.7        630.4          0.0          0.0  G2/R19
       0.0          0.0          0.0          0.0          0.0          0.0  G2/R19
       0.0          0.0          0.0          0.0          0.0          0.0  G2/R19
       0.0        577.8        614.7        669.4        733.1        796.2  G2/R19
     852.8        900.9        940.7        968.9        955.2          0.0  G2/R19
       0.0          0.0          0.0          0.0          0.0          0.0  G2/R19
     551.7        566.9        589.1        615.3        642.6        667.6  T3/R20
     689.9        708.9        787.5        624.6        514.4        541.1  T3/R20
     703.3        931.1        708.7        517.3        589.3        735.8  T3/R20
     867.6        910.7        484.6        559.1        616.0        665.4  T3/R20
     647.8        571.0        604.5        654.4        713.6        774.0  T3/R20
     829.9        878.6        920.0        950.5        941.9        314.9  T3/R20
     428.3        466.9        467.4        467.9        468.2        867.6  T3/R20
     554.5        571.1        595.1        622.8        651.0        676.3  T3/R20
     698.4        717.2        799.7        630.4          0.0          0.0  T3/R20
       0.0          0.0          0.0          0.0          0.0          0.0  T3/R20
       0.0          0.0          0.0          0.0          0.0          0.0  T3/R20
       0.0        577.8        614.7        669.4        733.1        796.2  T3/R20
     852.8        900.9        940.7        968.9        955.2          0.0  T3/R20
       0.0          0.0          0.0          0.0          0.0          0.0  T3/R20
  1                          3   1                    0.20000                R24
  2                          3   1                    0.20000                R24
  3                          3   1                    0.20000                R24
  4                          3   1                    0.20000                R24
  5                          3   1                    0.20000                R24
  6                          3   1                    0.20000                R24
  7                          3   1                    0.20000                R24
  8                          3   1                    0.20000                R24
  9                          3   1                    0.20000                R24
 10                          3   1                    0.20000                R24
 11                          3   1                    1.                     R24
 89   78 1                                                                    R24
 90   79 2                                                                    R24
 91   80 3                                                                    R24
 92   81 4                                                                    R24
 93   82 5                                                                    R24
 94   83 6                                                                    R24
 95   84 7                                                                    R24
 96   85 8                                                                    R24
 97   86 9                                                                    R24
 98   87                                                                      R24
 99   88                                                                      R24
100                          3   1                    0.20000                R24
```

101			3	1	0.20000	R24
102			3	1	0.20000	R24
103			3	1	0.20000	R24
104			3	1	0.20000	R24
105			3	1	0.20000	R24
106			3	1	0.20000	R24
107			3	1	0.20000	R24
108			3	1	0.20000	R24
109			3	1	0.20000	R24
110			3	1	1.	R24
199	188	1				R24
200	189	2				R24
201	190	3				R24
202	191	4				R24
203	192	5				R24
204	193	6				R24
205	194	7				R24
206	195	8				R24
207	196	9				R24
208	197					R24
209	198					R24
210			3	1	0.20000	R24
211			3	1	0.20000	R24
212			3	1	0.20000	R24
213			3	1	0.20000	R24
214			3	1	0.20000	R24
215			3	1	0.20000	R24
216			3	1	0.20000	R24
217			3	1	0.20000	R24
218			3	1	0.20000	R24
219			3	1	0.20000	R24
220			3	1	1.	R24
320	309	1				R24
321	310	2				R24
322	311	3				R24
323	312	4				R24
324	313	5				R24
325	314	6				R24
326	315	7				R24
327	316	8				R24
328	317	9				R24
329	318					R24
330	319					R24
331			3	1	0.20000	R24
332			3	1	0.20000	R24
333			3	1	0.20000	R24
334			3	1	0.20000	R24
335			3	1	0.20000	R24
336			3	1	0.20000	R24
337			3	1	0.20000	R24
338			3	1	0.20000	R24
339			3	1	0.20000	R24
340			3	1	0.20000	R24
341			3	1	1.	R24
452	441	1				R24
453	442	2				R24
454	443	3				R24

```
 455  444 4                                                                  R24
 456  445 5                                                                  R24
 457  446 6                                                                  R24
 458  447 7                                                                  R24
 459  448 8                                                                  R24
 460  449 9                                                                  R24
 461  450                                                                    R24
 462  451                                                                    R24
 463                        3   1                    0.20000                R24
 464                        3   1                    0.20000                R24
 465                        3   1                    0.20000                R24
 466                        3   1                    0.20000                R24
 467                        3   1                    0.20000                R24
 468                        3   1                    0.20000                R24
 469                        3   1                    0.20000                R24
 470                        3   1                    0.20000                R24
 471                        3   1                    0.20000                R24
 472                        3   1                    0.20000                R24
 473                        3   1                    1.                     R24
 617  606 1                                                                  R24
 618  607 2                                                                  R24
 619  608 3                                                                  R24
 620  609 4                                                                  R24
 621  610 5                                                                  R24
 622  611 6                                                                  R24
 623  612 7                                                                  R24
 624  613 8                                                                  R24
 625  614 9                                                                  R24
 626  615                                                                    R24
-627  616                                                                    R24
 1  0  0 -1  0  0  0  0  1  1  0  3  0  0  1  0  0  0  0  0  0  0  0  0  0    R 9
 2  0  0  0      3.2030                                                      R14
   1                       1   1                    0.00100                R24
   210001                                           0.00143                R24
   310002                                           0.00143                R24
   410003                                           0.00143                R24
   510004                                           0.00143                R24
   610005                                           0.00143                R24
   710006                                           0.00143                R24
   810007                                           0.00143                R24
   910008                                           0.00143                R24
  1010009                                           0.00143                R24
  11                       2   1                    1.                     R24
  89   78 1                                                                 R24
  90   79 2                                                                 R24
  91   80 3                                                                 R24
  92   81 4                                                                 R24
  93   82 5                                                                 R24
  94   83 6                                                                 R24
  95   84 7                                                                 R24
  96   85 8                                                                 R24
  97   86 9                                                                 R24
  98   87                                                                   R24
  99   88                                                                   R24
 100                       1   1                    0..0000                R24
 10110001                                           0.14285                R24
 10210002                                           0.14285                R24
```

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10310003                                        0.14285                 R24
10410004                                        0.14285                 R24
10510005                                        0.14285                 R24
10610006                                        0.14285                 R24
10710007                                        0.14285                 R24
10810008                                        0.14285                 R24
10910009                                        0.14285                 R24
110                         2    1              1.                      R24
199  188 1                                                             R24
200  189 2                                                             R24
201  190 3                                                             R24
202  191 4                                                             R24
203  192 5                                                             R24
204  193 6                                                             R24
205  194 7                                                             R24
206  195 8                                                             R24
207  196 9                                                             R24
208  197                                                               R24
209  198                                                               R24
210                         1    1              0.20000                 R24
21110001                                        0.28571                 R24
21210002                                        0.28571                 R24
21310003                                        0.28571                 R24
21410004                                        0.28571                 R24
21510005                                        0.28571                 R24
21610006                                        0.28571                 R24
21710007                                        0.28571                 R24
21810008                                        0.28571                 R24
21910009                                        0.28571                 R24
220                         2    1              1.                      R24
320  309 1                                                             R24
321  310 2                                                             R24
322  311 3                                                             R24
323  312 4                                                             R24
324  313 5                                                             R24
325  314 6                                                             R24
326  315 7                                                             R24
327  316 8                                                             R24
328  317 9                                                             R24
329  318                                                               R24
330  319                                                               R24
331                         1    1              0.20000                 R24
33210001                                        0.28571                 R24
33310002                                        0.28571                 R24
33410003                                        0.28571                 R24
33510004                                        0.28571                 R24
33610005                                        0.28571                 R24
33710006                                        0.28571                 R24
33810007                                        0.28571                 R24
33910008                                        0.28571                 R24
34010009                                        0.28571                 R24
341                         2    1              1.                      R24
452  441 1                                                             R24
453  442 2                                                             R24
454  443 3                                                             R24
455  444 4                                                             R24
456  445 5                                                             R24
```

```
 457  446 6                                                                     R24
 458  447 7                                                                     R24
 459  448 8                                                                     R24
 460  449 9                                                                     R24
 461  450                                                                       R24
 462  451                                                                       R24
 463                        1   1                      0.20000                  R24
 46410001                                              0.28571                  R24
 46510002                                              0.28571                  R24
 46610003                                              0.28571                  R24
 46710004                                              0.28571                  R24
 46810005                                              0.28571                  R24
 46910006                                              0.28571                  R24
 47010007                                              0.28571                  R24
 47110008                                              0.28571                  R24
 47210009                                              0.28571                  R24
 473                        2   1                      1.                       R24
 617  606 1                                                                     R24
 618  607 2                                                                     R24
 619  608 3                                                                     R24
 620  609 4                                                                     R24
 621  610 5                                                                     R24
 622  611 6                                                                     R24
 623  612 7                                                                     R24
 624  613 8                                                                     R24
 625  614 9                                                                     R24
 626  615                                                                       R24
-627  616                                                                       R24
 2  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
20  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
20  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
20  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
 1  0  0 -2  0  0  0  0  1  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
15  0  0 -2  0  0  0  0  0  1  0  0  0  0  0  0  0  0  0  0  0  0  0            R 9
```

1	0	0	-2	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	R	9
15	0	0	-2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	R	9
1	0	0	-1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	R	9
1	0	0	-1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	R	9
1	3	2	1	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	R	9

APPENDIX D.2: MCNP4B MODEL OF PBMR

```
ESKOM PEBBLE BED MODULAR REACTOR
c
c    MCNP4B model of the Eskom PBMR using geometry and material specifications
c    from the VSOP model of the reactor core.  Detailed description of a multi-
c    zoned core using a BCC lattice with homogenized pebbles.
c
c    J.R. Lebenhaft, MIT, June 2000.
c    ------------------------------------------------------------------------
c    CELL CARDS
c
1    0                    5: -25:  41          $ outside world
c
c    reactor structure (using VSOP specifications)
c
2    1   1.10208e-01   -5    6  -35           $ B1  upper shield
3    1   1.10208e-01   -5    6   36  -40      $ B28 upper shield
4    49  4.17597e-02   -5   25   40  -41      $ B49 vessel and gaps
5    6   1.16690e-01   -6    7  -35           $ B52 top graphite
6    6   1.16690e-01   -6    7   36  -37      $ B30 radial reflector, middle
7    1   2.49736e-02   -6    7   37  -39      $ B29 bottom shield
8    1   2.49736e-02   -6   10   39  -40      $ B44 radial shield
9    6   1.16690e-01   -7    8  -30           $ B52 top graphite
10   2   1.09546e-01   -7    8   30  -35      $ B2  cold helium chamber
11   2   1.09546e-01   -7    8   36  -39      $ B29 radial reflector, middle
12   0                 -8    9  -30           $ B53 helium gap
13   3   9.80197e-02   -8    9   30  -34      $ B3  top reflector
14   6   1.16690e-01   -8   21   34  -35      $ B10-B14 radial reflect, inside
15   6   1.16690e-01   -8   10   36  -37      $ B30 radial reflector, middle
17   40  8.06398e-02   -8   10   38  -39      $ B40 radial reflector, outside
18   0                 -9   10  -34           $ B4  helium cavity
19   6   1.16690e-01  -10   13   36  -37      $ B31 radial reflector, middle
21   40  8.06398e-02  -10   13   38  -39      $ B41 radial reflector, outside
22   1   1.10208e-01  -10   13   39  -40      $ B45 radial shield, inside
23   6   1.16690e-01  -13   21   36  -37      $ B32-B34 rad reflector, mid/out
25   40  8.06398e-02  -13   23   38  -39      $ B42-B55 rad reflector, out/bot
26   1   1.10208e-01  -13   22   39  -40      $ B46-B48 rad shield, insulate
27   7   1.08160e-01  -20   21   31  -34      $ B7  bottom reflector
28   6   1.16690e-01  -20   21   35  -36      $ B14 radial reflector, inside
29   50  1.01448e-01  -21   22   31  -34      $ B50 bottom shield, insulate
30   51  1.63465e-01  -21   22   34  -37      $ B51
31   8   8.55207e-02  -22   23   31  -34      $ B8  hot He chamber
32   1   1.10208e-01  -22   23   34  -37      $ B54 shield of discharge tube
33   1   1.10208e-01  -23   24   31  -37      $ B54
34   6   1.16690e-01  -22   23   39  -40      $ B15
35   6   1.16690e-01  -23   24   37  -40      $ B15
36   1   1.10208e-01  -24   25   31  -40      $ B9
37   7   1.08160e-01   20  -34   45           $ Bxx conus reflector
38   6   1.16690e-01  -20   25   30  -31      $ B6  discharge pipe wall
c
c    control/shutdown zone
c
40   6   1.16690e-01   -5   20   35  -36
                     (440:-441: 442:-443)
                     (444:-445: 446:-447)
                     (448:-449: 450:-451)
```

```
                        (452:-453: 454:-455)
                        (456:-457: 458:-459)
                        (460:-461: 462:-463)
                        (464:-465: 466:-467)
                        (468:-469: 470:-471)
                        (472:-473: 474:-475)
                        (476:-477: 478:-479)
                        (480:-481: 482:-483)
                        (484:-485: 486:-487)
                        (488:-489: 490:-491)
                        (492:-493: 494:-495)
                        (496:-497: 498:-499)
                        (500:-501: 502:-503)
                        (504:-505: 506:-507)
                        (508:-509: 510:-511)
                        (271:-272:(273  275):(276 -274))
                        (277:-278:(279  281):(282 -280))
                        (283:-284:(285  287):(288 -286))
                        (289:-290:(291  293):(294 -292))
                        (295:-296:(297  299):(300 -298))
                        (301:-302:(303  305):(306 -304))
                        (307:-308:(309  311):(312 -310))
                        (313:-314:(315  317):(318 -316))
                        (319:-320:(321  323):(324 -322))
                        (325:-326:(327  329):(330 -328))
                        (331:-332:(333  335):(336 -334))
                        (337:-338:(339  341):(342 -340))
                        (343:-344:(345  347):(348 -346))
                        (349:-350:(351  353):(354 -352))
                        (355:-356:(357  359):(360 -358))
                        (361:-362:(363  365):(366 -364))
                        (367:-368:(369  371):(372 -370))
c
c    helium channel zone
c
41   6   1.16690e-01   -8   23   37  -38
                       375  376  377  378  379  380
                       381  382  383  384  385  386
                       387  388  389  390  391  392
                       393  394  395  396  397  398
                       399  400  401  402  403  404
                       405  406  407  408  409  410
c
c    control sites
c
45   0   -5  20 -440  441 -442  443                fill=300(61)     $ CR1
46   0   -5  20 -444  445 -446  447                fill=300(62)     $ CR2
47   0   -5  20 -448  449 -450  451                fill=300(63)     $ CR3
48   0   -5  20 -452  453 -454  455                fill=300(64)     $ CR4
49   0   -5  20 -456  457 -458  459                fill=300(65)     $ CR5
50   0   -5  20 -460  461 -462  463                fill=300(66)     $ CR6
51   0   -5  20 -464  465 -466  467                fill=300(67)     $ CR7
52   0   -5  20 -468  469 -470  471                fill=300(68)     $ CR8
53   0   -5  20 -472  473 -474  475                fill=300(69)     $ CR9
54   0   -5  20 -476  477 -478  479                fill=300(70)     $ CR10
55   0   -5  20 -480  481 -482  483                fill=300(71)     $ CR11
56   0   -5  20 -484  485 -486  487                fill=300(72)     $ CR12
```

```
57   0    -5  20 -488  489 -490  491                    fill=300(73)      $ CR13
58   0    -5  20 -492  493 -494  495                    fill=300(74)      $ CR14
59   0    -5  20 -496  497 -498  499                    fill=300(75)      $ CR15
60   0    -5  20 -500  501 -502  503                    fill=300(76)      $ CR16
61   0    -5  20 -504  505 -506  507                    fill=300(77)      $ CR17
62   0    -5  20 -508  509 -510  511                    fill=300(78)      $ CR18
c
c    shutdown sites
c
65   60 -3.429e-03    -5  20 -271  272 (-273:-275) (274:-276)        $ KL1
66   60 -3.429e-03    -5  20 -277  278 (-279:-281) (280:-282)        $ KL2
67   60 -3.429e-03    -5  20 -283  284 (-285:-287) (286:-288)        $ KL3
68   60 -3.429e-03    -5  20 -289  290 (-291:-293) (292:-294)        $ KL4
69   60 -3.429e-03    -5  20 -295  296 (-297:-299) (298:-300)        $ KL5
70   60 -3.429e-03    -5  20 -301  302 (-303:-305) (304:-306)        $ KL6
71   60 -3.429e-03    -5  20 -307  308 (-309:-311) (310:-312)        $ KL7
72   60 -3.429e-03    -5  20 -313  314 (-315:-317) (316:-318)        $ KL8
73   60 -3.429e-03    -5  20 -319  320 (-321:-323) (322:-324)        $ KL9
74   60 -3.429e-03    -5  20 -325  326 (-327:-329) (328:-330)        $ KL10
75   60 -3.429e-03    -5  20 -331  332 (-333:-335) (334:-336)        $ KL11
76   60 -3.429e-03    -5  20 -337  338 (-339:-341) (340:-342)        $ KL12
77   60 -3.429e-03    -5  20 -343  344 (-345:-347) (346:-348)        $ KL13
78   60 -3.429e-03    -5  20 -349  350 (-351:-353) (352:-354)        $ KL14
79   60 -3.429e-03    -5  20 -355  356 (-357:-359) (358:-360)        $ KL15
80   60 -3.429e-03    -5  20 -361  362 (-363:-365) (364:-366)        $ KL16
81   60 -3.429e-03    -5  20 -367  368 (-369:-371) (370:-372)        $ KL17
c
c    helium coolant channels
c
85   60 -3.429e-03    -8  23 -375
86   60 -3.429e-03    -8  23 -376
87   60 -3.429e-03    -8  23 -377
88   60 -3.429e-03    -8  23 -378
89   60 -3.429e-03    -8  23 -379
90   60 -3.429e-03    -8  23 -380
91   60 -3.429e-03    -8  23 -381
92   60 -3.429e-03    -8  23 -382
93   60 -3.429e-03    -8  23 -383
94   60 -3.429e-03    -8  23 -384
95   60 -3.429e-03    -8  23 -385
96   60 -3.429e-03    -8  23 -386
97   60 -3.429e-03    -8  23 -387
98   60 -3.429e-03    -8  23 -388
99   60 -3.429e-03    -8  23 -389
100  60 -3.429e-03    -8  23 -390
101  60 -3.429e-03    -8  23 -391
102  60 -3.429e-03    -8  23 -392
103  60 -3.429e-03    -8  23 -393
104  60 -3.429e-03    -8  23 -394
105  60 -3.429e-03    -8  23 -395
106  60 -3.429e-03    -8  23 -396
107  60 -3.429e-03    -8  23 -397
108  60 -3.429e-03    -8  23 -398
109  60 -3.429e-03    -8  23 -399
110  60 -3.429e-03    -8  23 -400
111  60 -3.429e-03    -8  23 -401
112  60 -3.429e-03    -8  23 -402
```

```
113  60 -3.429e-03     -8  23 -403
114  60 -3.429e-03     -8  23 -404
115  60 -3.429e-03     -8  23 -405
116  60 -3.429e-03     -8  23 -406
117  60 -3.429e-03     -8  23 -407
118  60 -3.429e-03     -8  23 -408
119  60 -3.429e-03     -8  23 -409
120  60 -3.429e-03     -8  23 -410
c
c    ------------------------------------------------------------
c    universe 300: control site
c
125  0                   520            fill=301  u=300  $ control rod region
126  6   1.16690e-01    -520  538                u=300  $ graphite surroundings
127  60 -3.429e-03      -520 -538                u=300  $ region below control
rod
c
c    universe 301: absorber lattice
c
128  0                  -523  524 -525  526 -530
                         533
     lat=1  fill=302
     u=301
c
c    .. universe 302: unit cell
c
129  6   1.16690e-01     538                     u=302  $ graphite surroundings
130  60 -3.429e-03      -538  537                u=302  $ helium-filled gap
131  61 -8.0            -537  534  531           u=302  $ upper half joint
132  61 -8.0            -537  536 -531  532      u=302  $ outer sleeve of abs
133  62 -1.7            -536  535 -531  532      u=302  $ absorber
134  61 -8.0            -535  534 -531  532      u=302  $ inner sleeve of abs
135  61 -8.0            -537  534 -532           u=302  $ lower half joint
136  60 -3.429e-03      -534                     u=302  $ helium-filled inside
c
c    ------------------------------------------------------------
c    core
c
300  0  -10  20  -34  -45                         fill=5
c
c    discharge pipe
c
301  0  -20  25  -30                             fill=78(58)
c
c    channel 1
302  0  (-115  155): (-116 -155  156): (-117 -156  157):
        (-118 -157 158): (-119 -158 159): (-120 -159)
     fill=10  u=5
c
c    channel 2
303  0  (115 -125  155): (116 -126 -155  156): (117 -127 -156  157):
        (118 -128 -157 158): (119 -129 -158 159): (120 -130 -159)
     fill=11  u=5
c
c    channel 3
304  0  (125 -135  155): (126 -136 -155  156): (127 -137 -156  157):
        (128 -138 -157 158): (129 -139 -158 159): (130 -140 -159)
```

```
      fill=12  u=5
c
c     channel 4
305   0  (135 -145  155): (136 -146 -155  156): (137 -147 -156  157):
         (138 -148 -157 158): (139 -149 -158 159): (140 -150 -159)
      fill=13  u=5
c
c     channel 5
306   0  (145 155): (146 -155  156): (147 -156  157): (148 -157 158):
         (149 -158 19): (149 -19 159): (150 -159)
      fill=14  u=5
c
c     core layers
c
c     .. channel 1
c
307   0                 50            fill=21(1)   u=10  $ layer 1
308   0                -50   51       fill=22(2)   u=10  $ layer 2
309   0                -51   52       fill=23(3)   u=10  $ layer 3
310   0                -52   53       fill=24(4)   u=10  $ layer 4
311   0                -53   54       fill=25(5)   u=10  $ layer 5
312   0                -54   55       fill=26(6)   u=10  $ layer 6
313   0                -55   56       fill=27(7)   u=10  $ layer 7
314   0                -56   57       fill=28(8)   u=10  $ layer 8
315   0                -57            fill=29(9)   u=10  $ layer 9
c
c     .. channel 2
c
316   0                 60            fill=30(10)  u=11  $ layer 10
317   0                -60   61       fill=31(11)  u=11  $ layer 11
318   0                -61   62       fill=32(12)  u=11  $ layer 12
319   0                -62   63       fill=33(13)  u=11  $ layer 13
320   0                -63   64       fill=34(14)  u=11  $ layer 14
321   0                -64   65       fill=35(15)  u=11  $ layer 15
322   0                -65   66       fill=36(16)  u=11  $ layer 16
323   0                -66   67       fill=37(17)  u=11  $ layer 17
324   0                -67   68       fill=38(18)  u=11  $ layer 18
325   0                -68            fill=39(19)  u=11  $ layer 19
c
c     .. channel 3
c
326   0                 70            fill=40(20)  u=12  $ layer 20
327   0                -70   71       fill=41(21)  u=12  $ layer 21
328   0                -71   72       fill=42(22)  u=12  $ layer 22
329   0                -72   73       fill=43(23)  u=12  $ layer 23
330   0                -73   74       fill=44(24)  u=12  $ layer 24
331   0                -74   75       fill=45(25)  u=12  $ layer 25
332   0                -75   76       fill=46(26)  u=12  $ layer 26
333   0                -76   77       fill=47(27)  u=12  $ layer 27
334   0                -77   78       fill=48(28)  u=12  $ layer 28
335   0                -78   79       fill=49(29)  u=12  $ layer 29
336   0                -79            fill=50(30)  u=12  $ layer 30
c
c     .. channel 4
c
337   0                 85           fill=51(31)  u=13  $ layer 31
338   0                -85   86       fill=52(32)  u=13  $ layer 32
```

```
339  0                -86   87        fill=53(33)  u=13  $ layer 33
340  0                -87   88        fill=54(34)  u=13  $ layer 34
341  0                -88   89        fill=55(35)  u=13  $ layer 35
342  0                -89   90        fill=56(36)  u=13  $ layer 36
343  0                -90   91        fill=57(37)  u=13  $ layer 37
344  0                -91   92        fill=58(38)  u=13  $ layer 38
345  0                -92   93        fill=59(39)  u=13  $ layer 39
346  0                -93   94        fill=60(40)  u=13  $ layer 40
347  0                -94   95        fill=61(41)  u=13  $ layer 41
348  0                -95             fill=62(42)  u=13  $ layer 42
c
c    .. channel 5
c
349  0                 100            fill=63(43)  u=14  $ layer 43
350  0                -100  101       fill=64(44)  u=14  $ layer 44
351  0                -101  102       fill=65(45)  u=14  $ layer 45
352  0                -102  103       fill=66(46)  u=14  $ layer 46
353  0                -103  104       fill=67(47)  u=14  $ layer 47
354  0                -104  105       fill=68(48)  u=14  $ layer 48
355  0                -105  106       fill=69(49)  u=14  $ layer 49
356  0                -106  107       fill=70(50)  u=14  $ layer 50
357  0                -107  108       fill=71(51)  u=14  $ layer 51
358  0                -108  109       fill=72(52)  u=14  $ layer 52
359  0                -109  110       fill=73(53)  u=14  $ layer 53
360  0                -110  111       fill=74(54)  u=14  $ layer 54
361  0                -111  112       fill=75(55)  u=14  $ layer 55
362  0                -112  113       fill=76(56)  u=14  $ layer 56
363  0                -113            fill=77(57)  u=14  $ layer 57
c
c    ---------------------------------------------------
c    channel 1: inner graphite reflector with trace U
c    ---------------------------------------------------
c
c    universe 21: layer 1
c
375  0                  -206  205 -207  208 -209  210
     lat=1  fill=80
     u=21
c
c    unit cell with graphite balls
c
376  100  1.1655800e-01 -211                      u=80   $ [ 0  0  0]
377  100  1.1655800e-01 -212                      u=80   $ [ 1  1  1]
378  100  1.1655800e-01 -213                      u=80   $ [ 1  1 -1]
379  100  1.1655800e-01 -214                      u=80   $ [ 1 -1 -1]
380  100  1.1655800e-01 -215                      u=80   $ [ 1 -1  1]
381  100  1.1655800e-01 -216                      u=80   $ [-1  1  1]
382  100  1.1655800e-01 -217                      u=80   $ [-1  1 -1]
383  100  1.1655800e-01 -218                      u=80   $ [-1 -1 -1]
384  100  1.1655800e-01 -219                      u=80   $ [-1 -1  1]
385  60  -3.42900e-03    211  212  213  214  215
                        216  217  218  219       u=80   $ helium between balls
c
c    ---------------------------------------------------
c    universe 22: layer 2
c
386  0                  -206  205 -207  208 -209  210
```

```
     lat=1  fill=81
     u=22
c
c    unit cell with graphite balls
c
387  101  1.1655800e-01 -211                          u=81   $ [ 0  0  0]
388  101  1.1655800e-01 -212                          u=81   $ [ 1  1  1]
389  101  1.1655800e-01 -213                          u=81   $ [ 1  1 -1]
390  101  1.1655800e-01 -214                          u=81   $ [ 1 -1 -1]
391  101  1.1655800e-01 -215                          u=81   $ [ 1 -1  1]
392  101  1.1655800e-01 -216                          u=81   $ [-1  1  1]
393  101  1.1655800e-01 -217                          u=81   $ [-1  1 -1]
394  101  1.1655800e-01 -218                          u=81   $ [-1 -1 -1]
395  101  1.1655800e-01 -219                          u=81   $ [-1 -1  1]
396  60  -3.42900e-03    211  212  213  214  215
                         216  217  218  219          u=81   $ helium between balls
c
c    ---------------------------------------------------
c    universe 23: layer 3
c
397  0                  -206  205 -207  208 -209  210
     lat=1  fill=82
     u=23
c
c    unit cell with graphite balls
c
398  102  1.1655800e-01 -211                          u=82   $ [ 0  0  0]
399  102  1.1655800e-01 -212                          u=82   $ [ 1  1  1]
400  102  1.1655800e-01 -213                          u=82   $ [ 1  1 -1]
401  102  1.1655800e-01 -214                          u=82   $ [ 1 -1 -1]
402  102  1.1655800e-01 -215                          u=82   $ [ 1 -1  1]
403  102  1.1655800e-01 -216                          u=82   $ [-1  1  1]
404  102  1.1655800e-01 -217                          u=82   $ [-1  1 -1]
405  102  1.1655800e-01 -218                          u=82   $ [-1 -1 -1]
406  102  1.1655800e-01 -219                          u=82   $ [-1 -1  1]
407  60 -3.429e-03    211  212  213  214  215
                      216  217  218  219          u=82   $ helium between balls
c
c    ---------------------------------------------------
c    universe 24: layer 4
c
408  0                  -206  205 -207  208 -209  210
     lat=1  fill=83
     u=24
c
c    unit cell with graphite balls
c
409  103  1.1655800e-01 -211                          u=83   $ [ 0  0  0]
410  103  1.1655800e-01 -212                          u=83   $ [ 1  1  1]
411  103  1.1655800e-01 -213                          u=83   $ [ 1  1 -1]
412  103  1.1655800e-01 -214                          u=83   $ [ 1 -1 -1]
413  103  1.1655800e-01 -215                          u=83   $ [ 1 -1  1]
414  103  1.1655800e-01 -216                          u=83   $ [-1  1  1]
415  103  1.1655800e-01 -217                          u=83   $ [-1  1 -1]
416  103  1.1655800e-01 -218                          u=83   $ [-1 -1 -1]
417  103  1.1655800e-01 -219                          u=83   $ [-1 -1  1]
418  60  -3.429e-03      211  212  213  214  215
```

```
                          216  217  218  219       u=83   $ helium between balls
c
c    ---------------------------------------------
c    universe 25: layer 5
c
419  0                   -206  205 -207  208 -209  210
     lat=1  fill=84
     u=25
c
c    unit cell with graphite balls
c
420  104  1.1655800e-01 -211                        u=84   $ [ 0  0  0]
421  104  1.1655800e-01 -212                        u=84   $ [ 1  1  1]
422  104  1.1655800e-01 -213                        u=84   $ [ 1  1 -1]
423  104  1.1655800e-01 -214                        u=84   $ [ 1 -1 -1]
424  104  1.1655800e-01 -215                        u=84   $ [ 1 -1  1]
425  104  1.1655800e-01 -216                        u=84   $ [-1  1  1]
426  104  1.1655800e-01 -217                        u=84   $ [-1  1 -1]
427  104  1.1655800e-01 -218                        u=84   $ [-1 -1 -1]
428  104  1.1655800e-01 -219                        u=84   $ [-1 -1  1]
429  60  -3.429e-03      211  212  213  214  215
                          216  217  218  219       u=84   $ helium between balls
c
c    ---------------------------------------------
c    universe 26: layer 6
c
430  0                   -206  205 -207  208 -209  210
                                lat=1  fill=85  u=26
c    unit cell with graphite balls
431  105  1.1655800e-01 -211                        u=85   $ [ 0  0  0]
432  105  1.1655800e-01 -212                        u=85   $ [ 1  1  1]
433  105  1.1655800e-01 -213                        u=85   $ [ 1  1 -1]
434  105  1.1655800e-01 -214                        u=85   $ [ 1 -1 -1]
435  105  1.1655800e-01 -215                        u=85   $ [ 1 -1  1]
436  105  1.1655800e-01 -216                        u=85   $ [-1  1  1]
437  105  1.1655800e-01 -217                        u=85   $ [-1  1 -1]
438  105  1.1655800e-01 -218                        u=85   $ [-1 -1 -1]
439  105  1.1655800e-01 -219                        u=85   $ [-1 -1  1]
440  60  -3.42900e-03     211  212  213  214  215
                          216  217  218  219       u=85   $ helium between balls
c
c    ---------------------------------------------
c    universe 27: layer 7
c
441  0                -206  205 -207  208 -209  210
                             lat=1  fill=86  u=27
c    unit cell with graphite balls
442  106  1.1655800e-01 -211                        u=86   $ [ 0  0  0]
443  106  1.1655800e-01 -212                        u=86   $ [ 1  1  1]
444  106  1.1655800e-01 -213                        u=86   $ [ 1  1 -1]
445  106  1.1655800e-01 -214                        u=86   $ [ 1 -1 -1]
446  106  1.1655800e-01 -215                        u=86   $ [ 1 -1  1]
447  106  1.1655800e-01 -216                        u=86   $ [-1  1  1]
448  106  1.1655800e-01 -217                        u=86   $ [-1  1 -1]
449  106  1.1655800e-01 -218                        u=86   $ [-1 -1 -1]
450  106  1.1655800e-01 -219                        u=86   $ [-1 -1  1]
451  60  -3.42900e-03     211  212  213  214  215
```

```
                        216  217  218  219        u=86   $ helium between balls
c
c    ---------------------------------------------
c    universe 28: layer 8
c
452  0                   -206  205 -207  208 -209  210
                                lat=1  fill=87  u=28
c    unit cell with graphite balls
453  107  1.1655800e-01 -211                       u=87    $ [ 0  0  0]
454  107  1.1655800e-01 -212                       u=87    $ [ 1  1  1]
455  107  1.1655800e-01 -213                       u=87    $ [ 1  1 -1]
456  107  1.1655800e-01 -214                       u=87    $ [ 1 -1 -1]
457  107  1.1655800e-01 -215                       u=87    $ [ 1 -1  1]
458  107  1.1655800e-01 -216                       u=87    $ [-1  1  1]
459  107  1.1655800e-01 -217                       u=87    $ [-1  1 -1]
460  107  1.1655800e-01 -218                       u=87    $ [-1 -1 -1]
461  107  1.1655800e-01 -219                       u=87    $ [-1 -1  1]
462  60   -3.429e-03      211  212  213  214  215
                         216  217  218  219        u=87    $ helium between balls
c
c    ---------------------------------------------
c    universe 29: layer 9
c
463  0                   -206  205 -207  208 -209  210
                              lat=1  fill=88  u=29
c    unit cell with graphite balls
464  108  1.1655800e-01 -211                       u=88    $ [ 0  0  0]
465  108  1.1655800e-01 -212                       u=88    $ [ 1  1  1]
466  108  1.1655800e-01 -213                       u=88    $ [ 1  1 -1]
467  108  1.1655800e-01 -214                       u=88    $ [ 1 -1 -1]
468  108  1.1655800e-01 -215                       u=88    $ [ 1 -1  1]
469  108  1.1655800e-01 -216                       u=88    $ [-1  1  1]
470  108  1.1655800e-01 -217                       u=88    $ [-1  1 -1]
471  108  1.1655800e-01 -218                       u=88    $ [-1 -1 -1]
472  108  1.1655800e-01 -219                       u=88    $ [-1 -1  1]
473  60   -3.429e-03      211  212  213  214  215
                         216  217  218  219        u=88    $ helium between balls
c
c    ---------------------------------------------
c    channel 2: mixed fuel and moderator
c    ---------------------------------------------
c
c    universe 30: layer 10
c
484  0                   -206  205 -207  208 -209  210     $ unit cell boundaries
                              lat=1  fill=89  u=30
c    .. contents of unit cell
485  109  4.2400759e-01 -211                       u=89    $ [ 0  0  0]
486  109  4.2400759e-01 -212                       u=89    $ [ 1  1  1]
487  109  4.2400759e-01 -213                       u=89    $ [ 1  1 -1]
488  109  4.2400759e-01 -214                       u=89    $ [ 1 -1 -1]
489  109  4.2400759e-01 -215                       u=89    $ [ 1 -1  1]
490  109  4.2400759e-01 -216                       u=89    $ [-1  1  1]
491  109  4.2400759e-01 -217                       u=89    $ [-1  1 -1]
492  109  4.2400759e-01 -218                       u=89    $ [-1 -1 -1]
493  109  4.2400759e-01 -219                       u=89    $ [-1 -1  1]
494  60   -3.429e-03      211  212  213  214  215
```

```
                          216  217  218  219       u=89    $ helium between balls
c
c    ---------------------------------------------------
c    universe 31: layer 11
c
495  0                   -206  205 -207  208 -209  210     $ unit cell boundaries
                                  lat=1  fill=93  u=31
c    .. contents of unit cell
496  110  4.2400819e-01 -211                          u=93    $ [ 0  0  0]
497  110  4.2400819e-01 -212                          u=93    $ [ 1  1  1]
498  110  4.2400819e-01 -213                          u=93    $ [ 1  1 -1]
499  110  4.2400819e-01 -214                          u=93    $ [ 1 -1 -1]
500  110  4.2400819e-01 -215                          u=93    $ [ 1 -1  1]
501  110  4.2400819e-01 -216                          u=93    $ [-1  1  1]
502  110  4.2400819e-01 -217                          u=93    $ [-1  1 -1]
503  110  4.2400819e-01 -218                          u=93    $ [-1 -1 -1]
504  110  4.2400819e-01 -219                          u=93    $ [-1 -1  1]
505  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219       u=93    $ helium between balls
c
c    ---------------------------------------------------
c    universe 32: layer 12
c
506  0                   -206  205 -207  208 -209  210     $ unit cell boundaries
                                  lat=1  fill=97  u=32
c    .. contents of unit cell
507  111  4.2400879e-01 -211                          u=97    $ [ 0  0  0]
508  111  4.2400879e-01 -212                          u=97    $ [ 1  1  1]
509  111  4.2400879e-01 -213                          u=97    $ [ 1  1 -1]
510  111  4.2400879e-01 -214                          u=97    $ [ 1 -1 -1]
511  111  4.2400879e-01 -215                          u=97    $ [ 1 -1  1]
512  111  4.2400879e-01 -216                          u=97    $ [-1  1  1]
513  111  4.2400879e-01 -217                          u=97    $ [-1  1 -1]
514  111  4.2400879e-01 -218                          u=97    $ [-1 -1 -1]
515  111  4.2400879e-01 -219                          u=97    $ [-1 -1  1]
516  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219       u=97    $ helium between balls
c
c    ---------------------------------------------------
c    universe 33: layer 13
c
517  0                   -206  205 -207  208 -209  210     $ unit cell boundaries
                                  lat=1  fill=101 u=33
c    .. contents of unit cell
518  112  4.2400929e-01 -211                          u=101   $ [ 0  0  0]
519  112  4.2400929e-01 -212                          u=101   $ [ 1  1  1]
520  112  4.2400929e-01 -213                          u=101   $ [ 1  1 -1]
521  112  4.2400929e-01 -214                          u=101   $ [ 1 -1 -1]
522  112  4.2400929e-01 -215                          u=101   $ [ 1 -1  1]
523  112  4.2400929e-01 -216                          u=101   $ [-1  1  1]
524  112  4.2400929e-01 -217                          u=101   $ [-1  1 -1]
525  112  4.2400929e-01 -218                          u=101   $ [-1 -1 -1]
526  112  4.2400929e-01 -219                          u=101   $ [-1 -1  1]
527  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219       u=101   $ helium between balls
c
c    ---------------------------------------------------
```

```
c    universe 34: layer 14
c
528  0                    -206  205 -207  208 -209  210     $ unit cell boundaries
                                lat=1  fill=105  u=34
c    .. contents of unit cell
529  113  4.2401019e-01 -211                        u=105  $ [ 0  0  0]
530  113  4.2401019e-01 -212                        u=105  $ [ 1  1  1]
531  113  4.2401019e-01 -213                        u=105  $ [ 1  1 -1]
532  113  4.2401019e-01 -214                        u=105  $ [ 1 -1 -1]
533  113  4.2401019e-01 -215                        u=105  $ [ 1 -1  1]
534  113  4.2401019e-01 -216                        u=105  $ [-1  1  1]
535  113  4.2401019e-01 -217                        u=105  $ [-1  1 -1]
536  113  4.2401019e-01 -218                        u=105  $ [-1 -1 -1]
537  113  4.2401019e-01 -219                        u=105  $ [-1 -1  1]
538  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219        u=105  $ helium between balls
c
c    ---------------------------------------------------
c    universe 35: layer 15
c
539  0                    -206  205 -207  208 -209  210     $ unit cell boundaries
                                lat=1  fill=109  u=35
c    .. contents of unit cell
540  114  4.2401039e-01 -211                        u=109  $ [ 0  0  0]
541  114  4.2401099e-01 -212                        u=109  $ [ 1  1  1]
542  114  4.2401099e-01 -213                        u=109  $ [ 1  1 -1]
543  114  4.2401099e-01 -214                        u=109  $ [ 1 -1 -1]
544  114  4.2401099e-01 -215                        u=109  $ [ 1 -1  1]
545  114  4.2401099e-01 -216                        u=109  $ [-1  1  1]
546  114  4.2401099e-01 -217                        u=109  $ [-1  1 -1]
547  114  4.2401099e-01 -218                        u=109  $ [-1 -1 -1]
548  114  4.2401099e-01 -219                        u=109  $ [-1 -1  1]
549  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219        u=109  $ helium between balls
c
c    ---------------------------------------------------
c    universe 36: layer 16
c
550  0                -206  205 -207  208 -209  210       $ unit cell boundaries
                             lat=1  fill=113  u=36
c    .. contents of unit cell
551  115  4.2401180e-01 -211                        u=113  $ [ 0  0  0]
552  115  4.2401180e-01 -212                        u=113  $ [ 1  1  1]
553  115  4.2401180e-01 -213                        u=113  $ [ 1  1 -1]
554  115  4.2401180e-01 -214                        u=113  $ [ 1 -1 -1]
555  115  4.2401180e-01 -215                        u=113  $ [ 1 -1  1]
556  115  4.2401180e-01 -216                        u=113  $ [-1  1  1]
557  115  4.2401180e-01 -217                        u=113  $ [-1  1 -1]
558  115  4.2401180e-01 -218                        u=113  $ [-1 -1 -1]
559  115  4.2401180e-01 -219                        u=113  $ [-1 -1  1]
560  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219        u=113  $ helium between balls
c
c    ---------------------------------------------------
c    universe 37: layer 17
c
561  0                   -206  205 -207  208 -209  210    $ unit cell boundaries
```

```
                                lat=1  fill=117  u=37
c    .. contents of unit cell
562  116  4.2401239e-01 -211                        u=117  $ [ 0  0  0]
563  116  4.2401239e-01 -212                        u=117  $ [ 1  1  1]
564  116  4.2401239e-01 -213                        u=117  $ [ 1  1 -1]
565  116  4.2401239e-01 -214                        u=117  $ [ 1 -1 -1]
566  116  4.2401239e-01 -215                        u=117  $ [ 1 -1  1]
567  116  4.2401239e-01 -216                        u=117  $ [-1  1  1]
568  116  4.2401239e-01 -217                        u=117  $ [-1  1 -1]
569  116  4.2401239e-01 -218                        u=117  $ [-1 -1 -1]
570  116  4.2401239e-01 -219                        u=117  $ [-1 -1  1]
571  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219        u=117  $ helium between balls
c
c    ---------------------------------------------------
c    universe 38: layer 18
c
572  0                  -206  205 -207  208  209  210    $ unit cell boundaries
     lat=1  fill=121
     u=38
c
c    .. contents of unit cell
c
573  117  4.2401290e-01 -211                        u=121  $ [ 0  0  0]
574  117  4.2401290e-01 -212                        u=121  $ [ 1  1  1]
575  117  4.2401290e-01 -213                        u=121  $ [ 1  1 -1]
576  117  4.2401290e-01 -214                        u=121  $ [ 1 -1 -1]
577  117  4.2401290e-01 -215                        u=121  $ [ 1 -1  1]
578  117  4.2401290e-01 -216                        u=121  $ [-1  1  1]
579  117  4.2401290e-01 -217                        u=121  $ [-1  1 -1]
580  117  4.2401290e-01 -218                        u=121  $ [-1 -1 -1]
581  117  4.2401290e-01 -219                        u=121  $ [-1 -1  1]
582  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219        u=121  $ helium between balls
c
c    ---------------------------------------------------
c    universe 39: layer 19
c
583  0                  -206  205 -207  208 -209  210    $ unit cell boundaries
     lat=1  fill=125
     u=39
c
c    .. contents of unit cell
c
584  118  4.2401350e-01 -211                        u=125  $ [ 0  0  0]
585  118  4.2401350e-01 -212                        u=125  $ [ 1  1  1]
586  118  4.2401350e-01 -213                        u=125  $ [ 1  1 -1]
587  118  4.2401350e-01 -214                        u=125  $ [ 1 -1 -1]
588  118  4.2401350e-01 -215                        u=125  $ [ 1 -1  1]
589  118  4.2401350e-01 -216                        u=125  $ [-1  1  1]
590  118  4.2401350e-01 -217                        u=125  $ [-1  1 -1]
591  118  4.2401350e-01 -218                        u=125  $ [-1 -1 -1]
592  118  4.2401350e-01 -219                        u=125  $ [-1 -1  1]
593  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219        u=125 $ helium between balls
c
c    ---------------------------------------------------
```

```
c    channel 3: fuel
c    ------------------------------------------------
c    universe 40: layer 20
c
603  0                   -206  205 -207  208 -209  210
     lat=1  fill=129
     u=40
c
c    .. contents of unit cell
c
604  119  7.3386878e-01 -211                        u=129   $ [ 0  0  0]
605  119  7.3386878e-01 -212                        u=129   $ [ 1  1  1]
606  119  7.3386878e-01 -213                        u=129   $ [ 1  1 -1]
607  119  7.3386878e-01 -214                        u=129   $ [ 1 -1 -1]
608  119  7.3386878e-01 -215                        u=129   $ [ 1 -1  1]
609  119  7.3386878e-01 -216                        u=129   $ [-1  1  1]
610  119  7.3386878e-01 -217                        u=129   $ [-1  1 -1]
611  119  7.3386878e-01 -218                        u=129   $ [-1 -1 -1]
612  119  7.3386878e-01 -219                        u=129   $ [-1 -1  1]
613  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219        u=129   $ helium between balls
c    ------------------------------------------------
c    universe 41: layer 21
c
614  0                   -206  205 -207  208 -209  210
     lat=1  fill=133
     u=41                                                $ unit cell
c
c    .. contents of unit cell
c
615  120  7.3386961e-01 -211                        u=133   $ [ 0  0  0]
616  120  7.3386961e-01 -212                        u=133   $ [ 1  1  1]
617  120  7.3386961e-01 -213                        u=133   $ [ 1  1 -1]
618  120  7.3386961e-01 -214                        u=133   $ [ 1 -1 -1]
619  120  7.3386961e-01 -215                        u=133   $ [ 1 -1  1]
620  120  7.3386961e-01 -216                        u=133   $ [-1  1  1]
621  120  7.3386961e-01 -217                        u=133   $ [-1  1 -1]
622  120  7.3386961e-01 -218                        u=133   $ [-1 -1 -1]
623  120  7.3386961e-01 -219                        u=133   $ [-1 -1  1]
624  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219        u=133   $ helium between balls
c    ------------------------------------------------
c    universe 42: layer 22
c
625  0                   -206  205 -207  208 -209  210
     lat=1  fill=137
     u=42                                                $ unit cell
c
c    .. contents of unit cell
c
626  121  7.3387039e-01 -211                        u=137   $ [ 0  0  0]
627  121  7.3387039e-01 -212                        u=137   $ [ 1  1  1]
628  121  7.3387039e-01 -213                        u=137   $ [ 1  1 -1]
629  121  7.3387039e-01 -214                        u=137   $ [ 1 -1 -1]
630  121  7.3387039e-01 -215                        u=137   $ [ 1 -1  1]
631  121  7.3387039e-01 -216                        u=137   $ [-1  1  1]
632  121  7.3387039e-01 -217                        u=137   $ [-1  1 -1]
```

```
633  121  7.3387039e-01 -218                          u=137   $ [-1 -1 -1]
634  121  7.3387039e-01 -219                          u=137   $ [-1 -1  1]
635  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=137   $ helium between balls
c    ---------------------------------------------
c    universe 43: layer 23
c
636  0                  -206  205 -207  208 -209  210
     lat=1  fill=141
     u=43                                            $ unit cell
c
c    .. contents of unit cell
c
637  122  7.3387140e-01 -211                          u=141   $ [ 0  0  0]
638  122  7.3387140e-01 -212                          u=141   $ [ 1  1  1]
639  122  7.3387140e-01 -213                          u=141   $ [ 1  1 -1]
640  122  7.3387140e-01 -214                          u=141   $ [ 1 -1 -1]
641  122  7.3387140e-01 -215                          u=141   $ [ 1 -1  1]
642  122  7.3387140e-01 -216                          u=141   $ [-1  1  1]
643  122  7.3387140e-01 -217                          u=141   $ [-1  1 -1]
644  122  7.3387140e-01 -218                          u=141   $ [-1 -1 -1]
645  122  7.3387140e-01 -219                          u=141   $ [-1 -1  1]
646  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=141   $ helium between balls
c    ---------------------------------------------
c    universe 44: layer 24
c
647  0                  -206  205 -207  208 -209  210
     lat=1  fill=145
     u=44                                            $ unit cell
c
c    .. contents of unit cell
c
648  123  7.3387212e-01 -211                          u=145   $ [ 0  0  0]
649  123  7.3387212e-01 -212                          u=145   $ [ 1  1  1]
650  123  7.3387212e-01 -213                          u=145   $ [ 1  1 -1]
651  123  7.3387212e-01 -214                          u=145   $ [ 1 -1 -1]
652  123  7.3387212e-01 -215                          u=145   $ [ 1 -1  1]
653  123  7.3387212e-01 -216                          u=145   $ [-1  1  1]
654  123  7.3387212e-01 -217                          u=145   $ [-1  1 -1]
655  123  7.3387212e-01 -218                          u=145   $ [-1 -1 -1]
656  123  7.3387212e-01 -219                          u=145   $ [-1 -1  1]
657  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=145   $ helium between balls
c
c    ---------------------------------------------
c    universe 45: layer 25
c
658  0                  -206  205 -207  208 -209  210
     lat=1  fill=149
     u=45                                            $ unit cell
c
c    .. contents of unit cell
c
659  124  7.3387319e-01 -211                          u=149   $ [ 0  0  0]
660  124  7.3387319e-01 -212                          u=149   $ [ 1  1  1]
661  124  7.3387319e-01 -213                          u=149   $ [ 1  1 -1]
```

```
662  124  7.3387319e-01 -214                          u=149   $ [ 1 -1 -1]
663  124  7.3387319e-01 -215                          u=149   $ [ 1 -1  1]
664  124  7.3387319e-01 -216                          u=149   $ [-1  1  1]
665  124  7.3387319e-01 -217                          u=149   $ [-1  1 -1]
666  124  7.3387319e-01 -218                          u=149   $ [-1 -1 -1]
667  124  7.3387319e-01 -219                          u=149   $ [-1 -1  1]
668  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=149   $ helium between balls
c
c    ---------------------------------------------
c    universe 46: layer 26
c
669  0                  -206  205 -207  208 -209  210
     lat=1  fill=153
     u=46                                                   $ unit cell
c
c    .. contents of unit cell
c
670  125  7.3387408e-01 -211                          u=153   $ [ 0  0  0]
671  125  7.3387408e-01 -212                          u=153   $ [ 1  1  1]
672  125  7.3387408e-01 -213                          u=153   $ [ 1  1 -1]
673  125  7.3387408e-01 -214                          u=153   $ [ 1 -1 -1]
674  125  7.3387408e-01 -215                          u=153   $ [ 1 -1  1]
675  125  7.3387408e-01 -216                          u=153   $ [-1  1  1]
676  125  7.3387408e-01 -217                          u=153   $ [-1  1 -1]
677  125  7.3387408e-01 -218                          u=153   $ [-1 -1 -1]
678  125  7.3387408e-01 -219                          u=153   $ [-1 -1  1]
679  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=153   $ helium between balls
c
c    ---------------------------------------------
c    universe 47: layer 27
c
680  0                  -206  205 -207  208 -209  210
                             lat=1  fill=157  u=47    $ unit cell
c
c    .. universe 128: contents of unit cell
c
681  126  7.3387527e-01 -211                          u=157   $ [ 0  0  0]
682  126  7.3387527e-01 -212                          u=157   $ [ 1  1  1]
683  126  7.3387527e-01 -213                          u=157   $ [ 1  1 -1]
684  126  7.3387527e-01 -214                          u=157   $ [ 1 -1 -1]
685  126  7.3387527e-01 -215                          u=157   $ [ 1 -1  1]
686  126  7.3387527e-01 -216                          u=157   $ [-1  1  1]
687  126  7.3387527e-01 -217                          u=157   $ [-1  1 -1]
688  126  7.3387527e-01 -218                          u=157   $ [-1 -1 -1]
689  126  7.3387527e-01 -219                          u=157   $ [-1 -1  1]
690  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=157   $ helium between balls
c
c    ---------------------------------------------
c    universe 48: layer 28
c
691  0                  -206  205 -207  208 -209  210
     lat=1  fill=161
     u=48                                                   $ unit cell
c
```

```
c    .. contents of unit cell
c
692  127  7.3387587e-01 -211                          u=161   $ [ 0  0  0]
693  127  7.3387587e-01 -212                          u=161   $ [ 1  1  1]
694  127  7.3387587e-01 -213                          u=161   $ [ 1  1 -1]
695  127  7.3387587e-01 -214                          u=161   $ [ 1 -1 -1]
696  127  7.3387587e-01 -215                          u=161   $ [ 1 -1  1]
697  127  7.3387587e-01 -216                          u=161   $ [-1  1  1]
698  127  7.3387587e-01 -217                          u=161   $ [-1  1 -1]
699  127  7.3387587e-01 -218                          u=161   $ [-1 -1 -1]
700  127  7.3387587e-01 -219                          u=161   $ [-1 -1  1]
701  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219             u=161   $ helium between balls
c
c    ------------------------------------------------
c    universe 49: layer 29
c
702  0                  -206  205 -207  208 -209  210
     lat=1  fill=165
     u=49                                             $ unit cell
c    .. contents of unit cell
703  128  7.3387688e-01 -211                          u=165   $ [ 0  0  0]
704  128  7.3387688e-01 -212                          u=165   $ [ 1  1  1]
705  128  7.3387688e-01 -213                          u=165   $ [ 1  1 -1]
706  128  7.3387688e-01 -214                          u=165   $ [ 1 -1 -1]
707  128  7.3387688e-01 -215                          u=165   $ [ 1 -1  1]
708  128  7.3387688e-01 -216                          u=165   $ [-1  1  1]
709  128  7.3387688e-01 -217                          u=165   $ [-1  1 -1]
710  128  7.3387688e-01 -218                          u=165   $ [-1 -1 -1]
711  128  7.3387688e-01 -219                          u=165   $ [-1 -1  1]
712  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219             u=165   $ helium between balls
c
c    ------------------------------------------------
c    universe 50: layer 30
c
713  0                  -206  205 -207  208 -209  210
     lat=1  fill=169
     u=50                                             $ unit cell
c
c    .. contents of unit cell
c
714  129  7.3387718e-01 -211                          u=169   $ [ 0  0  0]
715  129  7.3387718e-01 -212                          u=169   $ [ 1  1  1]
716  129  7.3387718e-01 -213                          u=169   $ [ 1  1 -1]
717  129  7.3387718e-01 -214                          u=169   $ [ 1 -1 -1]
718  129  7.3387718e-01 -215                          u=169   $ [ 1 -1  1]
719  129  7.3387718e-01 -216                          u=169   $ [-1  1  1]
720  129  7.3387718e-01 -217                          u=169   $ [-1  1 -1]
721  129  7.3387718e-01 -218                          u=169   $ [-1 -1 -1]
722  129  7.3387718e-01 -219                          u=169   $ [-1 -1  1]
723  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219             u=169   $ helium between balls
c
c    ------------------------------------------------
c    channel 4
c    ------------------------------------------------
```

```
c    universe 51: layer 31
c
733  0                  -206  205 -207  208 -209  210
     lat=1  fill=173
     u=51                                                $ unit cell
c
c    .. contents of unit cell
c
734  130  7.3386890e-01 -211                      u=173   $ [ 0  0  0]
735  130  7.3386890e-01 -212                      u=173   $ [ 1  1  1]
736  130  7.3386890e-01 -213                      u=173   $ [ 1  1 -1]
737  130  7.3386890e-01 -214                      u=173   $ [ 1 -1 -1]
738  130  7.3386890e-01 -215                      u=173   $ [ 1 -1  1]
739  130  7.3386890e-01 -216                      u=173   $ [-1  1  1]
740  130  7.3386890e-01 -217                      u=173   $ [-1  1 -1]
741  130  7.3386890e-01 -218                      u=173   $ [-1 -1 -1]
742  130  7.3386890e-01 -219                      u=173   $ [-1 -1  1]
743  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219      u=173   $ helium between balls
c
c    ---------------------------------------------
c    universe 52: layer 32
c
744  0                  -206  205 -207  208 -209  210
     lat=1  fill=177
     u=52                                                $ unit cell
c
c    .. contents of unit cell
c
745  131  7.3386949e-01 -211                      u=177   $ [ 0  0  0]
746  131  7.3386949e-01 -212                      u=177   $ [ 1  1  1]
747  131  7.3386949e-01 -213                      u=177   $ [ 1  1 -1]
748  131  7.3386949e-01 -214                      u=177   $ [ 1 -1 -1]
749  131  7.3386949e-01 -215                      u=177   $ [ 1 -1  1]
750  131  7.3386949e-01 -216                      u=177   $ [-1  1  1]
751  131  7.3386949e-01 -217                      u=177   $ [-1  1 -1]
752  131  7.3386949e-01 -218                      u=177   $ [-1 -1 -1]
753  131  7.3386949e-01 -219                      u=177   $ [-1 -1  1]
754  60   -3.429e-03      211  212  213  214  215
                          216  217  218  219      u=177   $ helium between balls
c
c    ---------------------------------------------
c    universe 53: layer 33
c
755  0                  -206  205 -207  208 -209  210
     lat=1  fill=181
     u=53                                                $ unit cell
c
c    .. contents of unit cell
c
756  132  7.3387033e-01 -211                      u=181   $ [ 0  0  0]
757  132  7.3387033e-01 -212                      u=181   $ [ 1  1  1]
758  132  7.3387033e-01 -213                      u=181   $ [ 1  1 -1]
759  132  7.3387033e-01 -214                      u=181   $ [ 1 -1 -1]
760  132  7.3387033e-01 -215                      u=181   $ [ 1 -1  1]
761  132  7.3387033e-01 -216                      u=181   $ [-1  1  1]
762  132  7.3387033e-01 -217                      u=181   $ [-1  1 -1]
```

```
763  132  7.3387033e-01 -218                          u=181   $ [-1 -1 -1]
764  132  7.3387033e-01 -219                          u=181   $ [-1 -1  1]
765  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=181   $ helium between balls
c
c    ---------------------------------------------
c    universe 54: layer 34
c
766  0                  -206  205 -207  208 -209  210
     lat=1  fill=185
     u=54                                            $ unit cell
c
c    .. contents of unit cell
c
767  133  7.338711e-01  -211                         u=185   $ [ 0  0  0]
768  133  7.338711e-01  -212                         u=185   $ [ 1  1  1]
769  133  7.338711e-01  -213                         u=185   $ [ 1  1 -1]
770  133  7.338711e-01  -214                         u=185   $ [ 1 -1 -1]
771  133  7.338711e-01  -215                         u=185   $ [ 1 -1  1]
772  133  7.338711e-01  -216                         u=185   $ [-1  1  1]
773  133  7.338711e-01  -217                         u=185   $ [-1  1 -1]
774  133  7.338711e-01  -218                         u=185   $ [-1 -1 -1]
775  133  7.338711e-01  -219                         u=185   $ [-1 -1  1]
776  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=185   $ helium between balls
c
c    ---------------------------------------------
c    universe 55: layer 35
c
777  0                  -206  205 -207  208 -209  210
     lat=1  fill=189
     u=55                                            $ unit cell
c
c    .. contents of unit cell
c
778  134  7.3387200e-01 -211                         u=189   $ [ 0  0  0]
779  134  7.3387200e-01 -212                         u=189   $ [ 1  1  1]
780  134  7.3387200e-01 -213                         u=189   $ [ 1  1 -1]
781  134  7.3387200e-01 -214                         u=189   $ [ 1 -1 -1]
782  134  7.3387200e-01 -215                         u=189   $ [ 1 -1  1]
783  134  7.3387200e-01 -216                         u=189   $ [-1  1  1]
784  134  7.3387200e-01 -217                         u=189   $ [-1  1 -1]
785  134  7.3387200e-01 -218                         u=189   $ [-1 -1 -1]
786  134  7.3387200e-01 -219                         u=189   $ [-1 -1  1]
787  60  -3.429e-03   211  212  213  214  215
                     216  217  218  219              u=189   $ helium between balls
c
c    ---------------------------------------------
c    universe 56: layer 36
c
788  0                  -206  205 -207  208 -209  210
     lat=1  fill=193
     u=56                                            $ unit cell
c
c    .. contents of unit cell
c
789  135  7.3387271e-01 -211                         u=193   $ [ 0  0  0]
```

```
790  135  7.3387271e-01 -212                          u=193   $ [ 1  1  1]
791  135  7.3387271e-01 -213                          u=193   $ [ 1  1 -1]
792  135  7.3387271e-01 -214                          u=193   $ [ 1 -1 -1]
793  135  7.3387271e-01 -215                          u=193   $ [ 1 -1  1]
794  135  7.3387271e-01 -216                          u=193   $ [-1  1  1]
795  135  7.3387271e-01 -217                          u=193   $ [-1  1 -1]
796  135  7.3387271e-01 -218                          u=193   $ [-1 -1 -1]
797  135  7.3387271e-01 -219                          u=193   $ [-1 -1  1]
798  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219             u=193   $ helium between balls
c
c    ---------------------------------------------
c    universe 57: layer 37
c
799  0                  -206  205 -207  208 -209  210
     lat=1  fill=197
     u=57                                            $ unit cell
c
c    .. universe 189: contents of unit cell
c
800  136  7.3387378e-01 -211                          u=197   $ [ 0  0  0]
801  136  7.3387378e-01 -212                          u=197   $ [ 1  1  1]
802  136  7.3387378e-01 -213                          u=197   $ [ 1  1 -1]
803  136  7.3387378e-01 -214                          u=197   $ [ 1 -1 -1]
804  136  7.3387378e-01 -215                          u=197   $ [ 1 -1  1]
805  136  7.3387378e-01 -216                          u=197   $ [-1  1  1]
806  136  7.3387378e-01 -217                          u=197   $ [-1  1 -1]
807  136  7.3387378e-01 -218                          u=197   $ [-1 -1 -1]
808  136  7.3387378e-01 -219                          u=197   $ [-1 -1  1]
809  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219             u=197   $ helium between balls
c
c    ---------------------------------------------
c    universe 58: layer 38
c
810  0                  -206  205 -207  208 -209  210
     lat=1  fill=201
     u=58                                            $ unit cell
c
c    .. contents of unit cell
c
811  137  7.3387462e-01 -211                          u=201   $ [ 0  0  0]
812  137  7.3387462e-01 -212                          u=201   $ [ 1  1  1]
813  137  7.3387462e-01 -213                          u=201   $ [ 1  1 -1]
814  137  7.3387462e-01 -214                          u=201   $ [ 1 -1 -1]
815  137  7.3387462e-01 -215                          u=201   $ [ 1 -1  1]
816  137  7.3387462e-01 -216                          u=201   $ [-1  1  1]
817  137  7.3387462e-01 -217                          u=201   $ [-1  1 -1]
818  137  7.3387462e-01 -218                          u=201   $ [-1 -1 -1]
819  137  7.3387462e-01 -219                          u=201   $ [-1 -1  1]
820  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219             u=201   $ helium between balls
c
c    ---------------------------------------------
c    universe 59: layer 39
c
821  0                  -206  205 -207  208 -209  210
```

```
     lat=1  fill=205
     u=59                                                    $ unit cell
c
c    .. contents of unit cell
c
822  138  7.3387557e-01 -211                          u=205   $ [ 0  0  0]
823  138  7.3387557e-01 -212                          u=205   $ [ 1  1  1]
824  138  7.3387557e-01 -213                          u=205   $ [ 1  1 -1]
825  138  7.3387557e-01 -214                          u=205   $ [ 1 -1 -1]
826  138  7.3387557e-01 -215                          u=205   $ [ 1 -1  1]
827  138  7.3387557e-01 -216                          u=205   $ [-1  1  1]
828  138  7.3387557e-01 -217                          u=205   $ [-1  1 -1]
829  138  7.3387557e-01 -218                          u=205   $ [-1 -1 -1]
830  138  7.3387557e-01 -219                          u=205   $ [-1 -1  1]
831  60  -3.429e-03       211  212  213  214  215
                          216  217  218  219          u=205   $ helium between balls
c
c    ---------------------------------------------
c    universe 60: layer 40
c
832  0                   -206  205 -207  208 -209  210
     lat=1  fill=209
     u=60                                                    $ unit cell
c
c    .. contents of unit cell
c
833  139  7.3387623e-01 -211                          u=209   $ [ 0  0  0]
834  139  7.3387623e-01 -212                          u=209   $ [ 1  1  1]
835  139  7.3387623e-01 -213                          u=209   $ [ 1  1 -1]
836  139  7.3387623e-01 -214                          u=209   $ [ 1 -1 -1]
837  139  7.3387623e-01 -215                          u=209   $ [ 1 -1  1]
838  139  7.3387623e-01 -216                          u=209   $ [-1  1  1]
839  139  7.3387623e-01 -217                          u=209   $ [-1  1 -1]
840  139  7.3387623e-01 -218                          u=209   $ [-1 -1 -1]
841  139  7.3387623e-01 -219                          u=209   $ [-1 -1  1]
842  60  -3.429e-03       211  212  213  214  215
                          216  217  218  219          u=209   $ helium between balls
c
c    ---------------------------------------------
c    universe 61: layer 41
c
843  0                   -206  205 -207  208 -209  210
     lat=1  fill=213
     u=61                                                    $ unit cell
c
c    .. contents of unit cell
c
844  140  7.3387641e-01 -211                          u=213   $ [ 0  0  0]
845  140  7.3387641e-01 -212                          u=213   $ [ 1  1  1]
846  140  7.3387641e-01 -213                          u=213   $ [ 1  1 -1]
847  140  7.3387641e-01 -214                          u=213   $ [ 1 -1 -1]
848  140  7.3387641e-01 -215                          u=213   $ [ 1 -1  1]
849  140  7.3387641e-01 -216                          u=213   $ [-1  1  1]
850  140  7.3387641e-01 -217                          u=213   $ [-1  1 -1]
851  140  7.3387641e-01 -218                          u=213   $ [-1 -1 -1]
852  140  7.3387641e-01 -219                          u=213   $ [-1 -1  1]
853  60  -3.429e-03       211  212  213  214  215
```

```
                          216  217  218  219       u=213  $ helium between balls
c
c    ---------------------------------------------
c    universe 62: layer 42
c
854  0                   -206  205 -207  208 -209  210
     lat=1  fill=217
     u=62                                          $ unit cell
c
c    .. contents of unit cell
c
855  141  7.3387688e-01 -211                       u=217   $ [ 0  0  0]
856  141  7.3387688e-01 -212                       u=217   $ [ 1  1  1]
857  141  7.3387688e-01 -213                       u=217   $ [ 1  1 -1]
858  141  7.3387688e-01 -214                       u=217   $ [ 1 -1 -1]
859  141  7.3387688e-01 -215                       u=217   $ [ 1 -1  1]
860  141  7.3387688e-01 -216                       u=217   $ [-1  1  1]
861  141  7.3387688e-01 -217                       u=217   $ [-1  1 -1]
862  141  7.3387688e-01 -218                       u=217   $ [-1 -1 -1]
863  141  7.3387688e-01 -219                       u=217   $ [-1 -1  1]
864  60  -3.429e-03      211  212  213  214  215
                          216  217  218  219       u=217   $ helium between balls
c
c    ---------------------------------------------
c    channel 5
c    ---------------------------------------------
c    universe 63: layer 43
c
874  0                   -206  205 -207  208 -209  210
     lat=1  fill=221
     u=63                                          $ unit cell
c
c    .. contents of unit cell
c
875  142  7.3386949e-01 -211                       u=221   $ [ 0  0  0]
876  142  7.3386949e-01 -212                       u=221   $ [ 1  1  1]
877  142  7.3386949e-01 -213                       u=221   $ [ 1  1 -1]
878  142  7.3386949e-01 -214                       u=221   $ [ 1 -1 -1]
879  142  7.3386949e-01 -215                       u=221   $ [ 1 -1  1]
880  142  7.3386949e-01 -216                       u=221   $ [-1  1  1]
881  142  7.3386949e-01 -217                       u=221   $ [-1  1 -1]
882  142  7.3386949e-01 -218                       u=221   $ [-1 -1 -1]
883  142  7.3386949e-01 -219                       u=221   $ [-1 -1  1]
884  60  -3.429e-03      211  212  213  214  215
                          216  217  218  219       u=221   $ helium between balls
c
c    ---------------------------------------------
c    universe 64: layer 44
c
885  0                   -206  205 -207  208 -209  210
     lat=1  fill=225
     u=64                                          $ unit cell
c
c    .. contents of unit cell
c
886  143  7.3387003e-01 -211                       u=225   $ [ 0  0  0]
887  143  7.3387003e-01 -212                       u=225   $ [ 1  1  1]
```

```
888  143  7.3387003e-01 -213                          u=225   $ [ 1  1 -1]
889  143  7.3387003e-01 -214                          u=225   $ [ 1 -1 -1]
890  143  7.3387003e-01 -215                          u=225   $ [ 1 -1  1]
891  143  7.3387003e-01 -216                          u=225   $ [-1  1  1]
892  143  7.3387003e-01 -217                          u=225   $ [-1  1 -1]
893  143  7.3387003e-01 -218                          u=225   $ [-1 -1 -1]
894  143  7.3387003e-01 -219                          u=225   $ [-1 -1  1]
895  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219            u=225   $ helium between balls
c    ---------------------------------------------
c    universe 65: layer 45
c
896  0                  -206  205 -207  208 -209  210
     lat=1  fill=229
     u=65                                           $ unit cell
c
c    .. contents of unit cell
c
897  144  7.3387092e-01 -211                          u=229   $ [ 0  0  0]
898  144  7.3387092e-01 -212                          u=229   $ [ 1  1  1]
899  144  7.3387092e-01 -213                          u=229   $ [ 1  1 -1]
900  144  7.3387092e-01 -214                          u=229   $ [ 1 -1 -1]
901  144  7.3387092e-01 -215                          u=229   $ [ 1 -1  1]
902  144  7.3387092e-01 -216                          u=229   $ [-1  1  1]
903  144  7.3387092e-01 -217                          u=229   $ [-1  1 -1]
904  144  7.3387092e-01 -218                          u=229   $ [-1 -1 -1]
905  144  7.3387092e-01 -219                          u=229   $ [-1 -1  1]
906  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219            u=229   $ helium between balls
c
c    ---------------------------------------------
c    universe 66: layer 46
c
907  0                  -206  205 -207  208 -209  210
     lat=1  fill=233
     u=66                                           $ unit cell
c
c    .. contents of unit cell
c
908  145  7.3387158e-01 -211                          u=233   $ [ 0  0  0]
909  145  7.3387158e-01 -212                          u=233   $ [ 1  1  1]
910  145  7.3387158e-01 -213                          u=233   $ [ 1  1 -1]
911  145  7.3387158e-01 -214                          u=233   $ [ 1 -1 -1]
912  145  7.3387158e-01 -215                          u=233   $ [ 1 -1  1]
913  145  7.3387158e-01 -216                          u=233   $ [-1  1  1]
914  145  7.3387158e-01 -217                          u=233   $ [-1  1 -1]
915  145  7.3387158e-01 -218                          u=233   $ [-1 -1 -1]
916  145  7.3387158e-01 -219                          u=233   $ [-1 -1  1]
917  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219            u=233   $ helium between balls
c
c    ---------------------------------------------
c    universe 67: layer 47
c
918  0                  -206  205 -207  208 -209  210
     lat=1  fill=237
     u=67                                           $ unit cell
```

```
c
c    .. contents of unit cell
c
919  146  7.3387271e-01 -211                          u=237   $ [ 0  0  0]
920  146  7.3387271e-01 -212                          u=237   $ [ 1  1  1]
921  146  7.3387271e-01 -213                          u=237   $ [ 1  1 -1]
922  146  7.3387271e-01 -214                          u=237   $ [ 1 -1 -1]
923  146  7.3387271e-01 -215                          u=237   $ [ 1 -1  1]
924  146  7.3387271e-01 -216                          u=237   $ [-1  1  1]
925  146  7.3387271e-01 -217                          u=237   $ [-1  1 -1]
926  146  7.3387271e-01 -218                          u=237   $ [-1 -1 -1]
927  146  7.3387271e-01 -219                          u=237   $ [-1 -1  1]
928  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219          u=237   $ helium between balls
c
c    ------------------------------------------------
c    universe 68: layer 48
c
929  0                  -206  205 -207  208 -209  210      $ unit cell
     lat=1  fill=242
     u=68
c
c    .. contents of unit cell
c
930  147  7.3387343e-01 -211                          u=242   $ [ 0  0  0]
931  147  7.3387343e-01 -212                          u=242   $ [ 1  1  1]
932  147  7.3387343e-01 -213                          u=242   $ [ 1  1 -1]
933  147  7.3387343e-01 -214                          u=242   $ [ 1 -1 -1]
934  147  7.3387343e-01 -215                          u=242   $ [ 1 -1  1]
935  147  7.3387343e-01 -216                          u=242   $ [-1  1  1]
936  147  7.3387343e-01 -217                          u=242   $ [-1  1 -1]
937  147  7.3387343e-01 -218                          u=242   $ [-1 -1 -1]
938  147  7.3387343e-01 -219                          u=242   $ [-1 -1  1]
939  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219          u=242   $ helium between balls
c
c    ------------------------------------------------
c    universe 69: layer 49
c
940  0                  -206  205 -207  208 -209  210
     lat=1  fill=246
     u=69                                                 $ unit cell
c
c    .. contents of unit cell
c
941  148  7.3387438e-01 -211                          u=246   $ [ 0  0  0]
942  148  7.3387438e-01 -212                          u=246   $ [ 1  1  1]
943  148  7.3387438e-01 -213                          u=246   $ [ 1  1 -1]
944  148  7.3387438e-01 -214                          u=246   $ [ 1 -1 -1]
945  148  7.3387438e-01 -215                          u=246   $ [ 1 -1  1]
946  148  7.3387438e-01 -216                          u=246   $ [-1  1  1]
947  148  7.3387438e-01 -217                          u=246   $ [-1  1 -1]
948  148  7.3387438e-01 -218                          u=246   $ [-1 -1 -1]
949  148  7.3387438e-01 -219                          u=246   $ [-1 -1  1]
950  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219          u=246   $ helium between balls
c
```

```
c    ------------------------------------------------
c    universe 70: layer 50
c
951  0                   -206  205 -207  208 -209  210
     lat=1  fill=250
     u=70                                              $ unit cell
c
c    .. contents of unit cell
c
952  149  7.3387527e-01 -211                      u=250   $ [ 0  0  0]
953  149  7.3387527e-01 -212                      u=250   $ [ 1  1  1]
954  149  7.3387527e-01 -213                      u=250   $ [ 1  1 -1]
955  149  7.3387527e-01 -214                      u=250   $ [ 1 -1 -1]
956  149  7.3387527e-01 -215                      u=250   $ [ 1 -1  1]
957  149  7.3387527e-01 -216                      u=250   $ [-1  1  1]
958  149  7.3387527e-01 -217                      u=250   $ [-1  1 -1]
959  149  7.3387527e-01 -218                      u=250   $ [-1 -1 -1]
960  149  7.3387527e-01 -219                      u=250   $ [-1 -1  1]
961  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219       u=250   $ helium between balls
c
c    ------------------------------------------------
c    universe 71: layer 51
c
962  0                   -206  205 -207  208 -209  210
     lat=1  fill=254
     u=71                                              $ unit cell
c
c    .. contents of unit cell
c
963  150  7.3387629e-01 -211                      u=254   $ [ 0  0  0]
964  150  7.3387629e-01 -212                      u=254   $ [ 1  1  1]
965  150  7.3387629e-01 -213                      u=254   $ [ 1  1 -1]
966  150  7.3387629e-01 -214                      u=254   $ [ 1 -1 -1]
967  150  7.3387629e-01 -215                      u=254   $ [ 1 -1  1]
968  150  7.3387629e-01 -216                      u=254   $ [-1  1  1]
969  150  7.3387629e-01 -217                      u=254   $ [-1  1 -1]
970  150  7.3387629e-01 -218                      u=254   $ [-1 -1 -1]
971  150  7.3387629e-01 -219                      u=254   $ [-1 -1  1]
972  60  -3.429e-03      211  212  213  214  215
                        216  217  218  219       u=254   $ helium between balls
c    ------------------------------------------------
c    universe 72: layer 52
c
973  0                   -206  205 -207  208 -209  210
     lat=1  fill=258
     u=72                                              $ unit cell
c
c    .. contents of unit cell
c
974  151  7.3387671e-01 -211                      u=258   $ [ 0  0  0]
975  151  7.3387671e-01 -212                      u=258   $ [ 1  1  1]
976  151  7.3387671e-01 -213                      u=258   $ [ 1  1 -1]
977  151  7.3387671e-01 -214                      u=258   $ [ 1 -1 -1]
978  151  7.3387671e-01 -215                      u=258   $ [ 1 -1  1]
979  151  7.3387671e-01 -216                      u=258   $ [-1  1  1]
980  151  7.3387671e-01 -217                      u=258   $ [-1  1 -1]
```

```
981  151  7.3387671e-01 -218                          u=258   $ [-1 -1 -1]
982  151  7.3387671e-01 -219                          u=258   $ [-1 -1  1]
983  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=258   $ helium between balls
c    ---------------------------------------------
c    universe 73: layer 53
c
984  0                  -206  205 -207  208 -209  210
     lat=1  fill=262
     u=73                                            $ unit cell
c
c    .. contents of unit cell
c
985  152  7.3387688e-01 -211                          u=262   $ [ 0  0  0]
986  152  7.3387688e-01 -212                          u=262   $ [ 1  1  1]
987  152  7.3387688e-01 -213                          u=262   $ [ 1  1 -1]
988  152  7.3387688e-01 -214                          u=262   $ [ 1 -1 -1]
989  152  7.3387688e-01 -215                          u=262   $ [ 1 -1  1]
990  152  7.3387688e-01 -216                          u=262   $ [-1  1  1]
991  152  7.3387688e-01 -217                          u=262   $ [-1  1 -1]
992  152  7.3387688e-01 -218                          u=262   $ [-1 -1 -1]
993  152  7.3387688e-01 -219                          u=262   $ [-1 -1  1]
994  60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=262   $ helium between balls
c    ---------------------------------------------
c    universe 74: layer 54
c
995  0                  -206  205 -207  208 -209  210
     lat=1  fill=266
     u=74                                            $ unit cell
c
c    .. contents of unit cell
c
996  153  7.3387748e-01 -211                          u=266   $ [ 0  0  0]
997  153  7.3387748e-01 -212                          u=266   $ [ 1  1  1]
998  153  7.3387748e-01 -213                          u=266   $ [ 1  1 -1]
999  153  7.3387748e-01 -214                          u=266   $ [ 1 -1 -1]
1999 153  7.3387748e-01 -215                          u=266   $ [ 1 -1  1]
2000 153  7.3387748e-01 -216                          u=266   $ [-1  1  1]
2001 153  7.3387748e-01 -217                          u=266   $ [-1  1 -1]
2002 153  7.3387748e-01 -218                          u=266   $ [-1 -1 -1]
2003 153  7.3387748e-01 -219                          u=266   $ [-1 -1  1]
2004 60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=266   $ helium between balls
c    ---------------------------------------------
c    universe 75: layer 55
c
2005 0                  -206  205 -207  208 -209  210
     lat=1  fill=270
     u=75                                            $ unit cell
c
c    .. contents of unit cell
c
2006 154  7.3387808e-01 -211                          u=270   $ [ 0  0  0]
2007 154  7.3387808e-01 -212                          u=270   $ [ 1  1  1]
2008 154  7.3387808e-01 -213                          u=270   $ [ 1  1 -1]
2009 154  7.3387808e-01 -214                          u=270   $ [ 1 -1 -1]
```

```
2010 154  7.3387808e-01 -215                          u=270   $ [ 1 -1  1]
2011 154  7.3387808e-01 -216                          u=270   $ [-1  1  1]
2012 154  7.3387808e-01 -217                          u=270   $ [-1  1 -1]
2013 154  7.3387808e-01 -218                          u=270   $ [-1 -1 -1]
2014 154  7.3387808e-01 -219                          u=270   $ [-1 -1  1]
2015 60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=270   $ helium between balls
c
c    ---------------------------------------------
c    universe 76: layer 56
c
2016 0                   -206  205 -207  208 -209  210
     lat=1  fill=274
     u=76                                            $ unit cell
c
c    .. contents of unit cell
c
2017 155  7.3387849e-01 -211                          u=274   $ [ 0  0  0]
2018 155  7.3387849e-01 -212                          u=274   $ [ 1  1  1]
2019 155  7.3387849e-01 -213                          u=274   $ [ 1  1 -1]
2020 155  7.3387849e-01 -214                          u=274   $ [ 1 -1 -1]
2021 155  7.3387849e-01 -215                          u=274   $ [ 1 -1  1]
2022 155  7.3387849e-01 -216                          u=274   $ [-1  1  1]
2023 155  7.3387849e-01 -217                          u=274   $ [-1  1 -1]
2024 155  7.3387849e-01 -218                          u=274   $ [-1 -1 -1]
2025 155  7.3387849e-01 -219                          u=274   $ [-1 -1  1]
2026 60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=274   $ helium between balls
c
c   ---------------------------------------------
c    universe 77: layer 57
c
2027 0                   -206  205 -207  208 -209  210
     lat=1  fill=278
     u=77                                            $ unit cell
c
c    .. contents of unit cell
c
2028 156  7.3387891e-01 -211                          u=278   $ [ 0  0  0]
2029 156  7.3387891e-01 -212                          u=278   $ [ 1  1  1]
2030 156  7.3387891e-01 -213                          u=278   $ [ 1  1 -1]
2031 156  7.3387891e-01 -214                          u=278   $ [ 1 -1 -1]
2032 156  7.3387891e-01 -215                          u=278   $ [ 1 -1  1]
2033 156  7.3387891e-01 -216                          u=278   $ [-1  1  1]
2034 156  7.3387891e-01 -217                          u=278   $ [-1  1 -1]
2035 156  7.3387891e-01 -218                          u=278   $ [-1 -1 -1]
2036 156  7.3387891e-01 -219                          u=278   $ [-1 -1  1]
2037 60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=278   $ helium between balls
c    ---------------------------------------------
c    universe 78: discharge pipe
c
2038 0                   -206  205 -207  208 -209  210
     lat=1  fill=282
     u=78                                            $ unit cell
c
c    .. contents of unit cell
```

```
c
2039 156  7.3387891e-01 -211                          u=282   $ [ 0  0  0]
2040 156  7.3387891e-01 -212                          u=282   $ [ 1  1  1]
2041 156  7.3387891e-01 -213                          u=282   $ [ 1  1 -1]
2042 156  7.3387891e-01 -214                          u=282   $ [ 1 -1 -1]
2043 156  7.3387891e-01 -215                          u=282   $ [ 1 -1  1]
2044 156  7.3387891e-01 -216                          u=282   $ [-1  1  1]
2045 156  7.3387891e-01 -217                          u=282   $ [-1  1 -1]
2046 156  7.3387891e-01 -218                          u=282   $ [-1 -1 -1]
2047 156  7.3387891e-01 -219                          u=282   $ [-1 -1  1]
2048 60  -3.429e-03      211  212  213  214  215
                         216  217  218  219          u=282   $ helium between balls
c
c    ------------------------------------------------------------------

c    SURFACE CARDS
c
c    reactor structure axial divisions
5    pz      0.0
6    pz    -50.0
7    pz   -140.0
8    pz   -150.0
9    pz   -200.0
10   pz   -261.2
13   pz   -500.6
19   pz   -979.4
20   pz  -1066.2
21   pz  -1116.2
22   pz  -1166.2
23   pz  -1216.2
24   pz  -1266.2
25   pz  -1291.2
c
c    reactor structure radial divisions
30   cz     35.0
31   cz     45.0
34   cz    175.0
35   cz    181.0
36   cz    194.0
37   cz    225.0
38   cz    235.0
39   cz    257.0
40   cz    275.0
41   cz    331.0
c
c    conus
45    z   -979.4  175.0    -1066.2  35.0
c
c    layers in channel 1                              bottom of:
50   pz   -325.8662                                 $ layer 1
51   pz   -391.5263                                 $ layer 2
52   pz   -457.4383                                 $ layer 3
53   pz   -523.4468                                 $ layer 4
54   pz   -590.0280                                 $ layer 5
55   pz   -658.3862                                 $ layer 6
56   pz   -728.9344                                 $ layer 7
57   pz   -803.4993                                 $ layer 8
```

```
c
c    layers in channel 2
60   pz    -325.9992                                    $ layer 10
61   pz    -391.1913                                    $ layer 11
62   pz    -456.7378                                    $ layer 12
63   pz    -522.6889                                    $ layer 13
64   pz    -589.1911                                    $ layer 14
65   pz    -656.5009                                    $ layer 15
66   pz    -725.3721                                    $ layer 16
67   pz    -797.0067                                    $ layer 17
68   pz    -870.4246                                    $ layer 18
c
c    layers in channel 3
70   pz    -328.1101                                    $ layer 20
71   pz    -394.5977                                    $ layer 21
72   pz    -460.6103                                    $ layer 22
73   pz    -526.1077                                    $ layer 23
74   pz    -591.0684                                    $ layer 24
75   pz    -655.4955                                    $ layer 25
76   pz    -719.5168                                    $ layer 26
77   pz    -783.4268                                    $ layer 27
78   pz    -846.7093                                    $ layer 28
79   pz    -911.2618                                    $ layer 29
c
c    layers in channel 4
85   pz    -327.7736                                    $ layer 31
86   pz    -393.1451                                    $ layer 32
87   pz    -458.4412                                    $ layer 33
88   pz    -524.1719                                    $ layer 34
89   pz    -590.2695                                    $ layer 35
90   pz    -656.0625                                    $ layer 36
91   pz    -720.2756                                    $ layer 37
92   pz    -781.3543                                    $ layer 38
93   pz    -838.8892                                    $ layer 39
94   pz    -896.3219                                    $ layer 40
95   pz    -952.4894                                    $ layer 41
c
c    layers in channel 5
100  pz    -329.0798                                    $ layer 43
101  pz    -397.1589                                    $ layer 44
102  pz    -465.1485                                    $ layer 45
103  pz    -532.6207                                    $ layer 46
104  pz    -599.0450                                    $ layer 47
105  pz    -663.8527                                    $ layer 48
106  pz    -727.6718                                    $ layer 49
107  pz    -791.0222                                    $ layer 50
108  pz    -846.8144                                    $ layer 51
109  pz    -889.1656                                    $ layer 52
110  pz    -922.5213                                    $ layer 53
111  pz    -948.9672                                    $ layer 54
112  pz    -971.4881                                    $ layer 55
113  pz    -993.7430                                    $ layer 56
c
c    channel 1 outer boundary
115  z     -261.2  79.689    -476.3  78.376    -685.4  75.201
116  z     -685.4  75.201    -810.9  67.429    -841.3  59.001
117  z     -841.3  59.001    -871.7  49.587    -902.1  41.487
```

```
118  z    -902.1  41.487    -932.5  31.635    -962.9  24.848
119  z    -962.9  24.848    -993.3  18.937   -1019.4  15.215
120  z   -1019.4  15.215   -1044.4  13.355   -1066.2  12.588
c
c    channel 2 outer boundary
125  z    -261.2 112.36     -476.3 110.88     -685.4 107.61
126  z    -685.4 107.61     -810.9 100.74     -841.3  92.253
127  z    -841.3  92.253    -871.7  86.277    -902.1  74.661
128  z    -902.1  74.661    -932.5  60.933    -962.9  50.372
129  z    -962.9  50.372    -993.3  39.495   -1019.4  31.892
130  z   -1019.4  31.892   -1044.4  24.711   -1066.2  19.536
c
c    channel 3 outer boundary
135  z    -261.2 136.61     -476.3 135.90     -685.4 133.85
136  z    -685.4 133.85     -810.9 128.63     -841.3 124.54
137  z    -841.3 124.54     -871.7 117.89     -902.1 107.35
138  z    -902.1 107.35     -932.5  92.405    -962.9  75.213
139  z    -962.9  75.213    -993.3  61.706   -1019.4  50.245
140  z   -1019.4  50.245   -1044.4  39.397   -1066.2  22.922
c
c    channel 4 outer boundary/channel 5 inner boundary
145  z    -261.2 156.98     -476.3 156.98     -685.4 155.56
146  z    -685.4 155.56     -810.9 153.54     -841.3 150.81
147  z    -841.3 150.81     -871.7 144.02     -902.1 137.65
148  z    -902.1 137.65     -932.5 125.00     -962.9 111.13
149  z    -962.9 111.13     -993.3  92.609   -1019.4  72.973
150  z   -1019.4  72.973    -1044.4  50.909  -1066.2  26.214
c
155  pz   -685.4
156  pz   -841.3
157  pz   -902.1
158  pz   -962.9
159  pz  -1019.4
c
c    fuel element
c
c    .. fuel region
201  so      2.5
c
c    unit cell boundaries in core
c
205  px     -3.5921477                                    $ [-1  0  0]
206  px      3.5921477                                    $ [ 1  0  0]
207  py      3.5921477                                    $ [ 0  1  0]
208  py     -3.5921477                                    $ [ 0 -1  0]
209  pz      3.5921477                                    $ [ 0  0  1]
210  pz     -3.5921477                                    $ [ 0  0 -1]
c
c    balls in unit bcc cell
c
211  so      3.0
212  s       3.5921477  3.5921477  3.5921477  3.0
213  s       3.5921477  3.5921477 -3.5921477  3.0
214  s       3.5921477 -3.5921477 -3.5921477  3.0
215  s       3.5921477 -3.5921477  3.5921477  3.0
216  s      -3.5921477  3.5921477  3.5921477  3.0
217  s      -3.5921477  3.5921477 -3.5921477  3.0
```

```
218  s      -3.5921477 -3.5921477 -3.5921477  3.0
219  s      -3.5921477 -3.5921477  3.5921477  3.0
c
c    coated fuel particle (cfp)
c
220  so      0.025                                          $ UO2 kernel
221  so      0.034                                          $ 1st PyC layer
222  so      0.038                                          $ 2nd PyC layer
223  so      0.0415                                         $ SiC layer
224  so      0.0455                                         $ 3rd PyC layer
c
c    unit sc cell for cfp lattice in graphite matrix
c
225  px      0.0852133
226  px     -0.0852133
227  py      0.0852133
228  py     -0.0852133
229  pz      0.0852133
230  pz     -0.0852133
c
c    shutdown sites
c
c   .. KL1
271 81  px      3.0
272 81  px     -3.0
273 81  py      5.0
274 81  py     -5.0
275 81  c/z     0.0  5.0  3.0
276 81  c/z     0.0 -5.0  3.0
c
c   .. KL2
277 82  px      3.0
278 82  px     -3.0
279 82  py      5.0
280 82  py     -5.0
281 82  c/z     0.0  5.0  3.0
282 82  c/z     0.0 -5.0  3.0
c
c   .. KL3
283 83  px      3.0
284 83  px     -3.0
285 83  py      5.0
286 83  py     -5.0
287 83  c/z     0.0  5.0  3.0
288 83  c/z     0.0 -5.0  3.0
c
c   .. KL4
289 84  px      3.0
290 84  px     -3.0
291 84  py      5.0
292 84  py     -5.0
293 84  c/z     0.0  5.0  3.0
294 84  c/z     0.0 -5.0  3.0
c
c   .. KL5
295 85  px      3.0
296 85  px     -3.0
```

```
297 85  py      5.0
298 85  py     -5.0
299 85  c/z     0.0  5.0  3.0
300 85  c/z     0.0 -5.0  3.0
c
c    .. KL6
301 86  px      3.0
302 86  px     -3.0
303 86  py      5.0
304 86  py     -5.0
305 86  c/z     0.0  5.0  3.0
306 86  c/z     0.0 -5.0  3.0
c
c    .. KL7
307 87  px      3.0
308 87  px     -3.0
309 87  py      5.0
310 87  py     -5.0
311 87  c/z     0.0  5.0  3.0
312 87  c/z     0.0 -5.0  3.0
c
c    .. KL8
313 88  px      3.0
314 88  px     -3.0
315 88  py      5.0
316 88  py     -5.0
317 88  c/z     0.0  5.0  3.0
318 88  c/z     0.0 -5.0  3.0
c
c    .. KL9
319 89  px      3.0
320 89  px     -3.0
321 89  py      5.0
322 89  py     -5.0
323 89  c/z     0.0  5.0  3.0
324 89  c/z     0.0 -5.0  3.0
c
c    .. KL10
325 90  px      3.0
326 90  px     -3.0
327 90  py      5.0
328 90  py     -5.0
329 90  c/z     0.0  5.0  3.0
330 90  c/z     0.0 -5.0  3.0
c
c    .. KL11
331 91  px      3.0
332 91  px     -3.0
333 91  py      5.0
334 91  py     -5.0
335 91  c/z     0.0  5.0  3.0
336 91  c/z     0.0 -5.0  3.0
c
c    .. KL12
337 92  px      3.0
338 92  px     -3.0
339 92  py      5.0
```

```
340 92  py    -5.0
341 92  c/z    0.0  5.0  3.0
342 92  c/z    0.0 -5.0  3.0
c
c   .. KL13
343 93  px     3.0
344 93  px    -3.0
345 93  py     5.0
346 93  py    -5.0
347 93  c/z    0.0  5.0  3.0
348 93  c/z    0.0 -5.0  3.0
c
c   .. KL14
349 94  px     3.0
350 94  px    -3.0
351 94  py     5.0
352 94  py    -5.0
353 94  c/z    0.0  5.0  3.0
354 94  c/z    0.0 -5.0  3.0
c
c   .. KL15
355 95  px     3.0
356 95  px    -3.0
357 95  py     5.0
358 95  py    -5.0
359 95  c/z    0.0  5.0  3.0
360 95  c/z    0.0 -5.0  3.0
c
c   .. KL16
361 96  px     3.0
362 96  px    -3.0
363 96  py     5.0
364 96  py    -5.0
365 96  c/z    0.0  5.0  3.0
366 96  c/z    0.0 -5.0  3.0
c
c   .. KL17
367 97  px     3.0
368 97  px    -3.0
369 97  py     5.0
370 97  py    -5.0
371 97  c/z    0.0  5.0  3.0
372 97  c/z    0.0 -5.0  3.0
c
c   helium channels in reflector
c
375     c/z   230.000    0.000   4.0
376     c/z   226.506   39.940   4.0
377     c/z   216.129   78.660   4.0
378     c/z   199.186  115.000   4.0
379     c/z   176.190  147.840   4.0
380     c/z   147.841  176.190   4.0
381     c/z   115.000  199.190   4.0
382     c/z    78.665  216.130   4.0
383     c/z    39.939  226.510   4.0
384     c/z     0.000  230.000   4.0
385     c/z   -39.939  226.510   4.0
```

```
386      c/z   -78.665  216.130   4.0
387      c/z  -115.000  199.190   4.0
388      c/z  -147.841  176.190   4.0
389      c/z  -176.190  147.840   4.0
390      c/z  -199.186  115.000   4.0
391      c/z  -216.129   78.660   4.0
392      c/z  -226.506   39.940   4.0
393      c/z  -230.000    0.000   4.0
394      c/z  -226.506  -39.940   4.0
395      c/z  -216.129  -78.660   4.0
396      c/z  -199.186 -115.000   4.0
397      c/z  -176.190 -147.840   4.0
398      c/z  -147.841 -176.190   4.0
399      c/z  -115.000 -199.190   4.0
400      c/z   -78.665 -216.130   4.0
401      c/z   -39.939 -226.510   4.0
402      c/z     0.000 -230.000   4.0
403      c/z    39.939 -226.510   4.0
404      c/z    78.665 -216.130   4.0
405      c/z   115.000 -199.190   4.0
406      c/z   147.841 -176.190   4.0
407      c/z   176.190 -147.840   4.0
408      c/z   199.186 -115.000   4.0
409      c/z   216.129  -78.660   4.0
410      c/z   226.506  -39.940   4.0
c
c    control sites
c
c    .. CR1
440  61  px  6.1
441  61  px -6.1
442  61  py  6.1
443  61  py -6.1
c
c    .. CR2
444  62  px  6.1
445  62  px -6.1
446  62  py  6.1
447  62  py -6.1
c
c    .. CR3
448  63  px  6.1
449  63  px -6.1
450  63  py  6.1
451  63  py -6.1
c
c    .. CR4
452  64  px  6.1
453  64  px -6.1
454  64  py  6.1
455  64  py -6.1
c
c    .. CR5
456  65  px  6.1
457  65  px -6.1
458  65  py  6.1
459  65  py -6.1
```

```
c
c     .. CR6
460   66   px   6.1
461   66   px  -6.1
462   66   py   6.1
463   66   py  -6.1
c
c     .. CR7
464   67   px   6.1
465   67   px  -6.1
466   67   py   6.1
467   67   py  -6.1
c
c     .. CR8
468   68   px   6.1
469   68   px  -6.1
470   68   py   6.1
471   68   py  -6.1
c
c     .. CR9
472   69   px   6.1
473   69   px  -6.1
474   69   py   6.1
475   69   py  -6.1
c
c     .. CR10
476   70   px   6.1
477   70   px  -6.1
478   70   py   6.1
479   70   py  -6.1
c
c     .. CR11
480   71   px   6.1
481   71   px  -6.1
482   71   py   6.1
483   71   py  -6.1
c
c     .. CR12
484   72   px   6.1
485   72   px  -6.1
486   72   py   6.1
487   72   py  -6.1
c
c     .. CR13
488   73   px   6.1
489   73   px  -6.1
490   73   py   6.1
491   73   py  -6.1
c
c     .. CR14
492   74   px   6.1
493   74   px  -6.1
494   74   py   6.1
495   74   py  -6.1
c
c     .. CR15
496   75   px   6.1
```

```
497  75  px -6.1
498  75  py  6.1
499  75  py -6.1
c
c    .. CR16
500  76  px  6.1
501  76  px -6.1
502  76  py  6.1
503  76  py -6.1
c
c    .. CR17
504  77  px  6.1
505  77  px -6.1
506  77  py  6.1
507  77  py -6.1
c
c    .. CR18
508  78  px  6.1
509  78  px -6.1
510  78  py  6.1
511  78  py -6.1
c
c    control rods
c
520  pz   -462.45                          $ bottom of rod (1/4 inserted)
c    520  pz   -663.7                      $ bottom of rod (1/2 inserted)
c
c    .. lattice boundaries
523  px      6.0
524  px     -6.0
525  py      6.0
526  py     -6.0
c
c    .. absorber unit cell
530  pz     26.6                           $ top of joint (1/2 height)
531  pz     24.35                          $ top of absorber section
532  pz    -24.35                          $ bottom of absorber section
533  pz    -26.6                           $ bottom of joint (1/2 height)
534  cz      2.75                          $ inner surface of s/s sleeve
535  cz      3.0                           $ inner surface of absorber
536  cz      5.25                          $ outer surface of absorber
537  cz      5.5                           $ outer surface of s/s sleeve
538  cz      5.7                           $ inner surface of graphite
sleeve
c
c    surfaces for tallies
c
551  pz   -341.0
552  pz   -420.8
553  pz   -500.6
554  pz   -580.4
555  pz   -660.2
556  pz   -740.0
557  pz   -819.8
558  pz   -899.6
c
c    .. radial zones
```

```
561  cz      73.0                                          $ inner reflector
562  cz     107.94906                                      $ mixed mod/fuel zone
563  cz     134.07834                                      $ fuel zone 1
564  cz     155.88778                                      $ fuel zone 2
c
c    ---------------------------------------------------------------------

c    RUN PARAMETERS
c
c   problem type
c
mode  n
kcode 5000 1.0 5 205
ksrc   93.392  0  -280.176    93.392  0  -344.832    93.392  0  -409.488
       93.392  0  -474.144    93.392  0  -538.800    86.208  0  -610.640
       79.024  0  -675.296    79.024  0  -739.952    57.472  0  -811.792
       21.552  0  -890.816   122.128  0  -280.176   122.128  0  -344.832
      122.128  0  -409.488   122.128  0  -481.328   122.128  0  -545.984
      114.944  0  -610.640   114.944  0  -675.296   114.944  0  -739.952
      114.944  0  -804.608   100.576  0  -862.08     79.024  0  -926.736
      143.68   0  -280.176   143.68   0  -344.832   143.68   0  -409.488
      143.68   0  -474.144   143.68   0  -538.800   143.68   0  -610.640
      143.68   0  -675.296   136.496  0  -739.952   136.496  0  -797.424
      129.312  0  -854.896   114.944  0  -912.368    71.840  0  -969.840
      165.232  0  -280.176   165.232  0  -344.832   165.232  0  -416.672
      165.232  0  -481.328   165.232  0  -553.168   165.232  0  -617.824
      165.232  0  -682.480   158.048  0  -747.136   158.048  0  -811.792
      158.048  0  -862.080   150.864  0  -905.184   143.680  0  -941.104
      136.496  0  -969.840   122.128  0  -991.392    93.392  0 -1012.944
c
totnu
print
dbcn  9j  300
prdmp j  -60  1  2
c
c    neutron importance
imp:n 0                                                  $ outside world
      1 33r                                              $ structure (VSOP specifications)
      1                                                  $ control/shutdown zone
      1                                                  $ helium channel zone
      1 17r                                              $ control sites
      1 16r                                              $ shutdown sites
      1 35r                                              $ coolant channels
      1 11r                                              $ control site
      1                                                  $ core
      1                                                  $ discharge pipe
      1  4r                                              $ curved boundaries of channels 1-5
      1  8r  1  9r  1 10r  1 11r  1 14r                  $ layer boundaries in channels 1-5
      1 10r  1 10r  1 10r  1 10r  1 10r                  $ layers 1-9
      1 10r  1 10r  1 10r  1 10r
      1 10r  1 10r  1 10r  1 10r  1 10r                  $ layers 10-19
      1 10r  1 10r  1 10r  1 10r  1 10r
      1 10r  1 10r  1 10r  1 10r  1 10r                  $ layers 20 - 30
      1 10r  1 10r  1 10r  1 10r  1 10r
      1 10r
      1 10r  1 10r  1 10r  1 10r  1 10r                  $ layers 31 - 42
      1 10r  1 10r  1 10r  1 10r  1 10r
```

```
      1 10r  1 10r
      1 10r  1 10r  1 10r  1 10r  1 10r     $ layers 43 - 57
      1 10r  1 10r  1 10r  1 10r  1 10r
      1 10r  1 10r  1 10r  1 10r  1 10r
      1 10r                                 $ discharge pipe
c
c   transformations
c   channel 1
c
tr1      0       0    -280.176
tr2      0       0    -344.832
tr3      0       0    -409.488
tr4      0       0    -474.144
tr5      0       0    -538.800
tr6      0       0    -610.640
tr7      0       0    -675.296
tr8      0       0    -747.136
tr9      0       0    -818.976
c
c   channel 2
c
tr10    93.392   0    -280.176
tr11    93.392   0    -344.832
tr12    93.392   0    -409.488
tr13    93.392   0    -474.144
tr14    93.392   0    -538.800
tr15    86.208   0    -610.640
tr16    79.024   0    -675.296
tr17    79.024   0    -739.952
tr18    57.472   0    -811.792
tr19    21.552   0    -890.816
c
c   channel 3
c
tr20   122.128   0    -280.176
tr21   122.128   0    -344.832
tr22   122.128   0    -409.488
tr23   122.128   0    -481.328
tr24   122.128   0    -545.984
tr25   114.944   0    -610.640
tr26   114.944   0    -675.296
tr27   114.944   0    -739.952
tr28   114.944   0    -804.608
tr29   100.576   0    -862.08
tr30    79.024   0    -926.736
c
c   channel 4
c
tr31   143.68    0.0      -280.176
tr32   143.68    0.0      -344.832
tr33   143.68    0.0      -409.488
tr34   143.68    0.0      -474.144
tr35   143.68    0.0      -538.800
tr36   143.68    0.0      -610.640
tr37   143.68    0.0      -675.296
tr38   136.496   0.0      -739.952
tr39   136.496   0.0      -797.424
```

```
tr40  129.312    0.0      -854.896
tr41  114.944    0.0      -912.368
tr42   71.840    0.0      -969.84
c
c   channel 5
c
tr43  165.232    0.0      -280.176
tr44  165.232    0.0      -344.832
tr45  165.232    0.0      -416.672
tr46  165.232    0.0      -481.328
tr47  165.232    0.0      -553.168
tr48  165.232    0.0      -617.824
tr49  165.232    0.0      -682.480
tr50  158.048    0.0      -747.136
tr51  158.048    0.0      -811.792
tr52  158.048    0.0      -862.080
tr53  150.864    0.0      -905.184
tr54  143.680    0.0      -941.104
tr55  136.496    0.0      -969 840
tr56  122.128    0.0      -991.392
tr57   93.392    0.0     -1012.944
c
c   discharge pipe
c
tr58    0        0   -1084.784
c
c   control sites
c
*tr61  184.651  32.559   0.0   10   80  90  100   10  90  90  90  0  $ CR1
*tr62  162.380  93.750   0.0   30   60  90  120   30  90  90  90  0  $ CR2
*tr63  120.523  143.633  0.0   50   40  90  140   50  90  90  90  0  $ CR3
*tr64   64.129  176.192  0.0   70   20  90  160   70  90  90  90  0  $ CR4
*tr65    0.000  187.500  0.0   90    0  90  180   90  90  90  90  0  $ CR5
*tr66  -64.129  176.192  0.0  110   20  90 -160  110  90  90  90  0  $ CR6
*tr67 -120.523  143.633  0.0  130   40  90 -140  130  90  90  90  0  $ CR7
*tr68 -162.380   93.750  0.0  150   60  90 -120  150  90  90  90  0  $ CR8
*tr69 -184.651   32.559  0.0  170   80  90 -100  170  90  90  90  0  $ CR9
*tr70 -184.651  -32.559  0.0 -170  100  90  -80 -170  90  90  90  0  $ CR10
*tr71 -162.380  -93.750  0.0 -150  120  90  -60 -150  90  90  90  0  $ CR11
*tr72 -120.523 -143.633  0.0 -130  140  90  -40 -130  90  90  90  0  $ CR12
*tr73  -64.129 -176.192  0.0 -110  160  90  -20 -110  90  90  90  0  $ CR13
*tr74    0.000 -187.500  0.0  -90  180  90    0  -90  90  90  90  0  $ CR14
*tr75   64.129 -176.192  0.0  -70 -160  90   20  -70  90  90  90  0  $ CR15
*tr76  120.523 -143.633  0.0  -50 -140  90   40  -50  90  90  90  0  $ CR16
*tr77  162.380  -93.750  0.0  -30 -120  90   60  -30  90  90  90  0  $ CR17
*tr78  184.651  -32.559  0.0  -10 -100  90   80  -10  90  90  90  0  $ CR18
c
c   shutdown sites
c
*tr81  176.192   64.129  0.0   20   70  90  110   20  90  90  90  0  $ KL1
*tr82  143.633  120.523  0.0   40   50  90  130   40  90  90  90  0  $ KL2
*tr83   93.750  162.380  0.0   60   30  90  150   60  90  90  90  0  $ KL3
*tr84   32.559  184.651  0.0   80   10  90  170   80  90  90  90  0  $ KL4
*tr85  -32.559  184.651  0.0  100   10  90 -170  100  90  90  90  0  $ KL5
*tr86  -93.750  162.380  0.0  120   30  90 -150  120  90  90  90  0  $ KL6
*tr87 -143.633  120.523  0.0  140   50  90 -130  140  90  90  90  0  $ KL7
*tr88 -176.192   64.129  0.0  160   70  90 -110  160  90  90  90  0  $ KL8
```

```
 *tr89 -187.500    0.000  0.0  180   90  90  -90  180  90  90  90  0  $ KL9
 *tr90 -176.192  -64.129  0.0 -160  110  90  -70 -160  90  90  90  0  $ KL10
 *tr91 -143.633 -120.523  0.0 -140  130  90  -50 -140  90  90  90  0  $ KL11
 *tr92  -93.750 -162.380  0.0 -120  150  90  -30 -120  90  90  90  0  $ KL12
 *tr93  -32.559 -184.651  0.0 -100  170  90  -10 -100  90  90  90  0  $ KL13
 *tr94   32.559 -184.651  0.0  -80 -170  90   10  -80  90  90  90  0  $ KL14
 *tr95   93.750 -162.380  0.0  -60 -150  90   30  -60  90  90  90  0  $ KL15
 *tr96  143.633 -120.523  0.0  -40 -130  90   50  -40  90  90  90  0  $ KL16
 *tr97  176.192  -64.129  0.0  -20 -110  90   70  -20  90  90  90  0  $ KL17
c
c     tally specifications - from model with homogenized layers
c
 fc7   fission source for normalization (per unit mass)
       core
 f7:n  300
 sd7   1
c
 fc17   average fission power in inner reflector zone
        R-Z geometry, 9 x 80.5 cm regions top to bottom
        R1 = 73 cm
 f17:n  300
 fs17   561  551 552 553 554 555 556 557 558 559
 sd17   1 10r
c
 fc27   average prompt fission power in mixed mod/fuel zone
        R-Z geometry, 9 x 80.5 cm regions top to bottom
        R1 = 73 cm, R2 = 107.08 cm
 f27:n  300
 fs27  -561  562  551 552 553 554 555 556 557 558 559
 sd27   1 11r
c
 fc37   average prompt fission power in inner fuel zone
        R-Z geometry, 9 x 80.5 cm regions top to bottom
        R2 = 107.95 cm, R3 = 134.08 cm
 f37:n  300
 fs37  -562  563  551 552 553 554 555 556 557 558 559
 sd37   1 11r
c
 fc47   average prompt fission power in middle fuel zone
        R-Z geometry, 9 x 80.5 cm regions top to bottom
        R3 = 134.08 cm, R4 = 155.89 cm
 f47:n  300
 fs47  -563  564  551 552 553 554 555 556 557 558 559
 sd47   1 11r
c
 fc57   average prompt fission power in outer fuel zone
        R-Z geometry, 9 x 80.5 cm regions top to bottom
        R4 = 155.89 cm, R5 = 175 cm
 f57:n  300
 fs57  -564  34   551 552 553 554 555 556 557 558 559
 sd57   1 11r
c
 fc14   average neutron flux in inner reflector zone
        R-Z geometry, 9 x 80.5 cm regions top to bottom
        R1 = 73 cm
 f14:n  300
 fs14   561  551 552 553 554 555 556 557 558 559
```

```
sd14   1  1347694.55 9r
e14    1.86e-06  20
c
fc24   average neutron flux in mixed mod/fuel zone
       R-Z geometry, 9 x 80.5 cm regions top to bottom
       R1 = 73 cm, R2 = 107.09 cm
f24:n  300
fs24  -561  562  551 552 553 554 555 556 557 558 559
sd24   1  1  1599328.16 9r
e24    1.86e-06  20
c
fc34   average neutron flux in inner fuel zone
       R-Z geometry, 9 x 79.8 cm regions top to bottom
       R2 = 107.09 cm, R3 = 134.08 cm
f34:n  300
fs34  -562  563  551 552 553 554 555 556 557 558 559
sd34   1  1  1599328.70 9r
e34    1.86e-06  20
c
fc44   average neutron flux in middle fuel zone
       R-Z geometry, 9 x 79.8 cm regions top to bottom
       R3 = 134.08 cm, R4 = 155.89 cm
f44:n  300
fs44  -563  564  551 552 553 554 555 556 557 558 559
sd44   1  1  1599327.94 9r
e44    1.86e-06  20
c
fc54   average neutron flux in outer fuel zone
       R-Z geometry, 9 x 79.8 cm regions top to bottom
       R4 = 155.89 cm, R5 = 175 cm
f54:n  300
fs54  -564  34   551 552 553 554 555 556 557 558 559
sd54   1  1  1599328.28 9r
e54    1.86e-06  20
c
c     material specifications
c
c     structural materials
m1     5010.50c 2.97186e-03   5011.50c 2.00039e-02   6000.50c 8.52341e-02
mt1    grph.06t
m2     5010.50c 2.95398e-03   5011.50c 1.98835e-02   6000.50c 8.47225e-02
mt2    grph.06t
m3     5010.50c 2.64317e-03   5011.50c 1.77914e-02   6000.50c 7.58082e-02
mt3    grph.06t
m6     5010.50c 3.14663e-03   5011.50c 2.11803e-02   6000.50c 9.02479e-02
m7     5010.50c 2.91662e-03   5011.50c 1.96320e-02   6000.50c 8.36508e-02
mt6    grph.06t
m8     5010.50c 2.30612e-03   5011.50c 1.55227e-02   6000.50c 6.61415e-02
mt7    grph.06t
m40    5010.50c 2.17453e-03   5011.50c 1.46370e-02   6000.50c 6.23664e-02
mt40   grph.06t
m49   26000.50c 4.08572e-02   6000.50c 9.02479e-04
mt49   grph.06t
m50    5010.50c 2.77718e-03   5011.50c 1.85604e-02   6000.50c 7.82771e-02
mt50   grph.06t
m51    5010.50c 5.70121e-02   5011.50c 2.00242e-02   6000.50c 8.44504e-02
mt51   grph.06t
```

```
c
c    helium (4.814e-3 g/cc at 300K)
m60   2003.60c 0.00000137    2004.60c 0.99999863
c
c    stainless steel
m61  24000.50c -0.190       25055.50c -0.020       26000.50c -0.685
     28000.50c -0.095       14000.50c -0.010
c
c    boron carbide (B4C)
m62   6000.50c -0.2174       5010.50c -0.1557       5011.50c -0.6269
c
c    fuel corresponding to equilibrium burnup
c    VSOP cycle  261; layer   1; total N =  1.1655800E-01
M100 92235.50c 4.07262E-08  92236.50c 6.58900E-09  92238.50c 1.07094E-06
     93239.60c 7.50066E-11  94239.50c 3.63122E-09  94240.50c 2.10990E-09
     94241.50c 1.08681E-09  94242.50c 5.42479E-10  93237.50c 2.30932E-10
     54135.50c 5.84360E-13  36083.50c 1.70197E-10  42095.50c 2.10732E-09
     43099.50c 2.56441E-09  44101.50c 2.29166E-09  44103.50c 2.26484E-10
     45103.50c 1.15521E-09  45105.50c 4.14982E-12  46105.50c 8.38610E-10
     46108.50c 2.84020E-10  47109.50c 1.53964E-10  48000.50c 1.83462E-13
     54131.50c 1.10083E-09  55133.50c 2.75069E-09  55134.60c 1.52320E-10
     59141.50c 2.50604E-09  60143.50c 1.80634E-09  60145.50c 1.55532E-09
     61147.50c 5.84537E-10  61148.50c 3.77982E-12  62147.50c 1.17966E-10
     61149.50c 4.16566E-12  62149.50c 4.97450E-12  62150.50c 5.66122E-10
     62151.50c 2.87247E-11  62152.50c 2.78273E-10  63153.50c 1.80856E-10
     63154.50c 3.36616E-11  63155.50c 1.10601E-11  64155.50c 1.49528E-13
     64156.50c 6.06263E-11  64157.50c 7.28950E-14   5010.50c 3.28991E-09
     14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C    VSOP cycle  261; layer   2; total N =  1.1655800E-01
M101 92235.50c 3.98109E-08  92236.50c 6.72954E-09  92238.50c 1.07071E-06
     93239.60c 1.10818E-10  94239.50c 3.48284E-09  94240.50c 2.17671E-09
     94241.50c 1.05883E-09  94242.50c 5.62895E-10  93237.50c 2.32825E-10
     54135.50c 6.21233E-13  36083.50c 1.73786E-10  42095.50c 2.14275E-09
     43099.50c 2.62577E-09  44101.50c 2.34657E-09  44103.50c 2.41965E-10
     45103.50c 1.17273E-09  45105.50c 6.94228E-12  46105.50c 8.56632E-10
     46108.50c 2.91700E-10  47109.50c 1.58068E-10  48000.50c 1.74153E-13
     54131.50c 1.11721E-09  55133.50c 2.79548E-09  55134.60c 1.54946E-10
     59141.50c 2.56493E-09  60143.50c 1.82278E-09  60145.50c 1.59184E-09
     61147.50c 5.99805E-10  61148.50c 4.04966E-12  62147.50c 1.20406E-10
     61149.50c 6.77844E-12  62149.50c 4.09333E-12  62150.50c 5.76979E-10
     62151.50c 2.71804E-11  62152.50c 2.87516E-10  63153.50c 1.84517E-10
     63154.50c 3.44658E-11  63155.50c 1.11875E-11  64155.50c 9.73063E-14
     64156.50c 6.28466E-11  64157.50c 6.80328E-14   5010.50c 5.12410E-09
     14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C    VSOP cycle  261; layer   3; total N =  1.1655800E-01
M102 92235.50c 3.85522E-08  92236.50c 6.92302E-09  92238.50c 1.07039E-06
     93239.60c 1.58675E-10  94239.50c 3.28932E-09  94240.50c 2.26442E-09
     94241.50c 1.02490E-09  94242.50c 5.91133E-10  93237.50c 2.35537E-10
     54135.50c 6.26026E-13  36083.50c 1.78637E-10  42095.50c 2.18010E-09
     43099.50c 2.70995E-09  44101.50c 2.42206E-09  44103.50c 2.70728E-10
     45103.50c 1.18871E-09  45105.50c 9.29268E-12  46105.50c 8.81808E-10
     46108.50c 3.02266E-10  47109.50c 1.63675E-10  48000.50c 1.66918E-13
     54131.50c 1.13895E-09  55133.50c 2.85951E-09  55134.60c 1.59086E-10
     59141.50c 2.64583E-09  60143.50c 1.83993E-09  60145.50c 1.64190E-09
     61147.50c 6.21381E-10  61148.50c 4.88820E-12  62147.50c 1.22772E-10
     61149.50c 9.50137E-12  62149.50c 4.13281E-12  62150.50c 5.91321E-10
     62151.50c 2.58933E-11  62152.50c 2.99540E-10  63153.50c 1.89705E-10
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      63154.50c 3.56328E-11  63155.50c 1.13643E-11  64155.50c 6.12524E-14
      64156.50c 6.59242E-11  64157.50c 6.72216E-14   5010.50c 6.91338E-09
      14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C     VSOP cycle  261; layer   4; total N =  1.1655800E-01
M103  92235.50c 3.70386E-08  92236.50c 7.15576E-09  92238.50c 1.06998E-06
      93239.60c 2.02213E-10  94239.50c 3.08514E-09  94240.50c 2.36288E-09
      94241.50c 9.90698E-10  94242.50c 6.25492E-10  93237.50c 2.39004E-10
      54135.50c 6.17953E-13  36083.50c 1.84329E-10  42095.50c 2.22063E-09
      43099.50c 2.81086E-09  44101.50c 2.51284E-09  44103.50c 3.07426E-10
      45103.50c 1.20480E-09  45105.50c 1.09310E-11  46105.50c 9.12214E-10
      46108.50c 3.15006E-10  47109.50c 1.70373E-10  48000.50c 1.59703E-13
      54131.50c 1.16749E-09  55133.50c 2.94368E-09  55134.60c 1.64601E-10
      59141.50c 2.74303E-09  60143.50c 1.86155E-09  60145.50c 1.70182E-09
      61147.50c 6.47138E-10  61148.50c 5.77646E-12  62147.50c 1.25106E-10
      61149.50c 1.18185E-11  62149.50c 4.20694E-12  62150.50c 6.09694E-10
      62151.50c 2.50505E-11  62152.50c 3.13328E-10  63153.50c 1.96196E-10
      63154.50c 3.71304E-11  63155.50c 1.15600E-11  64155.50c 4.51662E-14
      64156.50c 6.97323E-11  64157.50c 6.64257E-14   5010.50c 8.84364E-09
      14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C     VSOP cycle  261; layer   5; total N =  1.1655800E-01
M104  92235.50c 3.54456E-08  92236.50c 7.40067E-09  92238.50c 1.06954E-06
      93239.60c 2.26988E-10  94239.50c 2.90579E-09  94240.50c 2.45858E-09
      94241.50c 9.61991E-10  94242.50c 6.62376E-10  93237.50c 2.42901E-10
      54135.50c 6.03558E-13  36083.50c 1.90147E-10  42095.50c 2.26508E-09
      43099.50c 2.91688E-09  44101.50c 2.60858E-09  44103.50c 3.43702E-10
      45103.50c 1.22298E-09  45105.50c 1.14781E-11  46105.50c 9.44908E-10
      46108.50c 3.28536E-10  47109.50c 1.77412E-10  48000.50c 1.53246E-13
      54131.50c 1.20228E-09  55133.50c 3.04293E-09  55134.60c 1.70928E-10
      59141.50c 2.84537E-09  60143.50c 1.89051E-09  60145.50c 1.76465E-09
      61147.50c 6.73503E-10  61148.50c 6.40090E-12  62147.50c 1.27483E-10
      61149.50c 1.29811E-11  62149.50c 4.28340E-12  62150.50c 6.30673E-10
      62151.50c 2.46821E-11  62152.50c 3.27412E-10  63153.50c 2.03347E-10
      63154.50c 3.88211E-11  63155.50c 1.17468E-11  64155.50c 4.04374E-14
      64156.50c 7.39185E-11  64157.50c 6.58863E-14   5010.50c 1.13633E-08
      14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C     VSOP cycle  261; layer   6; total N =  1.1655800E-01
M105  92235.50c 3.38890E-08  92236.50c 7.63976E-09  92238.50c 1.06909E-06
      93239.60c 2.35738E-10  94239.50c 2.75935E-09  94240.50c 2.54463E-09
      94241.50c 9.40618E-10  94242.50c 6.99365E-10  93237.50c 2.46988E-10
      54135.50c 5.86958E-13  36083.50c 1.95653E-10  42095.50c 2.31346E-09
      43099.50c 3.02039E-09  44101.50c 2.70245E-09  44103.50c 3.74714E-10
      45103.50c 1.24412E-09  45105.50c 1.13402E-11  46105.50c 9.77584E-10
      46108.50c 3.41946E-10  47109.50c 1.84315E-10  48000.50c 1.47843E-13
      54131.50c 1.24110E-09  55133.50c 3.14927E-09  55134.60c 1.77630E-10
      59141.50c 2.94555E-09  60143.50c 1.92644E-09  60145.50c 1.82585E-09
      61147.50c 6.98281E-10  61148.50c 6.76533E-12  62147.50c 1.29950E-10
      61149.50c 1.32003E-11  62149.50c 4.32258E-12  62150.50c 6.52527E-10
      62151.50c 2.45635E-11  62152.50c 3.40953E-10  63153.50c 2.10678E-10
      63154.50c 4.05953E-11  63155.50c 1.19199E-11  64155.50c 4.01376E-14
      64156.50c 7.82159E-11  64157.50c 6.55200E-14   5010.50c 1.44400E-08
      14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C     VSOP cycle  261; layer   7; total N =  1.1655800E-01
M106  92235.50c 3.24715E-08  92236.50c 7.85720E-09  92238.50c 1.06865E-06
      93239.60c 2.28293E-10  94239.50c 2.65173E-09  94240.50c 2.61727E-09
      94241.50c 9.26388E-10  94242.50c 7.34104E-10  93237.50c 2.50999E-10
      54135.50c 5.70051E-13  36083.50c 2.00509E-10  42095.50c 2.36533E-09
      43099.50c 3.11474E-09  44101.50c 2.78843E-09  44103.50c 3.96727E-10
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      45103.50c 1.26874E-09  45105.50c 1.06042E-11  46105.50c 1.00848E-09
      46108.50c 3.54408E-10  47109.50c 1.90666E-10  48000.50c 1.43727E-13
      54131.50c 1.28144E-09  55133.50c 3.25505E-09  55134.60c 1.84188E-10
      59141.50c 3.03709E-09  60143.50c 1.96815E-09  60145.50c 1.88148E-09
      61147.50c 7.19756E-10  61148.50c 6.86570E-12  62147.50c 1.32548E-10
      61149.50c 1.25154E-11  62149.50c 4.36572E-12  62150.50c 6.73693E-10
      62151.50c 2.46026E-11  62152.50c 3.53205E-10  63153.50c 2.17690E-10
      63154.50c 4.23267E-11  63155.50c 1.20772E-11  64155.50c 4.28534E-14
      64156.50c 8.23348E-11  64157.50c 6.54426E-14   5010.50c 1.85014E-08
      14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C     VSOP cycle  261; layer   8; total N =  1.1655800E-01
M107  92235.50c 3.12458E-08  92236.50c 8.04485E-09  92238.50c 1.06825E-06
      93239.60c 2.13446E-10  94239.50c 2.58354E-09  94240.50c 2.67645E-09
      94241.50c 9.17762E-10  94242.50c 7.65039E-10  93237.50c 2.54983E-10
      54135.50c 5.54225E-13  36083.50c 2.04580E-10  42095.50c 2.41983E-09
      43099.50c 3.19640E-09  44101.50c 2.86327E-09  44103.50c 4.08417E-10
      45103.50c 1.29674E-09  45105.50c 9.50911E-12  46105.50c 1.03644E-09
      46108.50c 3.65438E-10  47109.50c 1.96225E-10  48000.50c 1.40931E-13
      54131.50c 1.32077E-09  55133.50c 3.35395E-09  55134.60c 1.90315E-10
      59141.50c 3.11661E-09  60143.50c 2.01353E-09  60145.50c 1.92952E-09
      61147.50c 7.37095E-10  61148.50c 6.81389E-12  62147.50c 1.35287E-10
      61149.50c 1.12484E-11  62149.50c 4.41911E-12  62150.50c 6.93006E-10
      62151.50c 2.47330E-11  62152.50c 3.63691E-10  63153.50c 2.24110E-10
      63154.50c 4.39448E-11  63155.50c 1.22216E-11  64155.50c 4.81663E-14
      64156.50c 8.60758E-11  64157.50c 6.58135E-14   5010.50c 2.38964E-08
      14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C     VSOP cycle  261; layer   9; total N =  1.1655810E-01
M108  92235.50c 3.02662E-08  92236.50c 8.19319E-09  92238.50c 1.06787E-06
      93239.60c 1.96095E-10  94239.50c 2.60360E-09  94240.50c 2.71496E-09
      94241.50c 9.10929E-10  94242.50c 7.88761E-10  93237.50c 2.59726E-10
      54135.50c 5.07863E-13  36083.50c 2.07679E-10  42095.50c 2.47592E-09
      43099.50c 3.26022E-09  44101.50c 2.92219E-09  44103.50c 4.06959E-10
      45103.50c 1.32852E-09  45105.50c 7.62552E-12  46105.50c 1.05951E-09
      46108.50c 3.73910E-10  47109.50c 2.00359E-10  48000.50c 1.36512E-13
      54131.50c 1.35679E-09  55133.50c 3.44050E-09  55134.60c 1.95810E-10
      59141.50c 3.17939E-09  60143.50c 2.06095E-09  60145.50c 1.96715E-09
      61147.50c 7.48803E-10  61148.50c 6.92585E-12  62147.50c 1.38165E-10
      61149.50c 9.20910E-12  62149.50c 4.32926E-12  62150.50c 7.09414E-10
      62151.50c 2.45106E-11  62152.50c 3.72007E-10  63153.50c 2.29572E-10
      63154.50c 4.53945E-11  63155.50c 1.23787E-11  64155.50c 5.52293E-14
      64156.50c 8.91727E-11  64157.50c 5.95267E-14   5010.50c 3.23723E-08
      14000.50c 2.62384E-06   6000.50c 8.77334E-02   8016.50c 2.34059E-06
C     VSOP cycle  261; layer  10; total N =  4.2400759E-01
M109  92235.50c 3.97186E-06  92236.50c 6.56084E-07  92238.50c 9.16269E-05
      93239.60c 7.77269E-09  94239.50c 3.68020E-07  94240.50c 2.09775E-07
      94241.50c 1.08987E-07  94242.50c 5.38576E-08  93237.50c 2.31650E-08
      54135.50c 5.49556E-11  36083.50c 1.69440E-08  42095.50c 2.10482E-07
      43099.50c 2.55182E-07  44101.50c 2.28071E-07  44103.50c 2.20106E-08
      45103.50c 1.15497E-07  45105.50c 3.12717E-10  46105.50c 8.35589E-08
      46108.50c 2.82556E-08  47109.50c 1.53131E-08  48000.50c 1.86710E-11
      54131.50c 1.09870E-07  55133.50c 2.74429E-07  55134.60c 1.52235E-08
      59141.50c 2.49434E-07  60143.50c 1.80601E-07  60145.50c 1.54786E-07
      61147.50c 5.80413E-08  61148.50c 4.09661E-10  62147.50c 1.17835E-08
      61149.50c 3.23060E-10  62149.50c 5.60605E-10  62150.50c 5.63833E-08
      62151.50c 2.91539E-09  62152.50c 2.76134E-08  63153.50c 1.80414E-08
      63154.50c 3.36243E-09  63155.50c 1.10358E-09  64155.50c 1.70292E-11
      64156.50c 6.02348E-09  64157.50c 7.98278E-12   5010.50c 1.17845E-07
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     14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C    VSOP cycle  261; layer  11; total N =  4.2400819E-01
M110 92235.50c 3.90697E-06  92236.50c 6.66130E-07  92238.50c 9.16021E-05
     93239.60c 1.20278E-08  94239.50c 3.63611E-07  94240.50c 2.14788E-07
     94241.50c 1.06880E-07  94242.50c 5.52571E-08  93237.50c 2.35540E-08
     54135.50c 6.04063E-11  36083.50c 1.71960E-08  42095.50c 2.13904E-07
     43099.50c 2.59453E-07  44101.50c 2.31956E-07  44103.50c 2.24784E-08
     45103.50c 1.17379E-07  45105.50c 5.13256E-10  46105.50c 8.48871E-08
     46108.50c 2.88058E-08  47109.50c 1.55978E-08  48000.50c 1.79641E-11
     54131.50c 1.11161E-07  55133.50c 2.77821E-07  55134.60c 1.55057E-08
     59141.50c 2.53618E-07  60143.50c 1.82351E-07  60145.50c 1.57342E-07
     61147.50c 5.89074E-08  61148.50c 4.59501E-10  62147.50c 1.20237E-08
     61149.50c 5.07604E-10  62149.50c 4.39833E-10  62150.50c 5.72498E-08
     62151.50c 2.81105E-09  62152.50c 2.82025E-08  63153.50c 1.83624E-08
     63154.50c 3.44325E-09  63155.50c 1.11527E-09  64155.50c 1.32659E-11
     64156.50c 6.18399E-09  64157.50c 7.32931E-12   5010.50c 7.44660E-08
     14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C    VSOP cycle  261; layer  12; total N =  4.2400879E-01
M111 92235.50c 3.81547E-06  92236.50c 6.80299E-07  92238.50c 9.15662E-05
     93239.60c 1.75943E-08  94239.50c 3.57697E-07  94240.50c 2.22020E-07
     94241.50c 1.04161E-07  94242.50c 5.72354E-08  93237.50c 2.41186E-08
     54135.50c 6.26583E-11  36083.50c 1.75489E-08  42095.50c 2.17389E-07
     43099.50c 2.65494E-07  44101.50c 2.37464E-07  44103.50c 2.41027E-08
     45103.50c 1.19074E-07  45105.50c 7.21220E-10  46105.50c 8.68038E-08
     46108.50c 2.95948E-08  47109.50c 1.60049E-08  48000.50c 1.75525E-11
     54131.50c 1.12706E-07  55133.50c 2.82407E-07  55134.60c 1.59544E-08
     59141.50c 2.59545E-07  60143.50c 1.83970E-07  60145.50c 1.60953E-07
     61147.50c 6.02242E-08  61148.50c 5.54805E-10  62147.50c 1.22518E-08
     61149.50c 7.37100E-10  62149.50c 4.40201E-10  62150.50c 5.83444E-08
     62151.50c 2.71549E-09  62152.50c 2.89938E-08  63153.50c 1.88276E-08
     63154.50c 3.56218E-09  63155.50c 1.13461E-09  64155.50c 9.18740E-12
     64156.50c 6.41165E-09  64157.50c 7.40653E-12   5010.50c 5.86142E-08
     14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C    VSOP cycle  261; layer  13; total N =  4.2400929E-01
M112 92235.50c 3.70312E-06  92236.50c 6.97692E-07  92238.50c 9.15208E-05
     93239.60c 2.27314E-08  94239.50c 3.51920E-07  94240.50c 2.31101E-07
     94241.50c 1.01226E-07  94242.50c 5.96801E-08  93237.50c 2.48408E-08
     54135.50c 6.34184E-11  36083.50c 1.79774E-08  42095.50c 2.21045E-07
     43099.50c 2.72947E-07  44101.50c 2.44283E-07  44103.50c 2.65368E-08
     45103.50c 1.20724E-07  45105.50c 8.88688E-10  46105.50c 8.92281E-08
     46108.50c 3.05865E-08  47109.50c 1.65149E-08  48000.50c 1.72417E-11
     54131.50c 1.14694E-07  55133.50c 2.88476E-07  55134.60c 1.65527E-08
     59141.50c 2.66870E-07  60143.50c 1.85822E-07  60145.50c 1.65399E-07
     61147.50c 6.18732E-08  61148.50c 6.52729E-10  62147.50c 1.24714E-08
     61149.50c 9.45401E-10  62149.50c 4.58897E-10  62150.50c 5.97816E-08
     62151.50c 2.65306E-09  62152.50c 2.99241E-08  63153.50c 1.94201E-08
     63154.50c 3.71591E-09  63155.50c 1.15990E-09  64155.50c 6.69552E-12
     64156.50c 6.69770E-09  64157.50c 7.54381E-12   5010.50c 5.37807E-08
     14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C    VSOP cycle  261; layer  14; total N =  4.2401019E-01
M113 92235.50c 3.58224E-06  92236.50c 7.16378E-07  92238.50c 9.14703E-05
     93239.60c 2.57167E-08  94239.50c 3.47467E-07  94240.50c 2.41113E-07
     94241.50c 9.85758E-08  94242.50c 6.23414E-08  93237.50c 2.56466E-08
     54135.50c 6.33040E-11  36083.50c 1.84324E-08  42095.50c 2.24951E-07
     43099.50c 2.81021E-07  44101.50c 2.51700E-07  44103.50c 2.91745E-08
     45103.50c 1.22494E-07  45105.50c 9.73939E-10  46105.50c 9.19546E-08
     46108.50c 3.16866E-08  47109.50c 1.70785E-08  48000.50c 1.69892E-11
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      54131.50c 1.17167E-07  55133.50c 2.95809E-07  55134.60c 1.72369E-08
      59141.50c 2.74819E-07  60143.50c 1.88195E-07  60145.50c 1.70203E-07
      61147.50c 6.36328E-08  61148.50c 7.20646E-10  62147.50c 1.26903E-08
      61149.50c 1.06723E-09  62149.50c 4.76917E-10  62150.50c 6.14806E-08
      62151.50c 2.63221E-09  62152.50c 3.08998E-08  63153.50c 2.00835E-08
      63154.50c 3.89019E-09  63155.50c 1.18778E-09  64155.50c 5.73156E-12
      64156.50c 7.01808E-09  64157.50c 7.69998E-12   5010.50c 5.60492E-08
      14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C     VSOP cycle  261; layer  15; total N =  4.2401099E-01
M114  92235.50c 3.46218E-06  92236.50c 7.34897E-07  92238.50c 9.14186E-05
      93239.60c 2.67557E-08  94239.50c 3.44153E-07  94240.50c 2.51281E-07
      94241.50c 9.64714E-08  94242.50c 6.50255E-08  93237.50c 2.64794E-08
      54135.50c 6.27405E-11  36083.50c 1.88775E-08  42095.50c 2.29131E-07
      43099.50c 2.89099E-07  44101.50c 2.59156E-07  44103.50c 3.15829E-08
      45103.50c 1.24481E-07  45105.50c 9.94387E-10  46105.50c 9.47838E-08
      46108.50c 3.28163E-08  47109.50c 1.76550E-08  48000.50c 1.67887E-11
      54131.50c 1.20011E-07  55133.50c 3.03881E-07  55134.60c 1.79553E-08
      59141.50c 2.82790E-07  60143.50c 1.91132E-07  60145.50c 1.74998E-07
      61147.50c 6.53392E-08  61148.50c 7.57905E-10  62147.50c 1.29141E-08
      61149.50c 1.10671E-09  62149.50c 4.89569E-10  62150.50c 6.33018E-08
      62151.50c 2.63839E-09  62152.50c 3.18585E-08  63153.50c 2.07704E-08
      63154.50c 4.07294E-09  63155.50c 1.21606E-09  64155.50c 5.55936E-12
      64156.50c 7.35220E-09  64157.50c 7.85537E-12   5010.50c 6.24007E-08
      14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C     VSOP cycle  261; layer  16; total N =  4.2401180E-01
M115  92235.50c 3.35198E-06  92236.50c 7.51854E-07  92238.50c 9.13691E-05
      93239.60c 2.58797E-08  94239.50c 3.42508E-07  94240.50c 2.60814E-07
      94241.50c 9.50020E-08  94242.50c 6.75344E-08  93237.50c 2.72828E-08
      54135.50c 6.18879E-11  36083.50c 1.92799E-08  42095.50c 2.33566E-07
      43099.50c 2.96572E-07  44101.50c 2.66086E-07  44103.50c 3.33666E-08
      45103.50c 1.26748E-07  45105.50c 9.47973E-10  46105.50c 9.75280E-08
      46108.50c 3.38894E-08  47109.50c 1.82006E-08  48000.50c 1.66595E-11
      54131.50c 1.23055E-07  55133.50c 3.12099E-07  55134.60c 1.86489E-08
      59141.50c 2.90181E-07  60143.50c 1.94590E-07  60145.50c 1.79421E-07
      61147.50c 6.68409E-08  61148.50c 7.64716E-10  62147.50c 1.31482E-08
      61149.50c 1.05898E-09  62149.50c 5.02277E-10  62150.50c 6.50966E-08
      62151.50c 2.66277E-09  62152.50c 3.27368E-08  63153.50c 2.14283E-08
      63154.50c 4.25043E-09  63155.50c 1.24263E-09  64155.50c 5.90809E-12
      64156.50c 7.67492E-09  64157.50c 8.02495E-12   5010.50c 7.37780E-08
      14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C     VSOP cycle  261; layer  17; total N =  4.2401239E-01
M116  92235.50c 3.25703E-06  92236.50c 7.66422E-07  92238.50c 9.13237E-05
      93239.60c 2.39147E-08  94239.50c 3.43015E-07  94240.50c 2.69205E-07
      94241.50c 9.40886E-08  94242.50c 6.97298E-08  93237.50c 2.80368E-08
      54135.50c 6.08801E-11  36083.50c 1.96214E-08  42095.50c 2.38198E-07
      43099.50c 3.03050E-07  44101.50c 2.72127E-07  44103.50c 3.43177E-08
      45103.50c 1.29299E-07  45105.50c 8.53030E-10  46105.50c 1.00037E-07
      46108.50c 3.48443E-08  47109.50c 1.86839E-08  48000.50c 1.66162E-11
      54131.50c 1.26095E-07  55133.50c 3.19898E-07  55134.60c 1.92819E-08
      59141.50c 2.96611E-07  60143.50c 1.98414E-07  60145.50c 1.83245E-07
      61147.50c 6.80446E-08  61148.50c 7.51893E-10  62147.50c 1.33947E-08
      61149.50c 9.48003E-10  62149.50c 5.16133E-10  62150.50c 6.67420E-08
      62151.50c 2.69728E-09  62152.50c 3.34875E-08  63153.50c 2.20241E-08
      63154.50c 4.41407E-09  63155.50c 1.26645E-09  64155.50c 6.69059E-12
      64156.50c 7.96669E-09  64157.50c 8.23365E-12   5010.50c 9.13299E-08
      14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C     VSOP cycle  261; layer  18; total N =  4.2401290E-01
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M117 92235.50c 3.18168E-06  92236.50c 7.78013E-07  92238.50c 9.12843E-05
     93239.60c 2.09997E-08  94239.50c 3.44249E-07  94240.50c 2.73802E-07
     94241.50c 9.65338E-08  94242.50c 7.15905E-08  93237.50c 2.86601E-08
     54135.50c 6.31163E-11  36083.50c 1.98928E-08  42095.50c 2.42958E-07
     43099.50c 3.08306E-07  44101.50c 2.77065E-07  44103.50c 3.43923E-08
     45103.50c 1.31913E-07  45105.50c 7.33931E-10  46105.50c 1.02227E-07
     46108.50c 3.56668E-08  47109.50c 1.90996E-08  48000.50c 1.71947E-11
     54131.50c 1.28947E-07  55133.50c 3.26863E-07  55134.60c 1.98140E-08
     59141.50c 3.01845E-07  60143.50c 2.02456E-07  60145.50c 1.86338E-07
     61147.50c 6.89202E-08  61148.50c 6.91410E-10  62147.50c 1.36565E-08
     61149.50c 8.05996E-10  62149.50c 5.69800E-10  62150.50c 6.81381E-08
     62151.50c 2.77326E-09  62152.50c 3.40548E-08  63153.50c 2.25379E-08
     63154.50c 4.54699E-09  63155.50c 1.29282E-09  64155.50c 8.35935E-12
     64156.50c 8.21211E-09  64157.50c 9.38945E-12   5010.50c 1.19684E-07
     14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C    VSOP cycle  261; layer  19; total N =  4.2401350E-01
M118 92235.50c 3.11759E-06  92236.50c 7.87701E-07  92238.50c 9.12513E-05
     93239.60c 1.76288E-08  94239.50c 3.49643E-07  94240.50c 2.78881E-07
     94241.50c 9.58725E-08  94242.50c 7.30738E-08  93237.50c 2.92690E-08
     54135.50c 5.42900E-11  36083.50c 2.01124E-08  42095.50c 2.47749E-07
     43099.50c 3.12619E-07  44101.50c 2.81124E-07  44103.50c 3.37334E-08
     45103.50c 1.34862E-07  45105.50c 5.92464E-10  46105.50c 1.04030E-07
     46108.50c 3.63065E-08  47109.50c 1.94156E-08  48000.50c 1.63757E-11
     54131.50c 1.31494E-07  55133.50c 3.32803E-07  55134.60c 2.02639E-08
     59141.50c 3.06168E-07  60143.50c 2.06293E-07  60145.50c 1.88884E-07
     61147.50c 6.95387E-08  61148.50c 6.80266E-10  62147.50c 1.39293E-08
     61149.50c 6.53429E-10  62149.50c 5.09383E-10  62150.50c 6.93824E-08
     62151.50c 2.75217E-09  62152.50c 3.45894E-08  63153.50c 2.29625E-08
     63154.50c 4.66922E-09  63155.50c 1.30953E-09  64155.50c 9.21065E-12
     64156.50c 8.42520E-09  64157.50c 7.57218E-12   5010.50c 1.47687E-07
     14000.50c 2.27413E-04   6000.50c 8.70008E-02   8016.50c 2.02884E-04
C    VSOP cycle  261; layer  20; total N =  7.3386878E-01
M119 92235.50c 7.95072E-06  92236.50c 1.29511E-06  92238.50c 1.81968E-04
     93239.60c 1.43936E-08  94239.50c 7.37664E-07  94240.50c 4.10737E-07
     94241.50c 2.19564E-07  94242.50c 1.05179E-07  93237.50c 4.56119E-08
     54135.50c 1.05204E-10  36083.50c 3.34547E-08  42095.50c 4.15745E-07
     43099.50c 5.02976E-07  44101.50c 4.49383E-07  44103.50c 4.26355E-08
     45103.50c 2.28318E-07  45105.50c 4.30118E-10  46105.50c 1.64553E-07
     46108.50c 5.54821E-08  47109.50c 3.00841E-08  48000.50c 3.85076E-11
     54131.50c 2.17275E-07  55133.50c 5.42250E-07  55134.60c 2.98958E-08
     59141.50c 4.91624E-07  60143.50c 3.58006E-07  60145.50c 3.05170E-07
     61147.50c 1.14551E-07  61148.50c 7.97393E-10  62147.50c 2.32287E-08
     61149.50c 4.62327E-10  62149.50c 1.36386E-09  62150.50c 1.10991E-07
     62151.50c 5.90405E-09  62152.50c 5.42800E-08  63153.50c 3.54931E-08
     63154.50c 6.58361E-09  63155.50c 2.18005E-09  64155.50c 3.92018E-11
     64156.50c 1.17790E-08  64157.50c 1.97876E-11   5010.50c 5.03683E-07
     14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C    VSOP cycle  261; layer  21; total N =  7.3386961E-01
M120 92235.50c 7.86961E-06  92236.50c 1.30795E-06  92238.50c 1.81922E-04
     93239.60c 2.25011E-08  94239.50c 7.41727E-07  94240.50c 4.12554E-07
     94241.50c 2.22274E-07  94242.50c 1.06954E-07  93237.50c 4.63581E-08
     54135.50c 1.23677E-10  36083.50c 3.37715E-08  42095.50c 4.22386E-07
     43099.50c 5.08284E-07  44101.50c 4.54287E-07  44103.50c 4.16756E-08
     45103.50c 2.31883E-07  45105.50c 6.81811E-10  46105.50c 1.66330E-07
     46108.50c 5.62083E-08  47109.50c 3.04531E-08  48000.50c 3.83995E-11
     54131.50c 2.19331E-07  55133.50c 5.47205E-07  55134.60c 3.03358E-08
     59141.50c 4.96924E-07  60143.50c 3.61757E-07  60145.50c 3.08360E-07
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      61147.50c 1.15299E-07  61148.50c 8.75434E-10  62147.50c 2.37131E-08
      61149.50c 6.71210E-10  62149.50c 1.08824E-09  62150.50c 1.12278E-07
      62151.50c 5.85034E-09  62152.50c 5.48826E-08  63153.50c 3.59779E-08
      63154.50c 6.69977E-09  63155.50c 2.20916E-09  64155.50c 3.82194E-11
      64156.50c 1.19811E-08  64157.50c 1.88527E-11   5010.50c 3.11355E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  22; total N =  7.3387039E-01
M121  92235.50c 7.75469E-06  92236.50c 1.32620E-06  92238.50c 1.81854E-04
      93239.60c 3.32958E-08  94239.50c 7.47395E-07  94240.50c 4.15754E-07
      94241.50c 2.26271E-07  94242.50c 1.09588E-07  93237.50c 4.74317E-08
      54135.50c 1.36034E-10  36083.50c 3.42234E-08  42095.50c 4.28936E-07
      43099.50c 5.15910E-07  44101.50c 4.61348E-07  44103.50c 4.24788E-08
      45103.50c 2.34844E-07  45105.50c 9.93955E-10  46105.50c 1.68943E-07
      46108.50c 5.72873E-08  47109.50c 3.10039E-08  48000.50c 3.88587E-11
      54131.50c 2.21414E-07  55133.50c 5.53211E-07  55134.60c 3.10501E-08
      59141.50c 5.04535E-07  60143.50c 3.64980E-07  60145.50c 3.12931E-07
      61147.50c 1.16602E-07  61148.50c 1.02198E-09  62147.50c 2.41740E-08
      61149.50c 9.95580E-10  62149.50c 1.03881E-09  62150.50c 1.13799E-07
      62151.50c 5.82719E-09  62152.50c 5.57120E-08  63153.50c 3.66839E-08
      63154.50c 6.87023E-09  63155.50c 2.25815E-09  64155.50c 3.30662E-11
      64156.50c 1.22724E-08  64157.50c 1.98204E-11   5010.50c 2.27025E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  23; total N =  7.3387140E-01
M122  92235.50c 7.61049E-06  92236.50c 1.34912E-06  92238.50c 1.81765E-04
      93239.60c 4.38786E-08  94239.50c 7.55627E-07  94240.50c 4.20562E-07
      94241.50c 2.31607E-07  94242.50c 1.13098E-07  93237.50c 4.87981E-08
      54135.50c 1.45254E-10  36083.50c 3.47938E-08  42095.50c 4.35554E-07
      43099.50c 5.25646E-07  44101.50c 4.70393E-07  44103.50c 4.47606E-08
      45103.50c 2.37393E-07  45105.50c 1.29214E-09  46105.50c 1.72411E-07
      46108.50c 5.87232E-08  47109.50c 3.17411E-08  48000.50c 3.97908E-11
      54131.50c 2.23916E-07  55133.50c 5.61031E-07  55134.60c 3.20195E-08
      59141.50c 5.14248E-07  60143.50c 3.68262E-07  60145.50c 3.18748E-07
      61147.50c 1.18396E-07  61148.50c 1.16396E-09  62147.50c 2.46152E-08
      61149.50c 1.32872E-09  62149.50c 1.11393E-09  62150.50c 1.15756E-07
      62151.50c 5.86378E-09  62152.50c 5.67334E-08  63153.50c 3.75995E-08
      63154.50c 7.09158E-09  63155.50c 2.32576E-09  64155.50c 2.74284E-11
      64156.50c 1.26482E-08  64157.50c 2.14518E-11   5010.50c 1.89435E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  24; total N =  7.3387212E-01
M123  92235.50c 7.45706E-06  92236.50c 1.37352E-06  92238.50c 1.81668E-04
      93239.60c 4.96643E-08  94239.50c 7.68056E-07  94240.50c 4.26548E-07
      94241.50c 2.37663E-07  94242.50c 1.17079E-07  93237.50c 5.02924E-08
      54135.50c 1.51179E-10  36083.50c 3.54035E-08  42095.50c 4.42377E-07
      43099.50c 5.36202E-07  44101.50c 4.80240E-07  44103.50c 4.74859E-08
      45103.50c 2.39936E-07  45105.50c 1.44297E-09  46105.50c 1.76422E-07
      46108.50c 6.03505E-08  47109.50c 3.25803E-08  48000.50c 4.09757E-11
      54131.50c 2.27033E-07  55133.50c 5.70574E-07  55134.60c 3.31077E-08
      59141.50c 5.24783E-07  60143.50c 3.72188E-07  60145.50c 3.25032E-07
      61147.50c 1.20348E-07  61148.50c 1.24776E-09  62147.50c 2.50523E-08
      61149.50c 1.50827E-09  62149.50c 1.22452E-09  62150.50c 1.18100E-07
      62151.50c 5.97424E-09  62152.50c 5.78127E-08  63153.50c 3.86146E-08
      63154.50c 7.33723E-09  63155.50c 2.40181E-09  64155.50c 2.43773E-11
      64156.50c 1.30644E-08  64157.50c 2.32701E-11   5010.50c 1.87163E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  25; total N =  7.3387319E-01
M124  92235.50c 7.30502E-06  92236.50c 1.39768E-06  92238.50c 1.81567E-04
      93239.60c 5.17432E-08  94239.50c 7.81923E-07  94240.50c 4.33275E-07
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      94241.50c 2.44086E-07  94242.50c 1.21277E-07  93237.50c 5.18116E-08
      54135.50c 1.55356E-10  36083.50c 3.60103E-08  42095.50c 4.49448E-07
      43099.50c 5.46867E-07  44101.50c 4.90231E-07  44103.50c 5.01044E-08
      45103.50c 2.42670E-07  45105.50c 1.50259E-09  46105.50c 1.80675E-07
      46108.50c 6.20657E-08  47109.50c 3.34680E-08  48000.50c 4.22262E-11
      54131.50c 2.30654E-07  55133.50c 5.81171E-07  55134.60c 3.42328E-08
      59141.50c 5.35431E-07  60143.50c 3.76832E-07  60145.50c 3.31359E-07
      61147.50c 1.22286E-07  61148.50c 1.28531E-09  62147.50c 2.54942E-08
      61149.50c 1.57151E-09  62149.50c 1.31254E-09  62150.50c 1.20659E-07
      62151.50c 6.12453E-09  62152.50c 5.88924E-08  63153.50c 3.96618E-08
      63154.50c 7.59077E-09  63155.50c 2.48035E-09  64155.50c 2.35388E-11
      64156.50c 1.34968E-08  64157.50c 2.50492E-11   5010.50c 1.98107E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  26; total N =  7.3387408E-01
M125  92235.50c 7.16216E-06  92236.50c 1.42033E-06  92238.50c 1.81471E-04
      93239.60c 5.04060E-08  94239.50c 7.95376E-07  94240.50c 4.40116E-07
      94241.50c 2.50649E-07  94242.50c 1.25466E-07  93237.50c 5.32558E-08
      54135.50c 1.57764E-10  36083.50c 3.65826E-08  42095.50c 4.56765E-07
      43099.50c 5.57082E-07  44101.50c 4.99838E-07  44103.50c 5.22096E-08
      45103.50c 2.45706E-07  45105.50c 1.48395E-09  46105.50c 1.84940E-07
      46108.50c 6.37734E-08  47109.50c 3.43538E-08  48000.50c 4.34203E-11
      54131.50c 2.34599E-07  55133.50c 5.92147E-07  55134.60c 3.53183E-08
      59141.50c 5.45629E-07  60143.50c 3.82100E-07  60145.50c 3.37397E-07
      61147.50c 1.24085E-07  61148.50c 1.28396E-09  62147.50c 2.59484E-08
      61149.50c 1.53772E-09  62149.50c 1.38410E-09  62150.50c 1.23249E-07
      62151.50c 6.29082E-09  62152.50c 5.99308E-08  63153.50c 4.06815E-08
      63154.50c 7.83642E-09  63155.50c 2.55623E-09  64155.50c 2.43285E-11
      64156.50c 1.39243E-08  64157.50c 2.66539E-11   5010.50c 2.19848E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  27; total N =  7.3387527E-01
M126  92235.50c 7.03337E-06  92236.50c 1.44069E-06  92238.50c 1.81381E-04
      93239.60c 4.71475E-08  94239.50c 8.07961E-07  94240.50c 4.46604E-07
      94241.50c 2.57020E-07  94242.50c 1.29447E-07  93237.50c 5.45896E-08
      54135.50c 1.58511E-10  36083.50c 3.70995E-08  42095.50c 4.64279E-07
      43099.50c 5.66441E-07  44101.50c 5.08675E-07  44103.50c 5.35403E-08
      45103.50c 2.49091E-07  45105.50c 1.40195E-09  46105.50c 1.89026E-07
      46108.50c 6.53920E-08  47109.50c 3.51936E-08  48000.50c 4.45192E-11
      54131.50c 2.38650E-07  55133.50c 6.02901E-07  55134.60c 3.63214E-08
      59141.50c 5.54980E-07  60143.50c 3.87797E-07  60145.50c 3.42914E-07
      61147.50c 1.25648E-07  61148.50c 1.26342E-09  62147.50c 2.64188E-08
      61149.50c 1.43137E-09  62149.50c 1.44446E-09  62150.50c 1.25719E-07
      62151.50c 6.45777E-09  62152.50c 6.08851E-08  63153.50c 4.16353E-08
      63154.50c 8.06583E-09  63155.50c 2.62593E-09  64155.50c 2.63789E-11
      64156.50c 1.43287E-08  64157.50c 2.81046E-11   5010.50c 2.53002E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  28; total N =  7.3387587E-01
M127  92235.50c 6.92228E-06  92236.50c 1.45821E-06  92238.50c 1.81300E-04
      93239.60c 4.28177E-08  94239.50c 8.20965E-07  94240.50c 4.52414E-07
      94241.50c 2.62798E-07  94242.50c 1.33023E-07  93237.50c 5.58087E-08
      54135.50c 1.57136E-10  36083.50c 3.75452E-08  42095.50c 4.71920E-07
      43099.50c 5.74606E-07  44101.50c 5.16423E-07  44103.50c 5.39082E-08
      45103.50c 2.52842E-07  45105.50c 1.26208E-09  46105.50c 1.92764E-07
      46108.50c 6.68451E-08  47109.50c 3.59458E-08  48000.50c 4.54940E-11
      54131.50c 2.42603E-07  55133.50c 6.12940E-07  55134.60c 3.72130E-08
      59141.50c 5.63159E-07  60143.50c 3.93713E-07  60145.50c 3.47718E-07
      61147.50c 1.26888E-07  61148.50c 1.23619E-09  62147.50c 2.69067E-08
      61149.50c 1.26772E-09  62149.50c 1.50098E-09  62150.50c 1.27950E-07
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      62151.50c 6.61658E-09  62152.50c 6.17111E-08  63153.50c 4.24936E-08
      63154.50c 8.27412E-09  63155.50c 2.68674E-09  64155.50c 2.96326E-11
      64156.50c 1.46931E-08  64157.50c 2.93847E-11   5010.50c 3.03030E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  29; total N =  7.3387688E-01
M128  92235.50c 6.82638E-06  92236.50c 1.47328E-06  92238.50c 1.81227E-04
      93239.60c 3.83949E-08  94239.50c 8.34114E-07  94240.50c 4.57764E-07
      94241.50c 2.67497E-07  94242.50c 1.36187E-07  93237.50c 5.69345E-08
      54135.50c 1.52189E-10  36083.50c 3.79278E-08  42095.50c 4.79601E-07
      43099.50c 5.81687E-07  44101.50c 5.23170E-07  44103.50c 5.34617E-08
      45103.50c 2.56877E-07  45105.50c 1.11900E-09  46105.50c 1.96101E-07
      46108.50c 6.81285E-08  47109.50c 3.66072E-08  48000.50c 4.60232E-11
      54131.50c 2.46288E-07  55133.50c 6.21971E-07  55134.60c 3.79983E-08
      59141.50c 5.70276E-07  60143.50c 3.99548E-07  60145.50c 3.51881E-07
      61147.50c 1.27840E-07  61148.50c 1.20939E-09  62147.50c 2.74100E-08
      61149.50c 1.10509E-09  62149.50c 1.51442E-09  62150.50c 1.29942E-07
      62151.50c 6.74413E-09  62152.50c 6.24315E-08  63153.50c 4.32592E-08
      63154.50c 8.46390E-09  63155.50c 2.73814E-09  64155.50c 3.34629E-11
      64156.50c 1.50193E-08  64157.50c 2.97751E-11   5010.50c 3.61695E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  30; total N =  7.3387718E-01
M129  92235.50c 6.74810E-06  92236.50c 1.48553E-06  92238.50c 1.81169E-04
      93239.60c 3.11881E-08  94239.50c 8.45678E-07  94240.50c 4.62299E-07
      94241.50c 2.71325E-07  94242.50c 1.38858E-07  93237.50c 5.78279E-08
      54135.50c 1.45442E-10  36083.50c 3.82399E-08  42095.50c 4.87267E-07
      43099.50c 5.87538E-07  44101.50c 5.28753E-07  44103.50c 5.21475E-08
      45103.50c 2.61147E-07  45105.50c 9.42580E-10  46105.50c 1.98972E-07
      46108.50c 6.92075E-08  47109.50c 3.71637E-08  48000.50c 4.64230E-11
      54131.50c 2.49675E-07  55133.50c 6.29912E-07  55134.60c 3.85977E-08
      59141.50c 5.76148E-07  60143.50c 4.05190E-07  60145.50c 3.55313E-07
      61147.50c 1.28525E-07  61148.50c 1.13185E-09  62147.50c 2.79356E-08
      61149.50c 9.11300E-10  62149.50c 1.53931E-09  62150.50c 1.31623E-07
      62151.50c 6.84761E-09  62152.50c 6.30500E-08  63153.50c 4.38884E-08
      63154.50c 8.61767E-09  63155.50c 2.77722E-09  64155.50c 3.84686E-11
      64156.50c 1.52960E-08  64157.50c 2.99803E-11   5010.50c 4.52713E-07
      14000.50c 4.51608E-04   6000.50c 8.62698E-02   8016.50c 4.02897E-04
C     VSOP cycle  261; layer  31; total N =  7.3386890E-01
M130  92235.50c 7.95784E-06  92236.50c 1.29400E-06  92238.50c 1.81972E-04
      93239.60c 1.30156E-08  94239.50c 7.38860E-07  94240.50c 4.10613E-07
      94241.50c 2.19301E-07  94242.50c 1.05022E-07  93237.50c 4.55680E-08
      54135.50c 9.95483E-11  36083.50c 3.34266E-08  42095.50c 4.15744E-07
      43099.50c 5.02505E-07  44101.50c 4.48954E-07  44103.50c 4.23158E-08
      45103.50c 2.28409E-07  45105.50c 3.72010E-10  46105.50c 1.64438E-07
      46108.50c 5.54194E-08  47109.50c 3.00518E-08  48000.50c 3.86044E-11
      54131.50c 2.17270E-07  55133.50c 5.42119E-07  55134.60c 2.98526E-08
      59141.50c 4.91161E-07  60143.50c 3.58091E-07  60145.50c 3.04888E-07
      61147.50c 1.14426E-07  61148.50c 7.79751E-10  62147.50c 2.32328E-08
      61149.50c 4.07308E-10  62149.50c 1.42529E-09  62150.50c 1.10877E-07
      62151.50c 5.91914E-09  62152.50c 5.42189E-08  63153.50c 3.54559E-08
      63154.50c 6.57526E-09  63155.50c 2.17664E-09  64155.50c 4.04506E-11
      64156.50c 1.17617E-08  64157.50c 2.02350E-11   5010.50c 1.02196E-06
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  32; total N =  7.3386949E-01
M131  92235.50c 7.89054E-06  92236.50c 1.30466E-06  92238.50c 1.81932E-04
      93239.60c 1.94107E-08  94239.50c 7.44059E-07  94240.50c 4.12145E-07
      94241.50c 2.21497E-07  94242.50c 1.06481E-07  93237.50c 4.62194E-08
      54135.50c 1.18389E-10  36083.50c 3.36888E-08  42095.50c 4.22352E-07
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      43099.50c 5.06893E-07  44101.50c 4.53014E-07  44103.50c 4.07592E-08
      45103.50c 2.32123E-07  45105.50c 5.66357E-10  46105.50c 1.65934E-07
      46108.50c 5.60195E-08  47109.50c 3.03559E-08  48000.50c 3.85240E-11
      54131.50c 2.19236E-07  55133.50c 5.46605E-07  55134.60c 3.02034E-08
      59141.50c 4.95554E-07  60143.50c 3.61904E-07  60145.50c 3.07526E-07
      61147.50c 1.14936E-07  61148.50c 8.31214E-10  62147.50c 2.37249E-08
      61149.50c 5.54093E-10  62149.50c 1.14758E-09  62150.50c 1.12013E-07
      62151.50c 5.87844E-09  62152.50c 5.47091E-08  63153.50c 3.58648E-08
      63154.50c 6.67396E-09  63155.50c 2.19894E-09  64155.50c 4.14735E-11
      64156.50c 1.19296E-08  64157.50c 1.91623E-11   5010.50c 6.38926E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  33; total N =  7.3387033E-01
M132  92235.50c 7.79111E-06  92236.50c 1.32046E-06  92238.50c 1.81872E-04
      93239.60c 2.91607E-08  94239.50c 7.49575E-07  94240.50c 4.14962E-07
      94241.50c 2.24926E-07  94242.50c 1.08736E-07  93237.50c 4.71663E-08
      54135.50c 1.32890E-10  36083.50c 3.40799E-08  42095.50c 4.28812E-07
      43099.50c 5.13478E-07  44101.50c 4.59113E-07  44103.50c 4.09344E-08
      45103.50c 2.35202E-07  45105.50c 8.61470E-10  46105.50c 1.68184E-07
      46108.50c 5.69485E-08  47109.50c 3.08304E-08  48000.50c 3.89208E-11
      54131.50c 2.21113E-07  55133.50c 5.51817E-07  55134.60c 3.08054E-08
      59141.50c 5.02132E-07  60143.50c 3.65034E-07  60145.50c 3.11475E-07
      61147.50c 1.15983E-07  61148.50c 9.61226E-10  62147.50c 2.41946E-08
      61149.50c 8.48215E-10  62149.50c 1.04086E-09  62150.50c 1.13365E-07
      62151.50c 5.85293E-09  62152.50c 5.54238E-08  63153.50c 3.64771E-08
      63154.50c 6.82219E-09  63155.50c 2.24005E-09  64155.50c 3.72441E-11
      64156.50c 1.21817E-08  64157.50c 1.98974E-11   5010.50c 4.34333E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  34; total N =  7.3387110E-01
M133  92235.50c 7.66166E-06  92236.50c 1.34106E-06  92238.50c 1.81793E-04
      93239.60c 3.91538E-08  94239.50c 7.56543E-07  94240.50c 4.19329E-07
      94241.50c 2.29716E-07  94242.50c 1.11850E-07  93237.50c 4.83831E-08
      54135.50c 1.43384E-10  36083.50c 3.45929E-08  42095.50c 4.35279E-07
      43099.50c 5.22211E-07  44101.50c 4.67216E-07  44103.50c 4.26626E-08
      45103.50c 2.37806E-07  45105.50c 1.16131E-09  46105.50c 1.71282E-07
      46108.50c 5.82290E-08  47109.50c 3.14900E-08  48000.50c 3.97754E-11
      54131.50c 2.23329E-07  55133.50c 5.58679E-07  55134.60c 3.16503E-08
      59141.50c 5.10838E-07  60143.50c 3.68069E-07  60145.50c 3.16692E-07
      61147.50c 1.17549E-07  61148.50c 1.09568E-09  62147.50c 2.46446E-08
      61149.50c 1.17169E-09  62149.50c 1.09395E-09  62150.50c 1.15087E-07
      62151.50c 5.87688E-09  62152.50c 5.63468E-08  63153.50c 3.72914E-08
      63154.50c 7.01851E-09  63155.50c 2.29979E-09  64155.50c 3.12483E-11
      64156.50c 1.25176E-08  64157.50c 2.14284E-11   5010.50c 3.38636E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  35; total N =  7.3387200E-01
M134  92235.50c 7.52227E-06  92236.50c 1.36325E-06  92238.50c 1.81705E-04
      93239.60c 4.47900E-08  94239.50c 7.67610E-07  94240.50c 4.24787E-07
      94241.50c 2.35221E-07  94242.50c 1.15409E-07  93237.50c 4.97251E-08
      54135.50c 1.49654E-10  36083.50c 3.51483E-08  42095.50c 4.41895E-07
      43099.50c 5.31783E-07  44101.50c 4.76133E-07  44103.50c 4.48916E-08
      45103.50c 2.40352E-07  45105.50c 1.31023E-09  46105.50c 1.74923E-07
      46108.50c 5.96923E-08  47109.50c 3.22469E-08  48000.50c 4.08998E-11
      54131.50c 2.26111E-07  55133.50c 5.67208E-07  55134.60c 3.26105E-08
      59141.50c 5.20384E-07  60143.50c 3.71645E-07  60145.50c 3.22392E-07
      61147.50c 1.19288E-07  61148.50c 1.17972E-09  62147.50c 2.50896E-08
      61149.50c 1.34606E-09  62149.50c 1.20655E-09  62150.50c 1.17159E-07
      62151.50c 5.97319E-09  62152.50c 5.73313E-08  63153.50c 3.82027E-08
      63154.50c 7.23820E-09  63155.50c 2.36798E-09  64155.50c 2.75784E-11
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      64156.50c 1.28919E-08  64157.50c 2.32032E-11   5010.50c 3.21087E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  36; total N =  7.3387271E-01
M135  92235.50c 7.38410E-06  92236.50c 1.38524E-06  92238.50c 1.81613E-04
      93239.60c 4.68565E-08  94239.50c 7.80760E-07  94240.50c 4.30895E-07
      94241.50c 2.41050E-07  94242.50c 1.19145E-07  93237.50c 5.10959E-08
      54135.50c 1.53859E-10  36083.50c 3.57012E-08  42095.50c 4.48707E-07
      43099.50c 5.41441E-07  44101.50c 4.85166E-07  44103.50c 4.70362E-08
      45103.50c 2.43051E-07  45105.50c 1.36187E-09  46105.50c 1.78787E-07
      46108.50c 6.12289E-08  47109.50c 3.30441E-08  48000.50c 4.21095E-11
      54131.50c 2.29371E-07  55133.50c 5.76763E-07  55134.60c 3.36046E-08
      59141.50c 5.30021E-07  60143.50c 3.75883E-07  60145.50c 3.28123E-07
      61147.50c 1.21010E-07  61148.50c 1.21974E-09  62147.50c 2.55386E-08
      61149.50c 1.40255E-09  62149.50c 1.30066E-09  62150.50c 1.19433E-07
      62151.50c 6.11060E-09  62152.50c 5.83096E-08  63153.50c 3.91428E-08
      63154.50c 7.46509E-09  63155.50c 2.43846E-09  64155.50c 2.63211E-11
      64156.50c 1.32786E-08  64157.50c 2.49625E-11   5010.50c 3.30937E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  37; total N =  7.338737?E-01
M136  92235.50c 7.25620E-06  92236.50c 1.40557E-06  92238.50c 1.81526E-04
      93239.60c 4.55264E-08  94239.50c 7.94893E-07  94240.50c 4.37026E-07
      94241.50c 2.46886E-07  94242.50c 1.22791E-07  93237.50c 5.24010E-08
      54135.50c 1.55966E-10  36083.50c 3.62147E-08  42095.50c 4.55712E-07
      43099.50c 5.50532E-07  44101.50c 4.93704E-07  44103.50c 4.86235E-08
      45103.50c 2.46038E-07  45105.50c 1.32320E-09  46105.50c 1.82616E-07
      46108.50c 6.27291E-08  47109.50c 3.38241E-08  48000.50c 4.32978E-11
      54131.50c 2.32927E-07  55133.50c 5.86642E-07  55134.60c 3.45529E-08
      59141.50c 5.39099E-07  60143.50c 3.80720E-07  60145.50c 3.33502E-07
      61147.50c 1.22561E-07  61148.50c 1.22122E-09  62147.50c 2.59994E-08
      61149.50c 1.35257E-09  62149.50c 1.38240E-09  62150.50c 1.21712E-07
      62151.50c 6.26729E-09  62152.50c 5.92256E-08  63153.50c 4.00467E-08
      63154.50c 7.68310E-09  63155.50c 2.50558E-09  64155.50c 2.70821E-11
      64156.50c 1.36529E-08  64157.50c 2.66039E-11   5010.50c 3.64676E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  38; total N =  7.3387462E-01
M137  92235.50c 7.14163E-06  92236.50c 1.42374E-06  92238.50c 1.81445E-04
      93239.60c 4.23959E-08  94239.50c 8.08409E-07  94240.50c 4.42846E-07
      94241.50c 2.52502E-07  94242.50c 1.26216E-07  93237.50c 5.36013E-08
      54135.50c 1.56410E-10  36083.50c 3.66759E-08  42095.50c 4.62861E-07
      43099.50c 5.58802E-07  44101.50c 5.01499E-07  44103.50c 4.95057E-08
      45103.50c 2.49325E-07  45105.50c 1.23902E-09  46105.50c 1.86245E-07
      46108.50c 6.41381E-08  47109.50c 3.45577E-08  48000.50c 4.43995E-11
      54131.50c 2.36561E-07  55133.50c 5.96250E-07  55134.60c 3.54192E-08
      59141.50c 5.47363E-07  60143.50c 3.85928E-07  60145.50c 3.38382E-07
      61147.50c 1.23890E-07  61148.50c 1.20010E-09  62147.50c 2.64749E-08
      61149.50c 1.24750E-09  62149.50c 1.44430E-09  62150.50c 1.23871E-07
      62151.50c 6.42279E-09  62152.50c 6.00591E-08  63153.50c 4.08850E-08
      63154.50c 7.88508E-09  63155.50c 2.56677E-09  64155.50c 2.92424E-11
      64156.50c 1.40032E-08  64157.50c 2.80712E-11   5010.50c 4.14416E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  39; total N =  7.3387557E-01
M138  92235.50c 7.04327E-06  92236.50c 1.43931E-06  92238.50c 1.81372E-04
      93239.60c 3.87064E-08  94239.50c 8.22685E-07  94240.50c 4.48072E-07
      94241.50c 2.57546E-07  94242.50c 1.29254E-07  93237.50c 5.47132E-08
      54135.50c 1.54663E-10  36083.50c 3.70716E-08  42095.50c 4.70087E-07
      43099.50c 5.65964E-07  44101.50c 5.08287E-07  44103.50c 4.95328E-08
      45103.50c 2.52919E-07  45105.50c 1.10611E-09  46105.50c 1.89538E-07
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      46108.50c 6.53921E-08  47109.50c 3.52084E-08  48000.50c 4.53997E-11
      54131.50c 2.40078E-07  55133.50c 6.05149E-07  55134.60c 3.61897E-08
      59141.50c 5.54548E-07  60143.50c 3.91304E-07  60145.50c 3.42602E-07
      61147.50c 1.24912E-07  61148.50c 1.17793E-09  62147.50c 2.69654E-08
      61149.50c 1.09673E-09  62149.50c 1.50319E-09  62150.50c 1.25805E-07
      62151.50c 6.57235E-09  62152.50c 6.07670E-08  63153.50c 4.16385E-08
      63154.50c 8.06911E-09  63155.50c 2.61998E-09  64155.50c 3.27166E-11
      64156.50c 1.43158E-08  64157.50c 2.94118E-11   5010.50c 4.91822E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  40; total N =  7.3387623E-01
M139  92235.50c 6.95690E-06  92236.50c 1.45294E-06  92238.50c 1.81304E-04
      93239.60c 3.57331E-08  94239.50c 8.37367E-07  94240.50c 4.52993E-07
      94241.50c 2.61710E-07  94242.50c 1.31964E-07  93237.50c 5.57827E-08
      54135.50c 1.50142E-10  36083.50c 3.74170E-08  42095.50c 4.77309E-07
      43099.50c 5.72263E-07  44101.50c 5.14287E-07  44103.50c 4.89498E-08
      45103.50c 2.56708E-07  45105.50c 9.92255E-10  46105.50c 1.92492E-07
      46108.50c 6.65142E-08  47109.50c 3.57871E-08  48000.50c 4.60065E-11
      54131.50c 2.43322E-07  55133.50c 6.13124E-07  55134.60c 3.68918E-08
      59141.50c 5.60897E-07  60143.50c 3.96552E-07  60145.50c 3.46313E-07
      61147.50c 1.25691E-07  61148.50c 1.16711E-09  62147.50c 2.74667E-08
      61149.50c 9.69282E-10  62149.50c 1.51357E-09  62150.50c 1.27546E-07
      62151.50c 6.69464E-09  62152.50c 6.13822E-08  63153.50c 4.23271E-08
      63154.50c 8.24200E-09  63155.50c 2.66629E-09  64155.50c 3.66254E-11
      64156.50c 1.45990E-08  64157.50c 2.99384E-11   5010.50c 5.70871E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  41; total N =  7.3387641E-01
M140  92235.50c 6.88377E-06  92236.50c 1.46445E-06  92238.50c 1.81243E-04
      93239.60c 3.20549E-08  94239.50c 8.53041E-07  94240.50c 4.57359E-07
      94241.50c 2.65177E-07  94242.50c 1.34287E-07  93237.50c 5.67680E-08
      54135.50c 1.44873E-10  36083.50c 3.77081E-08  42095.50c 4.84479E-07
      43099.50c 5.77605E-07  44101.50c 5.19405E-07  44103.50c 4.77422E-08
      45103.50c 2.60648E-07  45105.50c 8.60436E-10  46105.50c 1.95088E-07
      46108.50c 6.74834E-08  47109.50c 3.62835E-08  48000.50c 4.65875E-11
      54131.50c 2.46260E-07  55133.50c 6.20159E-07  55134.60c 3.74986E-08
      59141.50c 5.66312E-07  60143.50c 4.01590E-07  60145.50c 3.49462E-07
      61147.50c 1.26219E-07  61148.50c 1.14553E-09  62147.50c 2.79805E-08
      61149.50c 8.30193E-10  62149.50c 1.53931E-09  62150.50c 1.29042E-07
      62151.50c 6.80391E-09  62152.50c 6.18917E-08  63153.50c 4.29347E-08
      63154.50c 8.39758E-09  63155.50c 2.70497E-09  64155.50c 4.14543E-11
      64156.50c 1.48462E-08  64157.50c 3.05374E-11   5010.50c 6.86703E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
C     VSOP cycle  261; layer  42; total N =  7.3387688E-01
M141  92235.50c 6.81897E-06  92236.50c 1.47460E-06  92238.50c 1.81193E-04
      93239.60c 2.67857E-08  94239.50c 8.64018E-07  94240.50c 4.61407E-07
      94241.50c 2.68296E-07  94242.50c 1.36432E-07  93237.50c 5.75571E-08
      54135.50c 1.40026E-10  36083.50c 3.79672E-08  42095.50c 4.91555E-07
      43099.50c 5.82431E-07  44101.50c 5.24012E-07  44103.50c 4.62658E-08
      45103.50c 2.64576E-07  45105.50c 7.79061E-10  46105.50c 1.97421E-07
      46108.50c 6.83703E-08  47109.50c 3.67423E-08  48000.50c 4.69727E-11
      54131.50c 2.48920E-07  55133.50c 6.26377E-07  55134.60c 3.79784E-08
      59141.50c 5.71167E-07  60143.50c 4.06231E-07  60145.50c 3.52294E-07
      61147.50c 1.26675E-07  61148.50c 1.07283E-09  62147.50c 2.85089E-08
      61149.50c 7.32365E-10  62149.50c 1.52444E-09  62150.50c 1.30394E-07
      62151.50c 6.88161E-09  62152.50c 6.23904E-08  63153.50c 4.34604E-08
      63154.50c 8.52799E-09  63155.50c 2.73681E-09  64155.50c 4.64021E-11
      64156.50c 1.50734E-08  64157.50c 3.06447E-11   5010.50c 7.80534E-07
      14000.50c 4.51608E-04   6000.50c 8.62699E-02   8016.50c 4.02898E-04
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C    VSOP cycle  261; layer  43; total N =  7.3386949E-01
M142 92235.50c 7.96081E-06  92236.50c 1.29351E-06  92238.50c 1.81976E-04
     93239.60c 1.14867E-08  94239.50c 7.38087E-07  94240.50c 4.10558E-07
     94241.50c 2.19214E-07  94242.50c 1.04974E-07  93237.50c 4.55050E-08
     54135.50c 9.64301E-11  36083.50c 3.34155E-08  42095.50c 4.15753E-07
     43099.50c 5.02334E-07  44101.50c 4.48790E-07  44103.50c 4.21914E-08
     45103.50c 2.28444E-07  45105.50c 3.49003E-10  46105.50c 1.64395E-07
     46108.50c 5.53074E-08  47109.50c 3.00415E-08  48000.50c 3.85692E-11
     54131.50c 2.17288E-07  55133.50c 5.42090E-07  55134.60c 2.98148E-08
     59141.50c 4.90979E-07  60143.50c 3.58125E-07  60145.50c 3.04782E-07
     61147.50c 1.14399E-07  61148.50c 7.54282E-10  62147.50c 2.32366E-08
     61149.50c 3.84678E-10  62149.50c 1.44707E-09  62150.50c 1.10837E-07
     62151.50c 5.92073E-09  62152.50c 5.42101E-08  63153.50c 3.54320E-08
     63154.50c 6.56764E-09  63155.50c 2.17456E-09  64155.50c 4.09186E-11
     64156.50c 1.17553E-08  64157.50c 2.02249E-11   5010.50c 1.52667E-06
     14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C    VSOP cycle  261; layer  44; total N =  7.3387003E-01
M143 92235.50c 7.89734E-06  92236.50c 1.30352E-06  92238.50c 1.81942E-04
     93239.60c 1.63352E-08  94239.50c 7.39970E-07  94240.50c 4.11974E-07
     94241.50c 2.21316E-07  94242.50c 1.06382E-07  93237.50c 4.60328E-08
     54135.50c 1.15787E-10  36083.50c 3.36639E-08  42095.50c 4.22364E-07
     43099.50c 5.06516E-07  44101.50c 4.52643E-07  44103.50c 4.04887E-08
     45103.50c 2.32187E-07  45105.50c 5.35559E-10  46105.50c 1.65815E-07
     46108.50c 5.59695E-08  47109.50c 3.03336E-08  48000.50c 3.83648E-11
     54131.50c 2.19261E-07  55133.50c 5.46469E-07  55134.60c 3.00971E-08
     59141.50c 4.95135E-07  60143.50c 3.61934E-07  60145.50c 3.07292E-07
     61147.50c 1.14898E-07  61148.50c 7.71997E-10  62147.50c 2.37356E-08
     61149.50c 5.17855E-10  62149.50c 1.15402E-09  62150.50c 1.11945E-07
     62151.50c 5.87271E-09  62152.50c 5.47042E-08  63153.50c 3.58006E-08
     63154.50c 6.65241E-09  63155.50c 2.19342E-09  64155.50c 4.23714E-11
     64156.50c 1.19153E-08  64157.50c 1.88690E-11   5010.50c 9.31666E-07
     14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C    VSOP cycle  261; layer  45; total N =  7.3387092E-01
M144 92235.50c 7.79701E-06  92236.50c 1.31937E-06  92238.50c 1.81890E-04
     93239.60c 2.51573E-08  94239.50c 7.38146E-07  94240.50c 4.14655E-07
     94241.50c 2.24865E-07  94242.50c 1.08722E-07  93237.50c 4.68062E-08
     54135.50c 1.31730E-10  36083.50c 3.40606E-08  42095.50c 4.28823E-07
     43099.50c 5.13242E-07  44101.50c 4.58833E-07  44103.50c 4.07508E-08
     45103.50c 2.35210E-07  45105.50c 8.67029E-10  46105.50c 1.68062E-07
     46108.50c 5.69152E-08  47109.50c 3.08220E-08  48000.50c 3.85391E-11
     54131.50c 2.21156E-07  55133.50c 5.51640E-07  55134.60c 3.06236E-08
     59141.50c 5.01790E-07  60143.50c 3.64956E-07  60145.50c 3.11313E-07
     61147.50c 1.16060E-07  61148.50c 8.77266E-10  62147.50c 2.42129E-08
     61149.50c 8.37070E-10  62149.50c 1.00759E-09  62150.50c 1.13309E-07
     62151.50c 5.82328E-09  62152.50c 5.54892E-08  63153.50c 3.63802E-08
     63154.50c 6.78475E-09  63155.50c 2.23189E-09  64155.50c 3.74280E-11
     64156.50c 1.21717E-08  64157.50c 1.93149E-11   5010.50c 5.84666E-07
     14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C    VSOP cycle  261; layer  46; total N =  7.3387158E-01
M145 92235.50c 7.66426E-06  92236.50c 1.34039E-06  92238.50c 1.81821E-04
     93239.60c 3.38866E-08  94239.50c 7.35074E-07  94240.50c 4.18650E-07
     94241.50c 2.29895E-07  94242.50c 1.12018E-07  93237.50c 4.77867E-08
     54135.50c 1.41762E-10  36083.50c 3.45886E-08  42095.50c 4.35309E-07
     43099.50c 5.22293E-07  44101.50c 4.67174E-07  44103.50c 4.26552E-08
     45103.50c 2.37723E-07  45105.50c 1.18108E-09  46105.50c 1.71220E-07
     46108.50c 5.82322E-08  47109.50c 3.15073E-08  48000.50c 3.91103E-11
     54131.50c 2.23462E-07  55133.50c 5.58657E-07  55134.60c 3.13734E-08
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      59141.50c 5.10724E-07  60143.50c 3.67885E-07  60145.50c 3.16706E-07
      61147.50c 1.17819E-07  61148.50c 9.91194E-10  62147.50c 2.46732E-08
      61149.50c 1.17000E-09  62149.50c 1.05104E-09  62150.50c 1.15043E-07
      62151.50c 5.82256E-09  62152.50c 5.65228E-08  63153.50c 3.71585E-08
      63154.50c 6.96068E-09  63155.50c 2.28802E-09  64155.50c 3.06776E-11
      64156.50c 1.25181E-08  64157.50c 2.06128E-11   5010.50c 4.43221E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  47; total N =  7.3387271E-01
M146 92235.50c 7.52146E-06  92236.50c 1.36301E-06  92238.50c 1.81745E-04
      93239.60c 3.85415E-08  94239.50c 7.34906E-07  94240.50c 4.23337E-07
      94241.50c 2.35631E-07  94242.50c 1.15793E-07  93237.50c 4.88547E-08
      54135.50c 1.47182E-10  36083.50c 3.51579E-08  42095.50c 4.41964E-07
      43099.50c 5.32177E-07  44101.50c 4.76313E-07  44103.50c 4.50151E-08
      45103.50c 2.40185E-07  45105.50c 1.32196E-09  46105.50c 1.74918E-07
      46108.50c 5.97241E-08  47109.50c 3.22856E-08  48000.50c 3.99087E-11
      54131.50c 2.26394E-07  55133.50c 5.67470E-07  55134.60c 3.22229E-08
      59141.50c 5.20479E-07  60143.50c 3.71410E-07  60145.50c 3.22578E-07
      61147.50c 1.19759E-07  61148.50c 1.06137E-09  62147.50c 2.51312E-08
      61149.50c 1.33691E-09  62149.50c 1.15469E-09  62150.50c 1.17124E-07
      62151.50c 5.89569E-09  62152.50c 5.76233E-08  63153.50c 3.80262E-08
      63154.50c 7.15630E-09  63155.50c 2.35070E-09  64155.50c 2.66673E-11
      64156.50c 1.29024E-08  64157.50c 2.21267E-11   5010.50c 4.15580E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  48; total N =  7.3387343E-01
M147 92235.50c 7.38139E-06  92236.50c 1.38519E-06  92238.50c 1.81668E-04
      93239.60c 3.97078E-08  94239.50c 7.36829E-07  94240.50c 4.28232E-07
      94241.50c 2.41582E-07  94242.50c 1.19722E-07  93237.50c 4.99223E-08
      54135.50c 1.50345E-10  36083.50c 3.57167E-08  42095.50c 4.48833E-07
      43099.50c 5.42011E-07  44101.50c 4.85439E-07  44103.50c 4.71642E-08
      45103.50c 2.42830E-07  45105.50c 1.35072E-09  46105.50c 1.78786E-07
      46108.50c 6.12616E-08  47109.50c 3.30887E-08  48000.50c 4.07647E-11
      54131.50c 2.29828E-07  55133.50c 5.77318E-07  55134.60c 3.30882E-08
      59141.50c 5.30190E-07  60143.50c 3.75653E-07  60145.50c 3.28403E-07
      61147.50c 1.21650E-07  61148.50c 1.08923E-09  62147.50c 2.55960E-08
      61149.50c 1.37303E-09  62149.50c 1.23973E-09  62150.50c 1.19381E-07
      62151.50c 6.00942E-09  62152.50c 5.87039E-08  63153.50c 3.89097E-08
      63154.50c 7.35503E-09  63155.50c 2.41332E-09  64155.50c 2.53709E-11
      64156.50c 1.32941E-08  64157.50c 2.35903E-11   5010.50c 4.27688E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  49; total N =  7.3387438E-01
M148 92235.50c 7.25217E-06  92236.50c 1.40563E-06  92238.50c 1.81595E-04
      93239.60c 3.81437E-08  94239.50c 7.39978E-07  94240.50c 4.32847E-07
      94241.50c 2.47460E-07  94242.50c 1.23552E-07  93237.50c 5.09222E-08
      54135.50c 1.51614E-10  36083.50c 3.62321E-08  42095.50c 4.55897E-07
      43099.50c 5.51209E-07  44101.50c 4.94002E-07  44103.50c 4.86941E-08
      45103.50c 2.45770E-07  45105.50c 1.29832E-09  46105.50c 1.82571E-07
      46108.50c 6.27458E-08  47109.50c 3.38645E-08  48000.50c 4.15953E-11
      54131.50c 2.33540E-07  55133.50c 5.87420E-07  55134.60c 3.39048E-08
      59141.50c 5.39275E-07  60143.50c 3.80499E-07  60145.50c 3.33837E-07
      61147.50c 1.23349E-07  61148.50c 1.08361E-09  62147.50c 2.60738E-08
      61149.50c 1.31261E-09  62149.50c 1.30810E-09  62150.50c 1.21621E-07
      62151.50c 6.13956E-09  62152.50c 5.97106E-08  63153.50c 3.97532E-08
      63154.50c 7.54396E-09  63155.50c 2.47147E-09  64155.50c 2.60899E-11
      64156.50c 1.36706E-08  64157.50c 2.49215E-11   5010.50c 4.67602E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  50; total N =  7.3387527E-01
M149 92235.50c 7.13774E-06  92236.50c 1.42370E-06  92238.50c 1.81528E-04
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      93239.60c 3.49554E-08  94239.50c 7.43677E-07  94240.50c 4.36945E-07
      94241.50c 2.52983E-07  94242.50c 1.27113E-07  93237.50c 5.18231E-08
      54135.50c 1.51129E-10  36083.50c 3.66882E-08  42095.50c 4.63105E-07
      43099.50c 5.59451E-07  44101.50c 5.01702E-07  44103.50c 4.94245E-08
      45103.50c 2.49026E-07  45105.50c 1.19470E-09  46105.50c 1.86103E-07
      46108.50c 6.41132E-08  47109.50c 3.45792E-08  48000.50c 4.23551E-11
      54131.50c 2.37299E-07  55133.50c 5.97156E-07  55134.60c 3.46357E-08
      59141.50c 5.47423E-07  60143.50c 3.85721E-07  60145.50c 3.38695E-07
      61147.50c 1.24781E-07  61148.50c 1.05705E-09  62147.50c 2.65674E-08
      61149.50c 1.19278E-09  62149.50c 1.36247E-09  62150.50c 1.23712E-07
      62151.50c 6.26929E-09  62152.50c 6.06131E-08  63153.50c 4.05243E-08
      63154.50c 7.71596E-09  63155.50c 2.52269E-09  64155.50c 2.82716E-11
      64156.50c 1.40178E-08  64157.50c 2.60893E-11   5010.50c 5.32385E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  51; total N =  7.3387629E-01
M150  92235.50c 7.03939E-06  92236.50c 1.43921E-06  92238.50c 1.81470E-04
      93239.60c 3.10435E-08  94239.50c 7.47811E-07  94240.50c 4.40451E-07
      94241.50c 2.57921E-07  94242.50c 1.30297E-07  93237.50c 5.26207E-08
      54135.50c 1.48693E-10  36083.50c 3.70794E-08  42095.50c 4.70382E-07
      43099.50c 5.66601E-07  44101.50c 5.08403E-07  44103.50c 4.93224E-08
      45103.50c 2.52569E-07  45105.50c 1.06164E-09  46105.50c 1.89283E-07
      46108.50c 6.53269E-08  47109.50c 3.52128E-08  48000.50c 4.29961E-11
      54131.50c 2.40914E-07  55133.50c 6.06113E-07  55134.60c 3.52642E-08
      59141.50c 5.54499E-07  60143.50c 3.91070E-07  60145.50c 3.42901E-07
      61147.50c 1.25917E-07  61148.50c 1.01970E-09  62147.50c 2.70772E-08
      61149.50c 1.04296E-09  62149.50c 1.40404E-09  62150.50c 1.25580E-07
      62151.50c 6.38841E-09  62152.50c 6.13967E-08  63153.50c 4.12073E-08
      63154.50c 7.86836E-09  63155.50c 2.56583E-09  64155.50c 3.16065E-11
      64156.50c 1.43276E-08  64157.50c 2.70362E-11   5010.50c 6.24542E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  52; total N =  7.3387671E-01
M151  92235.50c 6.95456E-06  92236.50c 1.45255E-06  92238.50c 1.81415E-04
      93239.60c 2.83670E-08  94239.50c 7.53622E-07  94240.50c 4.43623E-07
      94241.50c 2.61858E-07  94242.50c 1.33087E-07  93237.50c 5.33958E-08
      54135.50c 1.43343E-10  36083.50c 3.74137E-08  42095.50c 4.77644E-07
      43099.50c 5.72756E-07  44101.50c 5.14198E-07  44103.50c 4.85318E-08
      45103.50c 2.56327E-07  45105.50c 9.30825E-10  46105.50c 1.92088E-07
      46108.50c 6.63855E-08  47109.50c 3.57620E-08  48000.50c 4.33112E-11
      54131.50c 2.44225E-07  55133.50c 6.14070E-07  55134.60c 3.58255E-08
      59141.50c 5.60621E-07  60143.50c 3.96292E-07  60145.50c 3.46522E-07
      61147.50c 1.26763E-07  61148.50c 1.00213E-09  62147.50c 2.75981E-08
      61149.50c 9.02556E-10  62149.50c 1.41248E-09  62150.50c 1.27226E-07
      62151.50c 6.48545E-09  62152.50c 6.20629E-08  63153.50c 4.18207E-08
      63154.50c 8.00994E-09  63155.50c 2.60175E-09  64155.50c 3.55335E-11
      64156.50c 1.46022E-08  64157.50c 2.73529E-11   5010.50c 7.33437E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  53; total N =  7.3387688E-01
M152  92235.50c 6.88152E-06  92236.50c 1.46400E-06  92238.50c 1.81366E-04
      93239.60c 2.56954E-08  94239.50c 7.60770E-07  94240.50c 4.46416E-07
      94241.50c 2.65162E-07  94242.50c 1.35526E-07  93237.50c 5.41220E-08
      54135.50c 1.38415E-10  36083.50c 3.76996E-08  42095.50c 4.84834E-07
      43099.50c 5.78060E-07  44101.50c 5.19213E-07  44103.50c 4.72231E-08
      45103.50c 2.60189E-07  45105.50c 8.14958E-10  46105.50c 1.94550E-07
      46108.50c 6.73105E-08  47109.50c 3.62394E-08  48000.50c 4.36265E-11
      54131.50c 2.47190E-07  55133.50c 6.21035E-07  55134.60c 3.63142E-08
      59141.50c 5.65917E-07  60143.50c 4.01237E-07  60145.50c 3.49642E-07
      61147.50c 1.27374E-07  61148.50c 9.81107E-10  62147.50c 2.81295E-08
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      61149.50c 7.79917E-10  62149.50c 1.41852E-09  62150.50c 1.28651E-07
      62151.50c 6.56722E-09  62152.50c 6.26291E-08  63153.50c 4.23673E-08
      63154.50c 8.13865E-09  63155.50c 2.63173E-09  64155.50c 4.00645E-11
      64156.50c 1.48451E-08  64157.50c 2.77366E-11   5010.50c 8.61623E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  54; total N =  7.3387748E-01
M153  92235.50c 6.81504E-06  92236.50c 1.47441E-06  92238.50c 1.81320E-04
      93239.60c 2.39410E-08  94239.50c 7.67331E-07  94240.50c 4.49030E-07
      94241.50c 2.68122E-07  94242.50c 1.37782E-07  93237.50c 5.48161E-08
      54135.50c 1.35115E-10  36083.50c 3.79588E-08  42095.50c 4.91901E-07
      43099.50c 5.82902E-07  44101.50c 5.23805E-07  44103.50c 4.57309E-08
      45103.50c 2.64007E-07  45105.50c 7.50433E-10  46105.50c 1.96788E-07
      46108.50c 6.81658E-08  47109.50c 3.66798E-08  48000.50c 4.39253E-11
      54131.50c 2.49808E-07  55133.50c 6.27161E-07  55134.60c 3.67612E-08
      59141.50c 5.70763E-07  60143.50c 4.05756E-07  60145.50c 3.52489E-07
      61147.50c 1.27860E-07  61148.50c 9.64024E-10  62147.50c 2.86672E-08
      61149.50c 7.06732E-10  62149.50c 1.40105E-09  62150.50c 1.29937E-07
      62151.50c 6.63193E-09  62152.50c 6.31439E-08  63153.50c 4.28767E-08
      63154.50c 8.26005E-09  63155.50c 2.65861E-09  64155.50c 4.45016E-11
      64156.50c 1.50720E-08  64157.50c 2.80756E-11   5010.50c 9.54749E-07
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  55; total N =  7.3387808E-01
M154  92235.50c 6.75430E-06  92236.50c 1.48389E-06  92238.50c 1.81278E-04
      93239.60c 2.18885E-08  94239.50c 7.73157E-07  94240.50c 4.51476E-07
      94241.50c 2.70798E-07  94242.50c 1.39885E-07  93237.50c 5.54506E-08
      54135.50c 1.31652E-10  36083.50c 3.81949E-08  42095.50c 4.98829E-07
      43099.50c 5.87352E-07  44101.50c 5.28028E-07  44103.50c 4.41148E-08
      45103.50c 2.67750E-07  45105.50c 6.94569E-10  46105.50c 1.98862E-07
      46108.50c 6.89601E-08  47109.50c 3.70892E-08  48000.50c 4.41749E-11
      54131.50c 2.52157E-07  55133.50c 6.32674E-07  55134.60c 3.71557E-08
      59141.50c 5.75216E-07  60143.50c 4.09878E-07  60145.50c 3.55101E-07
      61147.50c 1.28254E-07  61148.50c 9.36760E-10  62147.50c 2.92117E-08
      61149.50c 6.45505E-10  62149.50c 1.38943E-09  62150.50c 1.31107E-07
      62151.50c 6.68684E-09  62152.50c 6.36236E-08  63153.50c 4.33458E-08
      63154.50c 8.37175E-09  63155.50c 2.68226E-09  64155.50c 4.89214E-11
      64156.50c 1.52845E-08  64157.50c 2.82975E-11   5010.50c 1.05245E-06
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  56; total N =  7.3387849E-01
M155  92235.50c 6.69424E-06  92236.50c 1.49324E-06  92238.50c 1.81238E-04
      93239.60c 2.05724E-08  94239.50c 7.75782E-07  94240.50c 4.53927E-07
      94241.50c 2.73467E-07  94242.50c 1.42022E-07  93237.50c 5.60373E-08
      54135.50c 1.30861E-10  36083.50c 3.84285E-08  42095.50c 5.05603E-07
      43099.50c 5.91796E-07  44101.50c 5.32244E-07  44103.50c 4.26710E-08
      45103.50c 2.71303E-07  45105.50c 6.93267E-10  46105.50c 2.00891E-07
      46108.50c 6.97617E-08  47109.50c 3.75033E-08  48000.50c 4.43319E-11
      54131.50c 2.54290E-07  55133.50c 6.37792E-07  55134.60c 3.75290E-08
      59141.50c 5.79649E-07  60143.50c 4.13554E-07  60145.50c 3.57705E-07
      61147.50c 1.28661E-07  61148.50c 9.10116E-10  62147.50c 2.97598E-08
      61149.50c 6.32685E-10  62149.50c 1.35046E-09  62150.50c 1.32248E-07
      62151.50c 6.72497E-09  62152.50c 6.41203E-08  63153.50c 4.38057E-08
      63154.50c 8.47923E-09  63155.50c 2.70533E-09  64155.50c 5.23584E-11
      64156.50c 1.55002E-08  64157.50c 2.82965E-11   5010.50c 1.06496E-06
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
C     VSOP cycle  261; layer  57; total N =  7.3387891E-01
M156  92235.50c 6.63336E-06  92236.50c 1.50270E-06  92238.50c 1.81202E-04
      93239.60c 1.86646E-08  94239.50c 7.73968E-07  94240.50c 4.56387E-07
      94241.50c 2.76235E-07  94242.50c 1.44278E-07  93237.50c 5.65301E-08
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      54135.50c 1.30543E-10  36083.50c 3.86661E-08  42095.50c 5.12241E-07
      43099.50c 5.96377E-07  44101.50c 5.36573E-07  44103.50c 4.14733E-08
      45103.50c 2.74645E-07  45105.50c 7.11743E-10  46105.50c 2.02962E-07
      46108.50c 7.05948E-08  47109.50c 3.79364E-08  48000.50c 4.43235E-11
      54131.50c 2.56327E-07  55133.50c 6.42798E-07  55134.60c 3.78682E-08
      59141.50c 5.84181E-07  60143.50c 4.16866E-07  60145.50c 3.60380E-07
      61147.50c 1.29141E-07  61148.50c 8.66630E-10  62147.50c 3.03130E-08
      61149.50c 6.38835E-10  62149.50c 1.30926E-09  62150.50c 1.33393E-07
      62151.50c 6.74863E-09  62152.50c 6.46678E-08  63153.50c 4.42558E-08
      63154.50c 8.57925E-09  63155.50c 2.72768E-09  64155.50c 5.46181E-11
      64156.50c 1.57250E-08  64157.50c 2.79526E-11   5010.50c 1.04494E-06
      14000.50c 4.51609E-04   6000.50c 8.62701E-02   8016.50c 4.02899E-04
c
c     thermal s(alpha,beta) cross sections for graphite at 1200K
c
mt100 grph.06t
mt101 grph.06t
mt102 grph.06t
mt103 grph.06t
mt104 grph.06t
mt105 grph.06t
mt106 grph.06t
mt107 grph.06t
mt108 grph.06t
mt109 grph.06t
mt110 grph.06t
mt111 grph.06t
mt112 grph.06t
mt113 grph.06t
mt114 grph.06t
mt115 grph.06t
mt116 grph.06t
mt117 grph.06t
mt118 grph.06t
mt119 grph.06t
mt120 grph.06t
mt121 grph.06t
mt122 grph.06t
mt123 grph.06t
mt124 grph.06t
mt125 grph.06t
mt126 grph.06t
mt127 grph.06t
mt128 grph.06t
mt129 grph.06t
mt130 grph.06t
mt131 grph.06t
mt132 grph.06t
mt133 grph.06t
mt134 grph.06t
mt135 grph.06t
mt136 grph.06t
mt137 grph.06t
mt138 grph.06t
mt139 grph.06t
mt140 grph.06t
mt141 grph.06t
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mt142 grph.06t
mt143 grph.06t
mt144 grph.06t
mt145 grph.06t
mt146 grph.06t
mt147 grph.06t
mt148 grph.06t
mt149 grph.06t
mt150 grph.06t
mt151 grph.06t
mt152 grph.06t
mt153 grph.06t
mt154 grph.06t
mt155 grph.06t
mt156 grph.06t
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APPENDIX D.3: Modified subroutine VORSHU

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      SUBROUTINE VORSHU(NPRINT,IN1,MRY,NKEEP,DECAF,ICONPO,BU,VOLREG,VOL,
     1                  DEN,DENIOD,HM,THBURN,FADOS3,NOPOW,HMETAL,TCHG2,
     2                  KRESHZ,LRZN,TCHG1,N240,NALT,NTYP1,TEMZUT,TCELS,
     3                  VERA,IHZ,VOLIHZ,VOLWEG,HMETAV,DAV,DA2,SCELS,
     4                  SEMZUT,IREG,JAD11,IBOX,RVCB,HPOS,
     5                  ABSIG,LA0,NHOT,SS,RPHIAV)
C
C
C     F U M A N   MANAGES FUELLING OPERATIONS
C
C     VORSHU MEANS: BEFORE SHUFFLING
C                   ----------------
C
C     Subroutine VORSHU was modified (J.R. Lebenhaft, MIT, January 2000) to
C     write layer-averaged atom densities and reaction rates to files FORT.98
C     and FORT.99.
C
      PARAMETER (NMC = 95)
C
C     COMMONS
C
      COMMON / BLOCK1 /
     1           IPRIN(15)          ,JTPE1             ,JTPE2
     2,          JTPE3              ,JTPE4             ,JTPE5
     3,          JTPE6              ,JTPE7             ,JTPE8
     4,          JTPE9              ,JTPE10            ,NXS
     5,          N26                ,KMAT              ,JN
     6,          N200               ,NDR               ,NO
     7,          NLUM               ,NC                ,POWER
     8,          JSER               ,NXE               ,NRSTRT
     9,          KINIT              ,MUHU(30)          ,K96
     X,          K42                ,IRR9              ,KFR
      COMMON / BLOCK1 /
     1           MMAF               ,NLB               ,PI
     2,          N20                ,KROT              ,NEND33
     3,          MBOX               ,IAVC              ,JD11
     4,          RINN               ,IBUCK             ,NVSOP
      EQUIVALENCE(JTPE2,NS)
     1,          (JTPE3,NT)
C
      COMMON / BLOCK3 /
     1           JNN                ,IRSUB             ,KREG
     2,          N71                ,CRT               ,DELDAY
     3,          DELSEC             ,NK                ,NL
     4,          XYZ                ,ZF1               ,ZF2
     5,          ZF3                ,ZF4               ,ZJNUM
     6,          VOLUME             ,FIWATT            ,DIRAC(49,5)
     7,          YIELD1(49)         ,YIELD2(49)        ,YIELD3(49)
     8,          YIELD4(49)         ,NP237             ,XNORM
     9,          N27                ,N28               ,N29
     X,          N31                ,N41(20)           ,SERCON
      COMMON / BLOCK3 /
     1           CORE               ,RADR(20)          ,NTYPE
     2,          REACT(2)           ,XPPNEW(95)        ,YPPNEW(95)
     3,          LSER               ,ZKFIND            ,AWT(13)
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     4,          GS(13)          ,GM(13)          ,HCORE
     5,          JS              ,JSS             ,KSS
     6,          KSIM            ,LSIM            ,JSIM
     7,          LBUMP           ,NBUMP           ,NQUIT
     8,          JSMAX           ,JSSMAX          ,JSPEC
     9,          SPECK(192)      ,TIME(192)       ,STORE(7,96)
     X,          NSTO(96)        ,NSWIT           ,JNUM
      COMMON / BLOCK3 /
     1           JNSTOP          ,NLT             ,JNSP
     2,          ISPEKT(20)      ,FIFA            ,HMTOT
     3,          HMANFG          ,REALNN(10)      ,YMNEW
     4,          XMNEW           ,FITOT1          ,XPNEW1
     5,          YPNEW1          ,LAYER(20)       ,FF(4)
     6,          NBOX                             ,IVSP(30)
     7,          XVSP(3)         ,IDIFF(20)       ,CO1S
     8,          CO2S            ,ZPPNEW(95)      ,ZMNEW
C
      COMMON / BLOCKR /
     1           NRESHZ          ,MAKEUP          ,NSPALT
     2,          XSPALT          ,AAAA            ,IDFISS(13)
     3,          FICOMP(13)      ,NNNN            ,NWRITE
     4,          NKT             ,JEEP            ,TDOWN
     5,          TSTORE          ,TREPRO          ,TFAB
     6,          BRUCH           ,KUGL            ,JTYP
     7,          KLASSE(10)      ,FIMAKL(20)      ,NOPILE
     8,          MREP            ,MARX(10)        ,NAJB(10)
     9,          FOJB(10)        ,NFUL(10)        ,NBTOT
     X,          NB0             ,NCY
C
      COMMON / DABLCK /
     1           NDA10           ,NXT10           ,JSUM10
     2,          NDA11           ,NXT11           ,JSUM11
     3,          JAD10(150)                       ,NXT30
     4,          NXT40           ,NDA8            ,NXT8
     5,          JSUM8           ,JAD8(20)        ,NDA9
     6,          NXT9            ,JSUM9           ,JAD9(20)
     7,          K10             ,K08
     8,          NDA29           ,NXT29           ,N33
     9,          NXT13           ,N13             ,NDA13
     X,          ND13            ,N14             ,NXT28
      COMMON / DABLCK /
     1           L8              ,L9              ,L10
     2,          L11             ,L13             ,L28
     3,          L29             ,L30             ,L40
     4,          IWRITE          ,IREAD           ,JSUM13
C
      COMMON / PROZ    / INZWX,   INZWXX,   INZW(10),   PRO(300)
     1,                  FABC(10),  REPC(10),              NNE,   LISTEQ
     2,                  DMAT(14,4,4),  NTIK
C
      COMMON / ORIGEN /
     1           LOB             ,NOR
     2,          VOR(50)         ,NTO(50)
C
      COMMON /GRENZE/ NURTHM
     1,                THERGR,IDGAM,IDZUT,IDTHER,NGAM,IDESIN,JJGM,MSTU,
     1                 MGHUS,NNOBG,                      NZT(10,2),
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```
     2                IZUT(10,2,10),SIRA(68),NIRPI,NID,NDA30
     3,               NKER,ITEMP(20)
C
      COMMON /SPECTI/ ITIK(10)
C
      COMMON /QVAR/ IVAR,ENDKEF,QVOLLL,QREDUZ,QREMAX,EPQ,EPC
     1,             DQDDC,DELC,DCN,SBU,TE(4,99),TA(99),N61,URZ
     2,             ZLEKA,ABXEN,TI(99),DQCMAX,PSPALT ,JRESTW,JRESTR
     3,             JREST,TAU,Q0,QMI,QMA,QRAT,DMOD,DAEM
C
      COMMON /OPT/ KENN,IOPUT,NIFKO,DZT,KONIN
C
      COMMON /MPUNKT/ IMPU,KMPU,EMPU,TTTEIN,TTTAUS
C
      COMMON /ANISO/ JH,IZONE(5),DU(5),KK,M1(6,4)
C
      COMMON / IFA /   FA0,   FA1,   FA2,   IEND,   N44
C
      COMMON /UI/ DUM(155),EM9
C                                                                      25.8.94
      COMMON / DECAYT / DECY(17)                                       25.8.94
C
      COMMON / MCNP / IPCYC                                            11.6.00
C
      DIMENSION    BU(6,KMAT)          ,VOLREG(NDR)         ,VOL(N200)
     1,            DEN(KMAT,N200)      ,DENIOD(N200)        ,HM(N200)
     2,            THBURN(N200)        ,FADOS3(N200)        ,NOPOW(N200)
     3,            HMETAL(N200)        ,TCHG2(N200)         ,KRESHZ(N200)
     4,            LRZN(N200)          ,TCHG1(N240)         ,NALT(N240)
     5,            NTYP1(N240)         ,TEMZUT(NXS)         ,TCELS(5,NXS)
     6,            VERA(N200)          ,IHZ(NDR)            ,VOLIHZ(NDR)
     7,            VOLWEG(NDR)         ,HMETAV(N200)        ,DAV(KMAT)
     8,            DA2(KMAT)           ,SCELS(NXS)          ,SEMZUT(NXS)
     9,            IREG(NDR)           ,JAD11(JD11)         ,IBOX(MBOX)
     X,            RVCB(MBOX)
C
      DIMENSION    ABSIG(LA0),NHOT(N200),SS(N26,N200),RPHIAV(N26,NDR)
C
      DIMENSION    ADEN(KMAT),JP(KMAT),ABSRAT(KMAT)
C
C     F O R M A T E
C
C
    5 FORMAT (2I3,5E12.5,I6)
   11 FORMAT (24I3)
   12 FORMAT(18I4)
  114 FORMAT (//' FOR THE NEXT CYCLE THE TEMPERATURES OF THE RESONANCE A
     1BSORBERS AND SCATTERING NUCLIDES HAVE BEEN CHANGED:'/)
  115 FORMAT (6E12.5)
  116 FORMAT (//' REPROCESSING MIXTURE:',I10,9I8)
  117 FORMAT (' FRACTIONS OF JUMBLE BOXES:',F6.2,9F8.2)
  500 FORMAT ('0' //  5('.'),' FOR OUT-OF-PILE BATCHES DECAY IS CALCULAT
     1ED FOR OUT-OF-PILE STORAGE TIME   TSTORE '
     2,G12.5,5('.') /// )
  501 FORMAT (I3,9X,I2,8X,E12.5,4(3X,E12.5))
  502 FORMAT ('0' //  5('.'),' FOR THE IN-PILE BATCHES DECAY IS CALCULAT
     1ED FOR THE DOWNTIME FOR REFUELLING TDOWN '
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```
     2,G12.5,5('.') /// )
   504 FORMAT (/ ' MATERIAL',18X,'CONCENTRATION')
   505 FORMAT ('0************************************************************
     1************************************************************'
     2 /30X,          ' END OF OPERATING CYCLE',I4,5X,' RELOAD NO', I4,'
     1 IS EXECUTED ' /1X,121('*') //)
   506 FORMAT (// ' OPTIONS FOR NEXT CYCLE  :'
     1/' IPRIN(1)=',I3,',IPRIN(2)=',I3,',IPRIN(3)=',I3,',IPRIN(4)=',I3,
     2',JNSTOP=',I3,',LIB=',I3,',NPRINT=',I3,',IBUCK=',I3,',MUHU(3)=',I3
     3,',XE-EXPL.=',I3/' NXE=',I3,',DELDAY=',E12.5,',POWER=',E12.5,',ZKF
     4IND=',E12.5,',TDOWN=',E12.5//)
   507 FORMAT (4I3,3E12.5,4E6.0)
   510 FORMAT (I5,6X,G12.5,8X,G12.5)
   511 FORMAT ('1','BATCHES BEFORE RELOAD NO ',I3//' BATCH   TOT.VOLUME (
     1CCM)   HEAVY METAL (GR)      FIMA       FUEL TYPE   BURNUP CLASS
     2 IRRADIATION AGE       FDOSE'/)
   512 FORMAT (1H ,6A4,E12.5)
   513 FORMAT ('+',45X,E12.5,6X,I2,12X,I2,9X,E12.5,5X,E12.5)
   599 FORMAT ('1')
C  601 FORMAT (/' AUF DIRECT-ACCESS-EINHEIT',I3,' WURDEN',I4,' SAETZE MITML 12.94
C     1 KONZENTRATIONEN VERBUCHT.'/)                                      ML 12.94
   601 FORMAT (/' ON DIRECT-ACCESS UNIT',I3,' - ',I4,' SETS WITH CONCENTRML 12.94
     1ATIONS ARE WRITTEN.'/)                                             ML 12.94
   603 FORMAT (18I4)
   604 FORMAT (12I6)
   700 FORMAT (////' OUT OF PILE BATCHES BEFORE RELOAD NO.',I5//' TYP   B
     1URNUP CLASS       VOLUME        AVG.AGE       AVG.BURNUP     AVG.F
     2-DOSE      HM-GRAM'/)
C  710 FORMAT (//' ***VORSICHT: DIE ZWISCHENBOX',I4,' MIT VOL. =',E12.5,'ML 12.94
C     1 WIRD GELOESCHT.'/14X,'SIE WIRD AUCH IN DER KOSTENRECHNUNG NICHT BML 12.94
C     2ERUECKSICHTIGT.***'//)                                             ML 12.94
   710 FORMAT (//' ***CAUTION: THE INTERMEDIATE BOX',I4,' WITH VOL. =',  ML 12.94
     1E12.5,' WILL BE DELETED.'/14X,'NO CONSIDERATION OF THIS BOX IN CALML 12.94
     2CULATION OF COSTS.***'//)                                          ML 12.94
   720 FORMAT (////' FROM RELOAD NO.',I5,' THE FOLLOWING STORAGE BOXES AR
     1E PREPARED.'/' THEY ARE AVAILABLE AT THIS RELOAD NO.',I5,' (DECAY
     2TIME IS NOT APPLIED).'//' BOX   TYPE   BURNUP CLASS      VOLUME
     3   AVG.IRR.TIME     AVG.BURNUP     AVG.F-DOSE   TOT.HEAVY METAL (G
     4R)'/)
   721 FORMAT (I3,I7,9X,I2,8X,E12.5,3(3X,E12.5),6X,E12.5)
C
C
      IF (TSTORE  .LT.  0.0)     TSTORE=-TIME(1)/AAAA
      TST=ABS(TSTORE)
      DELSTO = DELDAY * JNSTOP
C
C     NEW OPTIONS FOR NEXT CYCLE
C
      DO 29 I=1,3
      IVSP(I+24)= 0
      XVSP(I)   = 0.
   29 CONTINUE
      XTDOWN = 0.
      IVSP(28) = 0
      KONIN = 0
      JREST = 0
      IF(ITIK(1) .GT. 0) GO TO 3
```

```
      ITIK(10) = 0
      ITIK(9) = 0
      IT10 = 0
      IVAR = 0
      URZ = 0.
      JRESTW = 0
      JRESTR = 0
      EPQ = 0.
      DMOD = 0.5
      EM9 = 1.E-09
      DQCMAX = 0.
    3 CONTINUE
      IF(IVSP(1) .GE. 1) GO TO 21
C
C     CARD R9
C
      READ (NS,11) (IVSP(I), I=1,6),(IVSP(I), I=8,14),IVOID,(IVSP(I), I=
     115,17),(IVSP(I), I=19,24),MUHU(8)
C
      N44 = IVSP(12)
      IF(IVOID .LE. 0) GO TO 6
C
C     CARD R10
C
      READ (NS,12) JH,(IZONE(I),M1(I,1),M1(I,2), I=1,JH)
C
      KK = JH + 1
      M1(KK,1) = 0
      IVOID = 0
    6 CONTINUE
      IF(IVSP(20) .LT. 100) GO TO 4
      KONIN = IVSP(20) / 100
      IVSP(20) = IVSP(20) - 100 * KONIN
    4 CONTINUE
      IF(IVSP(20) .LT. 10) GO TO 1
      IT10 = IVSP(20) / 10
      IF(IT10 .NE. 6) GO TO 9
      ITIK(1) = 0
      ITIK(9) = 0
      IT10 = 5
      IVSP(20) = 51
    9 CONTINUE
      IVSP(20) = IVSP(20) - 10 * IT10
      IF(IT10 .EQ. 0) GO TO 1
      ITIK(10) = 1
      IF(IT10 .EQ. 1) GO TO 1
      IF(IT10 .LE. 4) GO TO 2
      IVAR = IT10 - 4
      IT10 = IT10 - 3
C
C     CARD R11
C
      READ (NS,115) ENDK,QVOLLL,QREMAX,EPR,EPC,URZ
C
      IF(EPR .NE. 0.) EPQ = EPR
      IF((ITIK(1) .EQ. 0) .OR. (ENDK .NE. 0)) ENDKEF = ENDK
C
```

```
C     CARD R12
C
      READ (NS,115) DQDDG,DELC,DCM,DQCMAZ,PSPALT,DMOT
C
      IMPU = 0
      IF(DQDDG .NE. 0.) DQDDC = DQDDG
      IF(DQCMAZ .NE. 0.) DQCMAX = DQCMAZ
      IF(DMOT .NE. 0.) DMOD = DMOT
      IF(DCM .NE. 0.) DCN = DCM
C
C     CARD R13
C
      IF(ITIK(1) .EQ. 0) READ (NS,5) JRESTW,JRESTR,Q0,QMI,QMA,QRAT,DAEM
C
      IF(ITIK(1) .EQ. 0) EMPU = 0.
      IF(QMI .NE. QMA) GO TO 2
      QMI = EPQ
      QMA = EPQ
    2 CONTINUE
      IF(QRAT .EQ. 0.) QRAT = 1.
      ITIK(10) = 2
      IF(ITIK(9) .GT. 0) GO TO 1
      ITIK(9) = IT10 - 5
    1 CONTINUE
      MUHU(29)=0
      IF (IVSP(3).LT.10) GOTO 22
      MUHU(29)=IVSP(3)/10
      IVSP(3)=IVSP(3)-10
   22 CONTINUE
      MUHU(1) = IVSP(23)
   21 CONTINUE
      N61 = 6
      IF(URZ .LT. 0.) N61 = 4
      NT=6
      IVSP(1) = IVSP(1) - 1
      ITIK(4) = IVSP(8)
      IPRIN(1) = IVSP(2)
      IPRIN(2) = IVSP(3)
      IPRIN(3) = IVSP(4)
      IPRIN(4) = IVSP(10)
      LIB = IVSP(21)
      NPRINT = IVSP(5)
      NTIK = IVSP(20)
      ITIK(6) = NTIK
      IF((NTIK .EQ. 3) .OR. (NTIK .EQ. 1)) ITIK(1) = 0
      NCYC = IVSP(14)
      NTYPE=0
      IF (IVSP(11).EQ.2) NTYPE=2
      IVSP(14) = 0
      IN2 = IVSP(9)
      NKEEP = IVSP(13)
      ISTORN = 0
      NKP = NKEEP - 10 * (NKEEP/10)
      IF(NKP .EQ. 2) ISTORN = 1
      IVSP(13) = 0
      LOB =-IVSP(22)
      PU = POWER
```

```
      HNUC = 0.
      CONPOI = 0.
      HPOS = 0.
C
C     CARD R14
C
      IF(IVSP(15) .EQ. 1) READ (NS,507) (IVSP(I), I=25,28), (XVSP(I), I=
     11,3),HNUC,HPOS,XTDOWN,CONPOI
C
      IF(IVSP(28) .GT. 0) NXE = 1
      IF(CONPOI .LT. 0.) JSER = 1
      ICONPO = IFIX(CONPOI)
      IF(HNUC .GT. 0.) IVSP(29) = IFIX(HNUC)
      HNUC = 0.
      IF(XTDOWN .GT. 0.) TDOWN = XTDOWN
      IF(XTDOWN .LT. 0.) TDOWN = 0.
      IF(XVSP(1) .NE. 0.)   DELDAY = XVSP(1)
      IF(XVSP(2) .NE. 0.)   POWER  = XVSP(2)
      IF(XVSP(3) .NE. 0.)   ZKFIND = XVSP(3)
      IF(IVSP(25).NE. 0 )   JNSTOP = IVSP(25)
      IF(IVSP(26).NE. 0 )   JNUM   = IVSP(26)
      IF(IVSP(24) .GT. 0) JNSTOP = -JNSTOP
      IVSP(24) = 0
      IVSP(15) = 0
      XVSP(2) = PU
      IF(IVSP(27) .GT. 0) MUHU(3) = IVSP(27)
      IF(NCYC .LE. 0) GO TO 42
      IF(NCY .EQ. 0) NCYC = -NCYC
      NCY = NCYC
C
C     CARD R15
C
      READ (NS,115) (FOJB(I), I=1,MREP)
C
      WRITE (NT,116) (     I , I=1,MREP)
      WRITE (NT,117) (FOJB(I), I=1,MREP)
   42 CONTINUE
      IF(IVSP(16) .LE. 0) GO TO 43
      IVSP(16) = 0
C
C     CARD R16
C
      READ (NS,603) (ISPEKT(I), I=1,18)
C
      ISPEKT(20) = 0
      DO 47 I=1,18
      IF(ISPEKT(I) .NE. 0) ISPEKT(20) = I
   47 CONTINUE
   43 CONTINUE
      IF(IVSP(17) .LE. 0) GO TO 49
      IVSP(17) = 0
C
C     CARD R17
C
      READ (NS,603) (IDIFF(I), I=1,18)
C
      IDIFF(20) = 0
```

```
      DO 48 I=1,18
      IF(IDIFF(I) .NE. 0) IDIFF(20) = I
   48 CONTINUE
   49 CONTINUE
      IF(ITIK(6) .EQ. 5) GO TO 41
      IF((NTIK .LT. 1) .OR. (NTIK .GT. 2)) GO TO 58
C
C     CARD R18
C
   41 READ (NS,603) (ITEMP(I), I=1,18)
C
      ITEMP(20) = 0
      DO 59 I=1,18
      IF(ITEMP(I) .NE. 0) ITEMP(20) = I
   59 CONTINUE
   58 CONTINUE
      IF(IVSP(19) .EQ. 0) GO TO 54
      IF(IVSP(19) .EQ. 2) GO TO 60
C
C     CARD R19
C
      READ (NS,115) (SEMZUT(I), I=1,NXS)
C
      DO 56 I=1,NXS
   56 IF(SEMZUT(I) .GT. 0.) TEMZUT(I) = SEMZUT(I)
      WRITE (NT,114)
      WRITE (NT,115) (TEMZUT(I), I=1,NXS)
      DO 53 J=1,NKER
C
C     CARD R20
C
      READ (NS,115) (SCELS(I),   I=1,NXS)
C
      DO 57 I=1,NXS
   57 IF(SCELS(I) .GT. 0.) TCELS(J,I) = SCELS(I)
      WRITE (NT,115) (TCELS(J,I), I=1,NXS)
   53 CONTINUE
      IF(IVSP(19) .EQ. 1) GO TO 54
   60 CONTINUE
      DO 61 I=1,IDESIN
      DO 61 J=1,2
C
C     CARD R21
C
      READ (NS,604)NZ,(IZUT(I,J,M), M=1,NZ)
C
      WRITE (NT,604) NZ,(IZUT(I,J,M), M=1,NZ)
      NZT(I,J) = NZ
   61 CONTINUE
   54 CONTINUE
      IVSP(19) = 0
      IF(IPRIN(3) .EQ. -2) NT = 4
      INZW(1) = IN2
      IF(NPRINT.GE.0) WRITE (NT,599)
      IN1=IPRIN(15)+1
      INZW(3) = IN1
      WRITE ( 6,505) IN1,IPRIN(15)
```

```
      WRITE ( 6,506) (IPRIN(I),I=1,4),JNSTOP,LIB,NPRINT,IBUCK,MUHU(3),IV
     1SP(28),NXE,DELDAY,POWER,ZKFIND,TDOWN
C
C     CALCULATE AVERAGE BATCH PROPERTIES BEFORE RELOAD
C
      IF (NPRINT.GE.1) WRITE (NT,511) IPRIN(15)
      NCX2 = 0
      MRY = 0
      DECAF = 0.
      NDA28 = 28
      NXT28 = 1
      IL = 0
C                                                                      11.6.00
C     repeat for each batch                                            11.6.00
      DO 191 IR=1,NRESHZ                                               11.6.00
C     --------------------                                             11.6.00
C     for fuel cycle ipcyc                                             11.6.00
C     --------------------                                             11.6.00
      IF (IPRIN(15).EQ.IPCYC) THEN                                     11.6.00
C        write cycle and batch number to file                          11.6.00
         WRITE (96,*) 'CYCLE = ',IPCYC,' BATCH = ',IR                  11.6.00
         WRITE (97,*) IR                                               11.6.00
c        check if new layer                                            11.6.00
         IF (MOD(IR,11).EQ.1) THEN                                     11.6.00
            IF ((IL.GE.1).AND.(IL.LE.57)) THEN                         11.6.00
C              print data on previous layer                            11.6.00
               WRITE (96,*) 'VOL OF LAYER ',IL,' = ',VOLAY             11.6.00
               WRITE (98,*) IPCYC,IL,ADENT,VOLAY,FF(1)                 11.6.00
               WRITE (99,*) IL                                         11.6.00
               DO 13 I=1,KMAT,5                                        11.6.00
                  KMAX = MIN(I+4,KMAT)                                 11.6.00
                  WRITE (98,*) (ADEN(K),K=I,KMAX)                      11.6.00
                  WRITE (99,*) (ABSRAT(K),K=I,KMAX)                    11.6.00
 13            CONTINUE                                                11.6.00
            END IF                                                     11.6.00
C           increment layer counter                                    11.6.00
            IL = IL+1                                                  11.6.00
C           initialize variables                                       11.6.00
            DO 19 I=1,KMAT                                             11.6.00
               ADEN(I) = 0.                                            11.6.00
               ABSRAT(I) = 0.                                          11.6.00
 19         CONTINUE                                                   11.6.00
            ADENT = 0.                                                 11.6.00
            VOLAY = 0.                                                 11.6.00
         END IF                                                        11.6.00
      END IF                                                           11.6.00
C     ----------------------                                           11.6.00
      NCX1 = NCX2+1
      NCX2 = KRESHZ(IR)
      IF ((IR.GT.1).AND.(NPRINT.EQ.2)) WRITE (NT,599)
      NALT(IR) = 1
      DO 55 M=1,KMAT
   55 DAV(M) = 0.0
      PARVOL=0.0
      HMETAV(IR) = 0.0
      HMGRM =0.0
      BURNRX = 0.0
```

```
      DOSNRX = 0.0
      MRZ = 0
      IR1=NCX1
   51 CONTINUE
      NCX = LRZN(IR1)
      DO 50 M=1,KMAT
   50 DAV(M) = DAV(M) + DEN(M,NCX) * VOL(NCX)
      HMETAV(IR) = HMETAV(IR) + HMETAL(NCX)*VOL(NCX)
      HMGRM =HMGRM+HM(NCX)
      BURNRX=BURNRX+THBURN(NCX)*VOL(NCX)
      DOSNRX=DOSNRX+FADOS3(NCX)*VOL(NCX)
      PARVOL=PARVOL+VOL(NCX)
      MRZ = MRZ + 1
      IR1 = IR1 + 1
      IF(IR1 .LE. NCX2) GO TO 51
      MRY = MAX0(MRY,MRZ)
      VERA(IR)=PARVOL
      HMETAV(IR) = HMETAV(IR) / PARVOL
      HMDEN =HMETAV(IR)
      BURNRX=BURNRX/PARVOL
      DOSNRX=DOSNRX/PARVOL
      TCHG1(IR)=TCHG2(IR)+TIME(1)
      IF (NPRINT.GE.1) WRITE (NT,510) IR,PARVOL,HMGRM
      IF (NPRINT .EQ. 2) WRITE(NT,504)
      HMEND = 0.
      DAVT = 0.
      IF (IPRIN(15).EQ.IPCYC) THEN                                    11.6.00
         WRITE (96,*) 'VOLUME OF BATCH ',IR,' = ',PARVOL              11.6.00
         VOLAY = VOLAY + PARVOL                                       11.6.00
      END IF                                                          11.6.00
      DO 52 M=1,KMAT
      DAV(M) = DAV(M)/PARVOL
C     ------------------------------------------------------          11.6.00
C     prepare layer averaged data for output if chosen cycle          11.6.00
C     ------------------------------------------------------          11.6.00
      IF (IPRIN(15).EQ.IPCYC) THEN                                    11.6.00
C        print number of atoms of material M in batch                 11.6.00
         WRITE (96,*) M,DAV(M)*PARVOL                                 11.6.00
         WRITE (97,*) DAV(M)                                          11.6.00
C        number of atoms of material M in layer                       11.6.00
         ADEN(M) = ADEN(M) + DAV(M)*PARVOL                            11.6.00
C        total number of atoms in layer                               11.6.00
         ADENT = ADENT + ADEN(M)                                      11.6.00
C        set up pointers into sigma and flux arrays                   11.6.00
         IF (IR.EQ.1) THEN                                            11.6.00
            LA = (NHOT(IR)-1)*KMAT                                    11.6.00
            DO 24 I=1,KMAT                                            11.6.00
               JP(I) = (LA+I-1)*N26                                   11.6.00
   24       CONTINUE                                                  11.6.00
         ELSE IF (NHOT(IR).NE.NHOT(IR-1)) THEN                        11.6.00
            LA = (NHOT(IR)-1)*KMAT                                    11.6.00
            DO 25 I=1,KMAT                                            11.6.00
               JP(I) = (LA+I-1)*N26                                   11.6.00
   25       CONTINUE                                                  11.6.00
         END IF                                                       11.6.00
C        prepare total absorption rate for material M in the batch    11.6.00
C        using effective macroscopic cross section                    11.6.00
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         DO 26 IG=1,N26                                                    11.6.00
            SSFAC = SS(IG,IR)*RPHIAV(IG,IL)                                11.6.00
            ABSRAT(M) = ABSRAT(M) + ABSIG(JP(M)+IG)*SSFAC                  11.6.00
 26       CONTINUE                                                         11.6.00
       END IF                                                             11.6.00
C      -------------------------------------                              11.6.00
       IF (M .LE. 13) HMEND = HMEND + DAV(M)
       IF (NPRINT    .NE. 2) GO TO 52
       WRITE (NT,512)(BU(N,M),N=1,6),DAV(M)
    52 CONTINUE
       IF (TDOWN  .EQ.  0.0)      GO TO 190
C
C      DECAY DURING RESHUFFLE PERIOD
C
       DAV(2) = 0.
       DAV(3) = 0.
       DAV(8) = 0.
       DAV(9) = 0.
       DAV(11) = 0.                                                       25.8.94
       IF (NXE  .LE.  0)
      1DAV(14) = 0.
       TDOWM = TDOWN
       IF(TDOWM .LT. 0.) TDOWM = ABS(TDOWN) * DELSTO
       TT = TDOWM*3600.*24.
       IR1=NCX1
  160 CONTINUE
       NX = LRZN(IR1)
       IF (NXE  .GT.  0)     GO TO 155
       DEC = EXP(-2.87E-05*TT)
       DEN(14,NX) = (DEN(14,NX)-3.72727*DENIOD(NX)*(EXP(-0.77E-05*TT)
     1              -1.0))*EXP(-2.1E-05*TT)
       DENIOD(NX) = DENIOD(NX)*DEC
  155 CONTINUE
       DEC = EXP(-TT*DECY(2))                                             25.8.94
       DC = DEN(2,NX) * (1.0-DEC)
       DEN(3,NX) = DEN(3,NX)+DC
       DEN(2,NX) = DEN(2,NX)*DEC
       DECAF = DECAF + DC * VOL(NX)
       DEC = EXP(-TT*DECY(8))                                             25.8.94
       DC = DEN(8,NX) * (1.0-DEC)
       DEN(9,NX) = DEN(9,NX)+DC
       DEN(8,NX) = DEN(8,NX)*DEC
       DECAF = DECAF + DC * VOL(NX)
       DEC = EXP(-TT*DECY(11))                                            25.8.94
       DEN(11,NX) = DEN(11,NX)*DEC                                        25.8.94
       DAV(2) = DAV(2) + DEN(2,NX) * VOL(NX)
       DAV(3) = DAV(3) + DEN(3,NX) * VOL(NX)
       DAV(8) = DAV(8) + DEN(8,NX) * VOL(NX)
       DAV(9) = DAV(9) + DEN(9,NX) * VOL(NX)
       DAV(11) = DAV(11) + DEN(11,NX) * VOL(NX)                           25.8.94
       IF (NXE  .LE.  0)
      1DAV(14) = DAV(14) + DEN(14,NX) * VOL(NX)
       IR1 = IR1 + 1
       IF(IR1 .LE. NCX2) GO TO 160
       DAV(2) = DAV(2)/PARVOL
       DAV(3) = DAV(3)/PARVOL
       DAV(8) = DAV(8)/PARVOL
```

```
      DAV(9) = DAV(9)/PARVOL
      DAV(11) = DAV(11)/PARVOL                                          25.8.94
      IF (NXE  .LE.  0)
     1DAV(14) = DAV(14)/PARVOL
  190 CONTINUE
C
C     FIND BURNUP (FIMA-VALUE) FOR THIS REGION
C
      IF (NOPOW(IR).EQ.0)  GOTO 182
      FIMA=0.
      GOTO 183
  182 CONTINUE
      FIMA = (HMETAV(IR)-HMEND)/HMETAV(IR)
      IF(FIMA .LE. 0.) FIMA = EM9
  183 CONTINUE
      NTP = NTYP1(IR)
      NTP1 = NTP-1
      KL = 0
      IF (NTP1   .LE.  0)   GO TO 175
      DO 170   I=1,NTP1
      KL = KL+KLASSE(I)
  170 CONTINUE
  175 CONTINUE
      IF(NOPOW(IR) .GT. 0) GO TO 184
      KLZ = KLASSE(NTP)
      DO 180   I=1,KLZ
      IKLASS = I
      IF (FIMA .LT. FIMAKL(KL+I))   GO TO 181
  180 CONTINUE
  184 CONTINUE
      IKLASS = 0
  181 CONTINUE
      IF(NPRINT.GE.1)
     1WRITE(NT,513) FIMA,NTP,IKLASS,TCHG1(IR),DOSNRX
      WRITE (97,*) PARVOL,FIMA
      JSATZ = 2+IR
      IF (JAD11(JSATZ)  .EQ.  0)     JAD11(JSATZ)=JSUM11
      NXT11 = JAD11(JSATZ)
      WRITE (NDA11,REC=NXT11)(DAV(L),L=1,KMAT),PARVOL,TCHG1(IR),NTP
     1,                        IKLASS,BURNRX,DOSNRX,HMGRM,HMDEN
      NXT11 = NXT11 + 1
      IF (JSUM11  .LT.  NXT11)     JSUM11=NXT11
      IF(IVSP(21) .GE. 0) GO TO 191
      NTYP = NTP * 100 + 1
      WRITE (NDA28,REC=NXT28) NTYP
      NXT28 = NXT28 + 1
      CALL WRDA(IWRITE,NDA28,NXT28,L28,DAV,KMAT)
  191 CONTINUE
      IF(IVSP(21) .GE. 0) GO TO 600
      IVSP(21) = 0
      NRS = NXT28 - 1
      WRITE (6,601) NDA28,NRS
  600 CONTINUE
      IF (NPRINT  .GT.  0)
     1WRITE (NT,502) TDOWN
      IF (KUGL  .LE.  0)     GO TO 199
C
```

```
C     IHZ(KR) = NUMBER OF BATCHES / LAYER
C     VOLIHZ(KR) = VOL. OF ONE      LAYER
C
      IRRE1 = 0
      DO 192 KR=1,NDR
      IRRE2 = IREG(KR)
      IHZ(KR) =  IRRE2-IRRE1
      VOLIHZ(KR) = VOLREG(KR)
      VOLWEG(KR) = 0.0
      IRRE1 = IRRE2
  192 CONTINUE
      IF(MBOX .LE. NBOX) GO TO 31
C
C     FILLING OF THE STORAGE BOXES FROM INTERMEDIATE BOXES
C
      DO 132 I=1,MBOX
  132 RVCB(I) = 0.
      K2 = KMAT + 8
      ANUL = 0.
      NB1 = NBOX + 1
      DO 33 I=NB1,MBOX
      RVCB(I) = 1.
      JSATZ = NRESHZ + 2 + I
      IF (JAD11(JSATZ)  .EQ.  0)      JAD11(JSATZ)=JSUM11
      NXT11 = JAD11(JSATZ)
      WRITE (NDA11,REC=NXT11) (ANUL, J=1,K2)
      NXT11 = NXT11 + 1
      IF (JSUM11  .LT.  NXT11)      JSUM11=NXT11
   33 CONTINUE
      IF(MBOX .EQ. 1) GO TO 31
      IF(ISTORN .EQ. 1) GO TO 31
      DO 34 I=1,NBOX
      JSATZ = NRESHZ + 2 + I
      JS2 = JSATZ
      NXT11 = JAD11(JSATZ)
      IF(NXT11 .EQ. 0) GO TO 34
      READ (NDA11,REC=NXT11) (DAV(L), L=1,KMAT),PARVOL,XCHNRX,NTPNRX,
     1                         IKLNRX,BURNRX,DOSNRX,HMGRM,HMDEN
      NXT11 = NXT11 + 1
      IF(IBOX(I) .EQ. 0) GO TO 32
      JSATZ = NRESHZ + 2 + IBOX(I)
      NXT11 = JAD11(JSATZ)
      READ (NDA11,REC=NXT11) (DA2(L), L=1,KMAT),PARVO2,XCHNR2,NTPNR2,
     1                         IKLNR2,BURNR2,DOSNR2,HMGR2,HMDE2
      NXT11 = NXT11 + 1
      PV = PARVOL + PARVO2
      PV1 = PARVOL / PV
      PV2 = PARVO2 / PV
      DO 35 L=1,KMAT
   35 DA2(L) = DAV(L) * PV1 + DA2(L) * PV2
      PARVO2 = PV
      XCHNR2 = XCHNRX * PV1 + XCHNR2 * PV2
      NTPNR2 = NTPNRX
      HMGR2 = HMGRM + HMGR2
      HMDE2 = HMDEN * PV1 + HMDE2 * PV2
      BURNR2 = BURNRX * PV1 + BURNR2 * PV2
      DOSNR2 = DOSNRX * PV1 + DOSNR2 * PV2
```

```
      DN2 = 0.
      DO 36 L=1,13
   36 DN2 = DN2 + DA2(L)
      FIMA = (HMDE2-DN2) / HMDE2
      IF(FIMA .LE. 0.) FIMA = EM9
      NTP1 = NTPNR2 - 1
      KL = 0
      IF(NTP1 .LE. 0) GO TO 39
      DO 20 L=1,NTP1
      KL = KL + KLASSE(L)
   20 CONTINUE
   39 CONTINUE
      KLZ = KLASSE(NTPNR2)
      DO 37 L=1,KLZ
      IKLNR2 = L
      IF(FIMA .LT. FIMAKL(KL+L)) GO TO 38
   37 CONTINUE
      IKLNR2 = 0
   38 CONTINUE
      NXT11 = JAD11(JSATZ)
      WRITE(NDA11,REC=NXT11) (DA2(L), L=1,KMAT),PARVO2,XCHNR2,NTPNR2,
     1                        IKLNR2,BURNR2,DOSNR2,HMGR2,HMDE2
      NXT11 = NXT11 + 1
   32 CONTINUE
      IF(IBOX(I) .EQ. 0 .AND. PARVOL .GT. 0.) WRITE (6,710) I,PARVOL
      NXT11 = JAD11(JS2)
      WRITE(NDA11,REC=NXT11) (ANUL, J=1,K2)
      NXT11 = NXT11 + 1
      IBOX(I) = 0
   34 CONTINUE
      IF(NPRINT .LT. 0 .OR. IPRIN(15) .EQ. 0) GO TO 40
      IPRO = IFIX(PRO(299))
      WRITE (NT,720) IPRO,IPRIN(15)
      DO 30 I=NB1,MBOX
      J = I - NBOX
      JSATZ = NRESHZ + 2 + I
      NXT11 = JAD11(JSATZ)
      READ(NDA11,REC=NXT11) (DA2(L), L=1,KMAT),PARVO2,XCHNR2,NTPNR2,
     1                       IKLNR2,BURNR2,DOSNR2,HMGR2,HMDE2
      NXT11 = NXT11 + 1
      WRITE (NT,721) J,NTPNR2,IKLNR2,PARVO2,XCHNR2,BURNR2,DOSNR2,HMGR2
   30 CONTINUE
   40 CONTINUE
   31 CONTINUE
C
C     DECAY OF OUT-OF-PILE BATCHES DURING LAST CYCLE AND RESHUFFLE
C
      TT=TST*3600.*24.
      IF(NPRINT .GE. 1) WRITE (NT,700) IPRIN(15)
      DO 194 N=1,NOPILE
      IR=NRESHZ+N
      JSATZ=2+MBOX+IR
      NXT11=JAD11(JSATZ)
      READ (NDA11,REC=NXT11) (DAV(L),L=1,KMAT),PARVOL,TXCHG,NTP,IKLASS,
     1                        BURNRX,DOSNRX,HMGRM,HMDEN
      NXT11 = NXT11 + 1
      IF (IKLASS .LE. 1)      GOTO 194
```

```
      TXCHG=TXCHG+TST*AAAA
      TCHG1(IR)=TXCHG
      IF (NXE  .LE.  0)
     1DAV(14)=0.
      DEC=EXP(-TT*DECY(2))                                                    25.8.94
      DC = DAV(2) * (1.-DEC)
      DAV(3)=DAV(3)+DC
      DAV(2)=DAV(2)*DEC
      DECAF = DECAF + DC * PARVOL
      DEC=EXP(-TT*DECY(8))                                                    25.8.94
      DC = DAV(8) * (1.-DEC)
      DAV(9)=DAV(9)+DC
      DAV(8)=DAV(8)*DEC
      DECAF = DECAF + DC * PARVOL
      DEC=EXP(-TT*DECY(11))                                                   25.8.94
      DAV(11)=DAV(11)*DEC                                                     25.8.94
      NXT11=JAD11(JSATZ)
      WRITE (NDA11,REC=NXT11)  (DAV(L),L=1,KMAT),PARVOL,TXCHG,NTP,IKLASS,
     1                          BURNRX,DOSNRX,HMGRM,HMDEN
      NXT11 = NXT11 + 1
      IF (NPRINT  .LT.  1)      GOTO 194
      WRITE (NT,501) NTP,IKLASS,PARVOL,TXCHG,BURNRX,DOSNRX,HMGRM
      IF (NPRINT  .NE.  2)     GOTO 194
      DO 193 L=1,KMAT
      WRITE (NT,512) (BU(I,L),I=1,6),DAV(L)
  193 CONTINUE
  194 CONTINUE
      IF (NPRINT  .GT.  0)
     1WRITE (NT,500) TST
  199 CONTINUE
      RETURN
      END
```

APPENDIX D.4: Program MCARDS

```
      program mcards
c
c     prepare mcnp material cards using vsop fuel compositions for
c     each layer. The compositions are homogenized over the volume
c     of a fuel sphere, with an adjustment to U238 composition.
c
      parameter (niso = 51)
      parameter (kmat = 65)
      parameter (layers = 57)
c
      real nvsop(kmat),rate(kmat),nmcnp(niso),vlay(layers)
      integer hit(kmat),ipoint(niso)
      character*9 zaid(niso)*9,matnam*4
c
c     mcnp material i.d.
c
      data zaid /
     1    '90232.50c','91233.50c','92233.50c','92234.50c','92235.50c',
     2    '92236.50c','92238.50c','93239.60c','94239.50c','94240.50c',
     3    '94241.50c','94242.50c','93237.50c','54135.50c','36083.50c',
     4    '42095.50c','43099.50c','44101.50c','44103.50c','45103.50c',
     5    '45105.50c','46105.50c','46108.50c','47109.50c','48000.50c',
     6    '54131.50c','55133.50c','55134.60c','59141.50c','60143.50c',
     7    '60145.50c','61147.50c','61148.50c','62147.50c','61149.50c',
     8    '62149.50c','62150.50c','62151.50c','62152.50c','63153.50c',
     9    '63154.50c','63155.50c','64155.50c','64156.50c','64157.50c',
     x    ' 5010.50c',' 5011.50c','26000.50c','14000.50c',' 6000.50c',
     y    ' 8016.50c' /
c
      data pf/0.61/,rfs/3.0/,pi/3.141592654/,scale/1.0/
c
c     mapping between vsop and mcnp
c
      data hit / 14*1,0,0,1,0,1,0,8*1,1,0,1,0,3*1,0,1,0,1,0,4*1,0,3*1,
     1           0,11*1,0,1,0,1,1 /
c
c     initializations
c
c     .. zaid pointer and mcnp atom density arrays
      do 5 iz=1,niso
         ipoint(iz) = 0
         nmcnp(iz) = 0.0
 5    continue
c     .. vsop material atom densities and reaction rates
      do 10 m=1,kmat
         nvsop(m) = 0.0
         rate(m) = 0.0
 10   continue
c     .. total reaction rate for non-hits
      rden = 0.0
c
c     volume of fuel sphere
c
      vfs = (4.0/3.0)*pi*rfs**3
c
```

```
      open (unit=98,file='fort.98',status='old')
      open (unit=99,file='fort.99',status='old')
      open (unit=100,file='mcards_new.dat',status='new')
c
c     start numbering mcnp material cards at m100
      matnum = 99
c
c     for each layer ..
      do 45 l=1, layers
c        input vsop cycle, layer number and total atom density
         read (98,*) ipcyc,laynum1,vlay(l),pf
         read (99,*) laynum2
         if (laynum1 .ne. laynum2) then
            stop 'mcards error: layer number mismatch'
         end if
c        input atom density and reaction rate for each material
         matnum = matnum + 1
         do 15 m=1,kmat,5
            kmax = min(m+4,kmat)
            read (98,*) (nvsop(k),k=m,kmax)
            read (99,*) (rate(k),k=m,kmax)
 15      continue
c        calculate number of fuel spheres in layer
         vol = vlay(l)
         nfs = int(pf*vol/vfs)
c
c        transfer atom densities to mcnp file if nuclides match
c        or sum up reaction rates otherwise
         im = 0
         iz = 0
         do 20 m=1,kmat
c           mcnp library exists and density not zero
            if ((hit(m).eq.1).and.(nvsop(m).ne.0.0)) then
c              include Pm148g with Pm148m (m=42)
               if (m.eq.43) then
                  nmcnp(im) = nmcnp(im) + nvsop(m)
c              B10
               else if (m.eq.58) then
                  im = im + 1
                  iz = iz + 1
                  nmcnp(im) = nvsop(m)
                  ib10 = im
                  ipoint(im) = iz
c              correct [U238] for heterogeneity
               else if (m.eq.7) then
                  im = im + 1
                  iz = iz + 1
                  nmcnp(im) = scale*nvsop(m)
                  ipoint(im) = iz
c              all other nuclides
               else
                  im = im + 1
                  iz = iz + 1
                  nmcnp(im) = nvsop(m)
                  ipoint(im) = iz
               end if
c           mcnp library exists but density is zero
```

```
            else if ((hit(m).eq.1).and.(nvsop(m).eq.0.0)) then
c              increment zaid array pointer
               iz = iz + 1
               if (m.eq.58) then
                  im = im + 1
                  nmcnp(im) = 0.0
                  ib10 = im
                  ipoint(im) = iz
               end if
c           mcnp library does not exist
            else
               rden = rden + nvsop(m)*rate(m)
            end if
 20      continue
c
         nmax = im
c        B10 atom density chosen to conserve total reaction rate
         nmcnp(ib10) = nmcnp(ib10) + rden/rate(58)
c
c        adjust atom densities to volume of spheres and calculate
c        total atom density in layer
c
         totn = 0.0
         do 22 i=1,niso
            nmcnp(i) = nmcnp(i)*vol/(nfs*vfs)
            totn = totn + nmcnp(i)
 22      continue
c
c        prepare mcnp material card
c
         write (100,25) ipcyc,laynum1,totn
 25      format ('C    VSOP cycle ',i4,'; layer ',i3,
     >           '; total N = ',1pe14.7)
         do 40 i=1,nmax,3
            jmax = min(i+2,nmax)
            if (i.eq.1) then
               numold = matnum
               call mchar(numold,matnam)
               write (100,30) matnam,((zaid(ipoint(j)),nmcnp(j)),
     >                                 j=i,jmax)
 30            format(a4,1x,3(a9,1pe12.5,2x))
            else
               write (100,35) ((zaid(ipoint(j)),nmcnp(j)),j=i,jmax)
 35            format(5x,3(a9,1pe12.5,2x))
            end if
 40      continue
 45   continue
c     end for loop
c
      close (unit=97)
      close (unit=98)
      close (unit=99)
      stop
      end
```

```
      subroutine mchar(num,number)
c
c     prepare character string Mn
c
      character*4 number
      character*1 digit(10)
      data digit /'0','1','2','3','4','5','6','7','8','9'/
c
      number = 'M   '
      i = 4
      if (num .gt. 999) stop 'number > 999'
 10   continue
      n = mod(num,10) + 1
      number(i:i) = digit(n)
      num = int(num/10)
      i = i - 1
      if (i .gt. 1) go to 10
c     write (6,15) number
c15   format(1x,'material =',a4)
      return
      end
```

APPENDIX E. Plutonium Production in a Modular Pebble Bed Reactor

Appendix E.1 contains the MCNP4B input file with added lines for a MOCUP burnup calculation, which uses a supercell model to calculate plutonium production in a special, depleted-uranium pebble. Details on this model and related analysis may be found in Chapter 8.

Appendix E.2 contains the Excel spreadsheets that were used to analyze the results of the VSOP94 fuel management for the preliminary PBMR core (see Appendix D.1). The nuclide densities of fuel spheres in the batches at the bottom of the core were extracted from the VSOP94 output file prior to reload number 261. The five sets of eleven batches correspond to the five pebble flow channels in the VSOP94 model. The mass of ^{239}Pu was determined from these nuclide densities.

APPENDIX E.1: MOCUP Supercell Model of Production Sphere

```
CRITICAL DRIVER LATTICE WITH PRODUCTION PEBBLE IN CENTER
c
c   MCNP4B model of a critical spherical assembly consisting of:
c
c   - solid outer reflector
c   - lattice of driver fuel pebbles with nuclide compositions that
c     correspond to the average VSOP model of equilibrium fuel cycle
c   - a production pebble in the center with depleted uranium core
c
c   J.R. Lebenhaft, MIT, July 2000  - MCNP4B model
c   K.D. Weaver,    INEEL           - MOCUP additions
c
c   ---------------------------------------------------------------------
c   cell cards
c   ---------------------------------------------------------------------
c
1   0                1                                      $ outside world
2   64  8.67418e-02 -1  2                                   $ graphite reflector
3   0               -2                        fill=1       $ pebble bed
c
c   core
c
4   0              -12  11 -14  13  15 -16
                                              fill=2  u=1  $ production cell
5   0              (12:-11: 14:-13:-15: 16)
                                              fill=5  u=1  $ driver core
c
c   ---------------------------------------------------------------------
c   universe 2: production cell
c
10  0                  -30                    fill=6  u=2  $ production [ 0  0  0]
11  4   8.7424986E-02  -31                            u=2  $ 1/8 driver [ 1  1  1]
12  4   8.7424986e-02  -32                            u=2  $ 1/8 driver [ 1  1 -1]
13  4   8.7424986e-02  -33                            u=2  $ 1/8 driver [ 1 -1 -1]
14  4   8.7424986e-02  -34                            u=2  $ 1/8 driver [ 1 -1  1]
15  4   8.7424986e-02  -35                            u=2  $ 1/8 driver [-1  1  1]
16  4   8.7424986e-02  -36                            u=2  $ 1/8 driver [-1  1 -1]
17  4   8.7424986e-02  -37                            u=2  $ 1/8 driver [-1 -1 -1]
18  4   8.7424986e-02  -38                            u=2  $ 1/8 driver [-1 -1  1]
19  1  -3.429e-03        30  31  32  33  34
                         35  36  37  38                u=2  $ helium
c
c   .. universe 6: contents of production ball
c
20  64  8.674180e-02    40                            u=6  $ graphite shell
21  3   7.02567e-02    -40                            u=6  $ target region
c
c   ---------------------------------------------------
c   universe 5: driver lattice
c
70  0                  -12  11 -14  13  15
                       -16           lat=1 fill=10  u=5  $ driver cell
c
```

```
c   .. universe 10: contents of driver cell
71  4   8.7424986e-02  -30                              u=10 $ 1   driver [ 0  0  0]
72  4   8.7424986e-02  -31                              u=10 $ 1/8 driver [ 1  1  1]
73  4   8.7424986e-02  -32                              u=10 $ 1/8 driver [ 1  1 -1]
74  4   8.7424986e-02  -33                              u=10 $ 1/8 driver [ 1 -1 -1]
75  4   8.7424986e-02  -34                              u=10 $ 1/8 driver [ 1 -1  1]
76  4   8.7424986e-02  -35                              u=10 $ 1/8 driver [-1  1  1]
77  4   8.7424986e-02  -36                              u=10 $ 1/8 driver [-1  1 -1]
78  4   8.7424986e-02  -37                              u=10 $ 1/8 driver [-1 -1 -1]
79  4   8.7424986e-02  -38                              u=10 $ 1/8 driver [-1 -1  1]
80  1  -3.429e-03       30  31  32  33  34
                       35  36  37  38                   u=10 $ helium

c   ------------------------------------------------------------
c   surface cards
c   ------------------------------------------------------------
c   universe boundaries
c
1      so 250.0                                          $ outer reflector
2      so 200.0                                          $ driver region
c      1      so 350.0                                   $ outer reflector
c      2      so 258.7                                   $ driver region
c
c   production cell boundaries
c
11     px  -3.592148
12     px   3.592148
13     py  -3.592148
14     py   3.592148
15     pz  -3.592148
16     pz   3.592148
c
c   balls in unit bcc lattice
c
30     so   3.0
31     s    3.592148  3.592148  3.592148  3.0
32     s    3.592148  3.592148 -3.592148  3.0
33     s    3.592148 -3.592148 -3.592148  3.0
34     s    3.592148 -3.592148  3.592148  3.0
35     s   -3.592148  3.592148  3.592148  3.0
36     s   -3.592148  3.592148 -3.592148  3.0
37     s   -3.592148 -3.592148 -3.592148  3.0
38     s   -3.592148 -3.592148  3.592148  3.0
c
c    production fuel
c
40     so   2.1                                         $ fueled region in ball

c   ------------------------------------------------------------
c   run time cards
c   ------------------------------------------------------------
c
c   ------------------------------------------------------------
c   material cards
c   ------------------------------------------------------------
c
c    helium (1200 K)
```

```
m1    2003.50c  0.00000137    2004.50c 0.99999863
c
c     UO2 (U235/U = 0.002)
m3      8016.60c 0.0468378
        36083.50c 1.000E-24
        40091.86c 1.000E-24  40093.86c 1.000E-24
        42095.50c 1.000E-24  42097.60c 1.000E-24
        42098.50c 1.000E-24  43099.60c 1.000E-24
        44101.50c 1.000E-24  45103.86c 1.000E-24
        45105.86c 1.000E-24  46105.50c 1.000E-24
        46107.96c 1.000E-24  47109.86c 1.000E-24
        48113.86c 1.000E-24  53129.86c 1.000E-24
        54131.86c 1.000E-24  54133.86c 1.000E-24
        55133.86c 1.000E-24  55134.86c 1.000E-24
        54135.54c 1.000E-24  55135.86c 1.000E-24
        57139.60c 1.000E-24  59141.50c 1.000E-24
        60143.50c 1.000E-24  60144.96c 1.000E-24
        60145.50c 1.000E-24  61147.50c 1.000E-24
        62147.50c 1.000E-24  60148.50c 1.000E-24
        61148.50c 1.000E-24  61148.91c 1.000E-24
        61149.50c 1.000E-24  62149.50c 1.000E-24
        62150.50c 1.000E-24  62151.50c 1.000E-24
        63151.50c 1.000E-24  62152.50c 1.000E-24
        63153.60c 1.000E-24  63154.50c 1.000E-24
        63155.50c 1.000E-24  64157.86c 1.000E-24
        90232.86c 1.000E-24
        91231.60c 1.000E-24
        91233.50c 1.000E-24
        92232.60c 1.000E-24
        92233.86c 1.000E-24
        92234.86c 1.000E-24
        92235.54c 4.680E-05
        92236.86c 1.000E-24
        92238.54c 2.33721E-02
        93237.50c 1.000E-24
        93238.35c 1.000E-24
        93239.60c 1.000E-24
        94238.86c 1.000E-24
        94239.82c 1.000E-24
        94240.82c 1.000E-24
        94241.82c 1.000E-24
        94242.82c 1.000E-24
        95241.98c 1.000E-24
        95242.92c 1.000E-24
        95243.88c 1.000E-24
        96244.98c 1.000E-24
c
c     VSOP cycle  261; layer average; total N =  8.7424986E-02
c
m4    92235.54c 7.26748E-06  92236.86c 7.90922E-07  92238.54c 1.38334E-04
      93239.60c 2.31130E-08  94239.82c 5.65635E-07  94240.82c 2.52409E-07
      94241.82c 1.22065E-07  94242.82c 3.42635E-08  93237.50c 1.99774E-08
      54135.54c 1.19503E-10  36083.50c 2.07351E-08  42095.50c 2.17681E-07
      43099.60c 2.87436E-07  44101.50c 2.51240E-07  44103.50c 3.27984E-08
      45103.86c 1.26674E-07  45105.86c 7.00813E-10  46105.50c 8.38273E-08
      46108.50c 2.51655E-08  47109.86c 1.40838E-08  48000.50c 2.99848E-11
      54131.86c 1.25169E-07  55133.86c 3.07103E-07  55134.86c 1.19076E-08
```

```
      59141.50c 2.78676E-07  60143.50c 2.18084E-07  60145.50c 1.76511E-07
      61147.50c 7.52556E-08  61148.50c 6.39397E-10  62147.50c 1.10404E-08
      61149.50c 7.32471E-10  62149.50c 1.03964E-09  62150.50c 5.90797E-08
      62151.50c 4.31815E-09  62152.50c 3.03251E-08  63153.60c 1.65125E-08
      63154.50c 2.34477E-09  63155.50c 1.10775E-09  64155.50c 1.68288E-11
      64156.50c 4.56568E-09  64157.86c 1.63416E-11   5010.50c 7.58592E-09
      14000.50c 3.41384E-04   6000.50c 8.66292E-02   8016.60c 3.04562E-04
mt4   grph.06t
c
c     graphite matrix in fuel pebble (N = 8.674180e-02)
c
m64    6000.50c  8.674169e-02     5011.50c  9.032424e-08
       5010.50c  2.244010e-08
mt64  grph.06t
c
c     U238 for (n,gamma) reaction rate tally
c m5   92238.50c 1
c
c Tally Materials
c
m701     36083.50c     1.000
m702     40091.86c     1.000
m703     40093.86c     1.000
m704     42095.50c     1.000
m705     42097.60c     1.000
m706     42098.50c     1.000
m707     43099.60c     1.000
m708     44101.50c     1.000
m709     45103.86c     1.000
m710     45105.86c     1.000
m711     46105.50c     1.000
m712     46107.96c     1.000
m713     47109.86c     1.000
m714     48113.86c     1.000
m715     53129.86c     1.000
m716     54131.86c     1.000
m717     54133.86c     1.000
m718     55133.86c     1.000
m719     55134.86c     1.000
m720     54135.54c     1.000
m721     55135.86c     1.000
m722     57139.60c     1.000
m723     59141.50c     1.000
m724     60143.50c     1.000
m725     60144.96c     1.000
m726     60145.50c     1.000
m727     61147.50c     1.000
m728     62147.50c     1.000
m729     60148.50c     1.000
m730     61148.50c     1.000
m731     61148.91c     1.000
m732     61149.50c     1.000
m733     62149.50c     1.000
m734     62150.50c     1.000
m735     62151.50c     1.000
m736     63151.50c     1.000
m737     62152.50c     1.000
```

```
m738     63153.60c    1.000
m739     63154.50c    1.000
m740     63155.50c    1.000
m741     64157.86c    1.000
m801     90232.86c    1.000
m802     91231.60c    1.000
m803     91233.50c    1.000
m804     92232.60c    1.000
m805     92233.86c    1.000
m806     92234.86c    1.000
m807     92235.54c    1.000
m808     92236.86c    1.000
m809     92238.54c    1.000
m810     93237.50c    1.000
m811     93238.35c    1.000
m812     93239.60c    1.000
m813     94238.86c    1.000
m814     94239.82c    1.000
m815     94240.82c    1.000
m816     94241.82c    1.000
m817     94242.82c    1.000
m818     95241.98c    1.000
m819     95242.92c    1.000
m820     95243.88c    1.000
m821     96244.98c    1.000
c
c   sources
c
ksrc  3.2   3.2   3.2
      2.5   2.5   2.5
     -3.2  -3.2   3.2
     -2.5  -2.5   2.5
      3.2  -3.2  -3.2
      2.5  -2.5  -2.5
     -3.2   3.2  -3.2
     -2.5   2.5  -2.5
c
c   ---------------------------------------------------------------
c   tally specifications
c   ---------------------------------------------------------------
c
fq0    e f
c
c fc7   fission source for normalization (per unit mass)
c f7:n  3
c sd7   1
c
c fc4   average neutron flux in production cell
c f4:n  4
c sd4   370.811
c e4    1.86e-6 29e-6 100e-3 20
c
c fc14  average U238 absorption rate in production ball
c f14:n (21 < 10 < 4 < 3)
c     atom density of depleted UO2 (1/b-cm)
c fm14  2.31457e-02  5  102
c     volume of target (cm3)
```

```
c sd14  38.7924
c e14   1.86e-6 20
c
c fc24  average U238 absorption rate in driver ball
c f24:n ((11 12 13 14 15 16 17 18) < 4 < 3)
c     atom density of U238 (1/b-cm) from m4 card
c fm24  1.11479e-04  5  102
c sd24  113.0973
c e24   1.86e-6 20
c
c  ---------------------------------------------------------------------
c
c       (total fuel volume = 38.79 cm*3)
fc54    Total Fissions       Total Fission Neutrons
fm54   (-38.79   3  (-6)  (-6 -7))
f54:n  21
c
c  ---------------------------------------------------------------------
c
c    begin_mocup_flux_tallies
c    time dependent flux
fc94    Cell-averaged neutron flux (neutrons/cm**2 per source neutron)
f94:n 21
c    end_mocup_flux_tallies
c
c  ---------------------------------------------------------------------
c
c    begin_mocup_reaction_rate_tallies
c    time dependent reaction rates
fc904  (n,x) reactions - fuel region
f904:n 21
fm904   (1.0 701                          (102))
        (1.0 702                          (102))
        (1.0 703                          (102))
        (1.0 704                          (102))
        (1.0 705                          (102))
        (1.0 706                          (102))
        (1.0 707                          (102))
        (1.0 708                          (102))
        (1.0 709                          (102))
        (1.0 710                          (102))
        (1.0 711                          (102))
        (1.0 712                          (102))
        (1.0 713                          (102))
        (1.0 714                          (102))
        (1.0 715                          (102))
        (1.0 716                          (102))
        (1.0 717                          (102))
        (1.0 718                          (102))
        (1.0 719                          (102))
        (1.0 720                          (102))
        (1.0 721                          (102))
        (1.0 722                          (102))
        (1.0 723                          (102))
        (1.0 724                          (102))
        (1.0 725                          (102))
        (1.0 726                          (102))
```

```
         (1.0 727                          (102))
         (1.0 728                          (102))
         (1.0 729                          (102))
         (1.0 730                          (102))
         (1.0 731                          (102))
         (1.0 732                          (102))
         (1.0 733                          (102))
         (1.0 734                          (102))
         (1.0 735                          (102))
         (1.0 736                          (102))
         (1.0 737                          (102))
         (1.0 738                          (102))
         (1.0 739                          (102))
         (1.0 740                          (102))
         (1.0 741                          (102))
         (1.0 801 (16) (17) (18)           (102))$
         (1.0 802 (16) (17) (18)           (102))$
         (1.0 803 (16) (17) (18)           (102))$
         (1.0 804 (16) (17) (18)           (102))$
         (1.0 805 (16) (17) (18)           (102))$
         (1.0 806 (16) (17)       (19:20)  (102))$
         (1.0 807 (16) (17)       (19:20)  (102))$
         (1.0 808 (16) (17)       (19:20)  (102))$
         (1.0 809 (16) (17)       (19:20)  (102))$
         (1.0 810 (16) (17) (18)           (102))$
         (1.0 811 (16) (17)       (19)     (102))$
         (1.0 812 (16) (17) (18)           (102))$
         (1.0 813 (16) (17)       (19:20)  (102))$
         (1.0 814 (16) (17) (18)           (102))$
         (1.0 815 (16) (17)       (19:20)  (102))$
         (1.0 816 (16) (17) (18)           (102))$
         (1.0 817 (16) (17) (18)           (102))$
         (1.0 818 (16) (17) (18)           (102))$
         (1.0 819 (16) (17)       (19:20)  (102))$
         (1.0 820 (16) (17)       (19:20)  (102))$
         (1.0 821 (16) (17)       (19:20)  (102))$
c    end_mocup_reaction_rate_tallies
c
c  ---------------------------------------------------------------------
c
c   neutron importance
c
imp:n  0                                                  $ outside world
       1                                                  $ outer reflector
       1                                                  $ pebble bed
       1 1                                                $ u=1:  target, driver
core
       1 9r                                               $ u=2:  production cell
       1 1                                                $ u=6:  production ball
       1                                                  $ u=5:  driver lattice
       1 9r                                               $ u=10: unit driver fuel
cell
c
mode  n
phys:p  1j 1
kcode  5000  1.0  10  210
prdmp  55  55  55
```

```
print  -60  -85  -130  -140
```

APPENDIX E.2: Excel analysis of VSOP94 equilibrium core results

Data used in calculations:

Gram atomic weights

U235	U236	U238	Pu239	Pu240	Pu241	Pu242	NP237
235.0439	236.0456	238.0508	239.0522	240.0538	241.0568	242.0587	237.0482

Avogadro's number	6.02E+23	
pebble volume	113.0973	cm3
packing fraction	0.61	

Composition of used fuel balls in batches at bottom of core before removal:

discharge burnup 79677 MWd/t
average enrichment 4.33 % 9 g HM; 0.97885 g fissile per fuel sphere
passes through core 10
avg. fuel residence tim 198.5 days

	batch	(cm3) volume	HM	atom density (1/b-cm) U-235	U-236	U-238	NP-239	PU-239	PU-240	PU-241	PU-242	NP-237
1	89	636 42	30.893	7.12E-06	4.05E-07	1.13E-04	2.07E-08	1.76E-07	4.52E-08	4.49E-09	3.48E-10	1.70E-09
	90	637.96	30.968	5.95E-06	6.08E-07	1.12E-04	2.06E-08	2.58E-07	1.55E-07	2.80E-08	4.93E-09	5.00E-09
	91	638.86	31.012	4.96E-06	7.75E-07	1.12E-04	2.05E-08	2.91E-07	2.48E-07	5.90E-08	1.68E-08	1.04E-08
	92	639.76	31.056	4.13E-06	9.11E-07	1.11E-04	2.05E-08	3.03E-07	3.16E-07	9.00E-08	3.67E-08	1.73E-08
	93	640.67	31.099	3.44E-06	1.02E-06	1.11E-04	2.04E-08	3.07E-07	3.62E-07	1.17E-07	6.32E-08	2.51E-08
	94	641.57	31.143	2.86E-06	1.11E-06	1.10E-04	2.03E-08	3.07E-07	3.92E-07	1.37E-07	9.45E-08	3.35E-08
	95	642.47	31.187	2.37E-06	1.18E-06	1.10E-04	2.02E-08	3.07E-07	4.10E-07	1.52E-07	1.29E-07	4.22E-08
	96	643.38	31.231	1.96E-06	1.24E-06	1.09E-04	2.01E-08	3.06E-07	4.21E-07	1.63E-07	1.65E-07	5.09E-08
	97	644.29	31.275	1.62E-06	1.28E-06	1.09E-04	2.00E-08	3.05E-07	4.28E-07	1.70E-07	2.02E-07	5.95E-08
	98	645.2	31.319	1.33E-06	1.32E-06	1.08E-04	1.99E-08	3.03E-07	4.31E-07	1.74E-07	2.39E-07	6.77E-08
	99	1.27E+06	47.795	5 06E-10	2.88E-11	9.45E-08	1.74E-11	1.47E-10	3.78E-11	3.76E-12	2.91E-13	1.21E-13
2	199	63642	3089.3	7.55E-06	3.49E-07	1.13E-04	2.18E-08	2.80E-07	5.80E-08	5.22E-09	3.02E-10	2.23E-09
	200	63729	3093.6	6.30E-06	5.60E-07	1.12E-04	2.17E-08	3.88E-07	1.66E-07	2.68E-08	3.67E-09	6.62E-09
	201	63819	3097.9	5.26E-06	7.33E-07	1.12E-04	2.16E-08	4.30E-07	2.60E-07	5.88E-08	1.38E-08	1.30E-08
	202	63909	3102.3	4.38E-06	8.75E-07	1.11E-04	2.15E-08	4.45E-07	3.31E-07	9.24E-08	3 17E-08	2.07E-08
	203	63999	3106.7	3.65E-06	9.91E-07	1.11E-04	2.14E-08	4.50E-07	3.79E-07	1.22E-07	5.64E-08	2.92E-08
	204	64090	3111.1	3.03E-06	1.08E-06	1.10E-04	2.13E-08	4.51E-07	4.10E-07	1.46E-07	8.62E-08	3.83E-08
	205	64180	3115.4	2.51E-06	1.16E-06	1.10E-04	2.12E-08	4.50E-07	4.30E-07	1.63E-07	1.19E-07	4.75E-08
	206	64270	3119.8	2.08E-06	1 22E-06	1.09E-04	2.11E-08	4.49E-07	4.42E-07	1.75E-07	1.55E-07	5.66E-08
	207	64361	3124.2	1.71E-06	1.27E-06	1.09E-04	2.10E-08	4.47E-07	4.49E-07	1.83E-07	1.90E-07	6.56E-08
	208	64452	3128.6	1.40E-06	1.30E-06	1 08E-04	2.09E-08	4.45E-07	4.52E-07	1.88E-07	2.26E-07	7.42E-08
	209	6.32E+05	23.866	5.36E-10	2.48E-11	9.44E-08	1.82E-11	2.34E-10	4.86E-11	4.37E-12	2.53E-13	1.59E-13
3	320	1.27E+05	6178.6	8.19E-06	2.57E-07	1.13E-04	1.94E-08	3 30E-07	5.03E-08	7.29E-09	3.02E-10	1.66E-09
	321	1.27E+05	6187.4	6.84E-06	4.83E-07	1 12E-04	1.93E-08	4.69E-07	1.38E-07	3.86E-08	3.59E-09	6.23E-09
	322	1.28E+05	6196.1	5.71E-06	6.69E-07	1.12E-04	1.92E-08	5.24E-07	2.17E-07	8.53E-08	1.31E-08	1.27E-08
	323	1.28E+05	6204.8	4.75E-06	8.22E-07	1.11E-04	1.91E-08	5.44E-07	2.76E-07	1.34E-07	3.00E-08	2.06E-08
	324	1 28E+05	6213.6	3.96E-06	9.46E-07	1.11E-04	1.91E-08	5.51E-07	3.16E-07	1.76E-07	5.36E-08	2.93E-08
	325	1.28E+05	6222.3	3.29E-06	1.05E-06	1.10E-04	1.90E-08	5.52E-07	3.43E-07	2.08E-07	8.24E-08	3.84E-08
	326	1.28E+05	6231.1	2.72E-06	1 13E-06	1.10E-04	1.89E-08	5.51E-07	3.59E-07	2.33E-07	1.15E-07	4.77E-08
	327	1.29E+05	6239 9	2.25E-06	1.19E-06	1.09E-04	1.88E-08	5.49E-07	3.69E-07	2.49E-07	1.49E-07	5.70E-08
	328	1.29E+05	6248.7	1.85E-06	1.24E-06	1 09E-04	1.87E-08	5.46E-07	3.75E-07	2.60E-07	1.85E-07	6.60E-08
	329	1.21E+05	5862.9	1.52E-06	1.28E-06	1.08E-04	1.86E-08	5.44E-07	3.78E-07	2.67E-07	2.21E-07	7.47E-08
	330	1	3.77E-05	5.82E-10	1.82E-11	9.43E-08	1.62E-11	2.76E-10	4.21E-11	6.10E-12	2.53E-13	1.18E-13
4	452	1.27E+05	6178.6	8.28E-06	2.42E-07	1.13E-04	1.67E-08	3.31E-07	4.66E-08	6.31E-09	2.44E-10	1.54E-09
	453	1.27E+05	6187.4	6.91E-06	4.71E-07	1.12E-04	1.66E-08	4.77E-07	1.34E-07	3.62E-08	3.24E-09	6.04E-09
	454	1.28E+05	6196.1	5.77E-06	6.59E-07	1.12E-04	1.65E-08	5.35E-07	2.14E-07	8.23E-08	1.23E-08	1.25E-08
	455	1.28E+05	6204.8	4.80E-06	8.14E-07	1.11E-04	1.64E-08	5.57E-07	2.75E-07	1.31E-07	2.87E-08	2.03E-08
	456	1.28E+05	6213.6	4.00E-06	9.40E-07	1.11E-04	1.64E-08	5.64E-07	3.16E-07	1.73E-07	5.19E-08	2.90E-08
	457	1.28E+05	6222.3	3.32E-06	1.04E-06	1.10E-04	1.63E-08	5.65E-07	3.43E-07	2.06E-07	8.05E-08	3.82E-08
	458	1.28E+05	6231.1	2.75E-06	1.12E-06	1.10E-04	1.62E-08	5.64E-07	3.60E-07	2.31E-07	1.13E-07	4.75E-08
	459	1.29E+05	6239.9	2.27E-06	1.19E-06	1.09E-04	1.62E-08	5.62E-07	3.71E-07	2.48E-07	1.47E-07	5.68E-08
	460	1.29E+05	6248.7	1.87E-06	1.24E-06	1.09E-04	1.61E-08	5.60E-07	3.77E-07	2.59E-07	1.83E-07	6.59E-08
	461	1.21E+05	5863	1.54E-06	1.28E-06	1.08E-04	1.60E-08	5.57E-07	3.80E-07	2.66E-07	2.18E-07	7.46E-08
	462	1	3.77E-05	5.88E-10	1.72E-11	9.44E-08	1.39E-11	2.77E-10	3.90E-11	5.28E-12	2.04E-13	1.09E-13
5	617	1.27E+05	6178.6	8.06E-06	2.75E-07	1.13E-04	1.16E-08	3.05E-07	5.24E-08	8.48E-09	4.00E-10	1.68E-09
	618	1.27E+05	6187.4	6.73E-06	4.99E-07	1.12E-04	1.16E-08	4.30E-07	1.41E-07	4.26E-08	4.30E-09	6.03E-09
	619	1.28E+05	6196.1	5.61E-06	6.83E-07	1.12E-04	1.15E-08	4.79E-07	2.17E-07	9.04E-08	1.47E-08	1.23E-08
	620	1.28E+05	6204.8	4.68E-06	8.33E-07	1.11E-04	1.15E-08	4.97E-07	2.74E-07	1.39E-07	3.25E-08	2.00E-08
	621	1.28E+05	6213.6	3.89E-06	9.57E-07	1.11E-04	1.14E-08	5.03E-07	3.12E-07	1.80E-07	5.70E-08	2.85E-08
	622	1.28E+05	6222.3	3.23E-06	1.06E-06	1.10E-04	1.14E-08	5.04E-07	3.37E-07	2.12E-07	8.65E-08	3.75E-08
	623	1.28E+05	6231.1	2.67E-06	1.14E-06	1.10E-04	1.13E-08	5.03E-07	3.53E-07	2.35E-07	1.19E-07	4.66E-08
	624	1.29E+05	6239.9	2.21E-06	1.20E-06	1.09E-04	1.13E-08	5.01E-07	3.62E-07	2.51E-07	1.54E-07	5.58E-08
	625	1.29E+05	6248.7	1.82E-06	1.25E-06	1.09E-04	1.12E-08	4.99E-07	3.67E-07	2.62E-07	1.90E-07	6.47E-08
	626	1.21E+05	5863.1	1.49E-06	1.29E-06	1.08E-04	1.12E-08	4.97E-07	3.70E-07	2.68E-07	2.26E-07	7.33E-08
	627	1	3.77E-05	5.73E-10	1.95E-11	9.44E-08	9.72E-12	2.56E-10	4.39E-11	7.10E-12	3.35E-13	1.19E-13

discharge volume = 4.27E+05

Mass of uranium and plutonium in batches at bottom of core before removal:

channel	batch	U-235	U-236	U-238	PU-239	PU-240	PU-241	PU-242	NP-237	total HM	Pu	compare with HM	# pebbles	HM is the total heavy metal content reported by VSOP.
						mass (g)								
1	89	1.77E+00	1.01E-01	2.84E+01	4.43E-02	1.15E-02	1.14E-03	8.91E-05	4.26E-04	30.32	[illegible]	30.893	[illegible]	<-- first pass through core
	90	1.48E+00	1.52E-01	2.83E+01	6.54E-02	3.95E-02	7.16E-03	1.26E-03	1.26E-03	30.09	1.13E-01	30 968	3	
	91	1.24E+00	1.94E-01	2.83E+01	7.37E-02	6.32E-02	1.51E-02	4.32E-03	2.62E-03	29.85	1.58E-01	31.012	3	
	92	1.03E+00	2.28E-01	2.82E+01	7.69E-02	8.06E-02	2.30E-02	9.43E-03	4.35E-03	29.63	1.90E-01	31 056	3	
	93	8.61E-01	2.57E-01	2.81E+01	7.80E-02	9.24E-02	2.99E-02	1.63E-02	6.34E-03	29.43	2.17E-01	31.099	3	
	94	7.16E-01	2.79E-01	2.80E+01	7.83E-02	1.00E-01	3.52E-02	2.44E-02	8.47E-03	29.25	2.38E-01	31 143	3	
	95	5.94E-01	2.98E-01	2.79E+01	7.83E-02	1.05E-01	3.91E-02	3.33E-02	1.07E-02	29.08	2.56E-01	31 187	3	
	96	4.92E-01	3.13E-01	2.78E+01	7.81E-02	1.08E-01	4.19E-02	4.27E-02	1.29E-02	28.92	2.71E-01	31 231	3	
	97	4.08E-01	3.24E-01	2.78E+01	7.79E-02	1 10E-01	4.37E-02	5.23E-02	1.51E-02	28.78	2.84E-01	31.275	3	
	98	3.34E-01	3.33E-01	2.77E+01	7.77E-02	1.11E-01	4.49E-02	6.19E-02	1.72E-02	28.64	2.95E-01	31.319	[illegible]	<-- discharge
	99	2.50E-01	1.43E-02	4.73E+01	7.39E-02	1 91E-02	1.90E-03	1.48E-04	6.02E-05	47.66	9.50E-02	47 795	6830	<-- graphite balls with trace fissile (not included in claculations he
2	199	1.87E+02	8.71E+00	2.84E+03	7.07E+00	1.47E+00	1.33E-01	7.73E-03	5.59E-02	3040.87	[illegible]	3089 3	[illegible]	<-- first pass through core
	200	1.57E+02	1.40E+01	2.83E+03	9.81E+00	4 21E+00	6.85E-01	9.41E-02	1.66E-01	3013.20	1.48E+01	3093 6	343	
	201	1.31E+02	1.83E+01	2.82E+03	1.09E+01	6.62E+00	1.50E+00	3.54E-01	3.26E-01	2988.39	1.94E+01	3097 9	344	
	202	1.09E+02	2.19E+01	2 81E+03	1.13E+01	8.42E+00	2.36E+00	8.15E-01	5.20E-01	2965.64	2.29E+01	3102.3	344	
	203	9.11E+01	2.49E+01	2.80E+03	1.14E+01	9.66E+00	3.13E+00	1.45E+00	7.36E-01	2944.92	2.57E+01	3106.7	345	
	204	7.58E+01	2.72E+01	2.79E+03	1.15E+01	1.05E+01	3.73E+00	2.22E+00	9 65E-01	2926.02	2.79E+01	3111 1	345	
	205	6.29E+01	2.92E+01	2.79E+03	1.15E+01	1 10E+01	4.18E+00	3.08E+00	1.20E+00	2908.88	2.97E+01	3115.4	346	
	206	5.21E+01	3.07E+01	2.78E+03	1.14E+01	1.13E+01	4.50E+00	3.99E+00	1.43E+00	2892.80	3.13E+01	3119.8	346	
	207	4.30E+01	3.19E+01	2.77E+03	1.14E+01	1.15E+01	4.72E+00	4.93E+00	1.66E+00	2877.91	3.26E+01	3124.2	347	
	208	3.53E+01	3 28E+01	2.76E+03	1.14E+01	1 16E+01	4.85E+00	5.86E+00	1.88E+00	2863.97	3.37E+01	3128.6	[illegible]	<-- discharge
	209	1.32E-01	8.14E-03	2.36E+01	5 88E-02	1.22E-02	1.11E-03	6 43E-05	3.95E-05	23.80	7 22E-02	23 866	3410	<-- 1:1 mix of graphite and fuel
3	320	4.07E+02	1.28E+01	5.67E+03	1.67E+01	2.55E+00	3 71E-01	1.54E-02	8 33E-02	6109 64	[illegible]	6178 6	[illegible]	<-- first pass through core
	321	3.40E+02	2.41E+01	5.65E+03	2.37E+01	7 03E+00	1.97E+00	1.84E-01	3.12E-01	6051.17	3.29E+01	6187.4	687	
	322	2.84E+02	3.35E+01	5.64E+03	2.65E+01	1.10E+01	4.36E+00	6.74E-01	6.40E-01	5997.82	4.26E+01	6196.1	688	
	323	2.37E+02	4.12E+01	5.62E+03	2.76E+01	1.41E+01	6 84E+00	1.54E+00	1 04E+00	5949.98	5.00E+01	6204 8	689	
	324	1.98E+02	4.75E+01	5 60E+03	2.80E+01	1.61E+01	8 99E+00	2.78E+00	1.47E+00	5906.14	5.59E+01	6213.6	690	
	325	1 64E+02	5 26E+01	5 59E+03	2.81E+01	1.75E+01	1.07E+01	4.25E+00	1.94E+00	5866 21	6 05E+01	6222.3	691	
	326	1.36E+02	5.68E+01	5.57E+03	2.81E+01	1 84E+01	1 19E+01	5.92E+00	2.41E+00	5829 66	6.43E+01	6231.1	692	
	327	1.13E+02	6.01E+01	5.55E+03	2.80E+01	1.89E+01	1 28E+01	7 72E+00	2.88E+00	5796 99	6 75E+01	6239 9	693	
	328	9.32E+01	6.28E+01	5.54E+03	2.79E+01	1.92E+01	1 34E+01	9.57E+00	3.35E+00	5765.32	7 01E+01	6248.7	694	
	329	7 17E+01	8 07E+01	5 17E+03	2.61E+01	1 82E+01	1.29E+01	1.07E+01	3 55E+00	5374 50	6.79E+01	5862.9	[illegible]	<-- discharge
	330	2.27E-07	7.14E-09	3.73E-05	1 10E-07	1.68E-08	2.44E-09	1.02E-10	4 65E-11	3.77E-05	1.29E-07	3 77E-05	0	<-- graphite balls with trace fissile
4	452	4.11E+02	1.21E+01	5.67E+03	1 67E+01	2.37E+00	3.22E-01	1.25E-02	7 69E-02	6114.13	[illegible]	6178 6	[illegible]	<-- first pass through core
	453	3.44E+02	2.35E+01	5.65E+03	2.42E+01	6.83E+00	1.85E+00	1.66E-01	3 03E-01	6055.33	3.30E+01	6187.4	687	
	454	2.87E+02	3.30E+01	5 64E+03	2.71E+01	1 09E+01	4.21E+00	6.32E-01	6.29E-01	6001.62	4.29E+01	6196.1	688	
	455	2 40E+02	4 08E+01	5.62E+03	2.82E+01	1 40E+01	6.69E+00	1 48E+00	1 02E+00	5952.96	5.04E+01	6204.8	689	
	456	2.00E+02	4.72E+01	5.60E+03	2.86E+01	1 61E+01	8.87E+00	2.67E+00	1 46E+00	5908 83	5.63E+01	6213 6	690	
	457	1.68E+02	5.24E+01	5.59E+03	2.87E+01	1.75E+01	1.06E+01	4.15E+00	1.93E+00	5869.15	6 10E+01	6222 3	691	
	458	1.38E+02	5.66E+01	5.57E+03	2.87E+01	1.84E+01	1.19E+01	5 81E+00	2 40E+00	5832.39	6.48E+01	6231.1	692	
	459	1.14E+02	6.00E+01	5 55E+03	2 87E+01	1.90E+01	1 28E+01	7.60E+00	2 88E+00	5799 02	6 80E+01	6239 9	693	
	460	9.41E+01	6.26E+01	5.54E+03	2.86E+01	1.93E+01	1 34E+01	9.45E+00	3 34E+00	5767 69	7.07E+01	6248 7	694	
	461	7 24E+01	6 06E+01	5.17E+03	2.67E+01	1 83E+01	1 29E+01	1.06E+01	3 55E+00	5376.59	6.85E+01	5863	[illegible]	<-- discharge
	462	2.29E-07	6 75E-09	3.73E-05	1 10E-07	1 56E-08	2.12E-09	8.21E-11	4.29E-11	3 77E-05	1.28E-07	3 77E-05	0	<-- graphite balls with trace fissile
5	617	4 01E+02	1.37E+01	5.67E+03	1.54E+01	2.66E+00	4.32E-01	2 04E-02	8.41E-02	6104.12	[illegible]	6178 6	[illegible]	<-- first pass through core
	618	3.35E+02	2.49E+01	5.65E+03	2.18E+01	7 16E+00	2.17E+00	2.20E-01	3.02E-01	6045.96	3.13E+01	6187 4	687	
	619	2.80E+02	3.41E+01	5 64E+03	2.43E+01	1.11E+01	4 62E+00	7.55E-01	6.20E-01	5993.49	4.07E+01	6196 1	688	
	620	2 33E+02	4.18E+01	5 62E+03	2 52E+01	1.39E+01	7.09E+00	1 67E+00	1 01E+00	5945 53	4 79E+01	6204 8	689	
	621	1 94E+02	4.80E+01	5 60E+03	2.56E+01	1 59E+01	9 21E+00	2.93E+00	1.44E+00	5902.02	5 36E+01	6213 6	690	
	622	1.61E+02	5 31E+01	5.59E+03	2 57E+01	1.72E+01	1.09E+01	4.45E+00	1.89E+00	5862.41	5 82E+01	6222 3	691	
	623	1 34E+02	5.72E+01	5.57E+03	2.56E+01	1.80E+01	1.21E+01	6.16E+00	2 36E+00	5826 13	6 19E+01	6231.1	692	
	624	1 11E+02	6 05E+01	5 55E+03	2.56E+01	1 86E+01	1.29E+01	7 98E+00	2.82E+00	5793 18	6 50E+01	6239 9	693	
	625	9.13E+01	6.31E+01	5.54E+03	2.55E+01	1 89E+01	1.35E+01	9 85E+00	3 28E+00	5762 23	6.77E+01	6248 7	694	
	626	7 01E+01	6.10E+01	5.17E+03	2 38E+01	1.78E+01	1 30E+01	1 10E+01	3 48E+00	5371 75	6.56E+01	5863 1	[illegible]	<-- discharge
	627	2.23E-07	7 65E-09	3 73E-05	1.01E-07	1.75E-08	2.84E-09	1 34E-10	4 69E-11	3.77E-05	1.22E-07	3 77E-05	0	<-- graphite balls with trace fissile

Total plutonium in batch groups: 6.406 d bumup step

batch group	total Pu	grams Pu239	% Pu239	# pebbles	time/peb	gPu/FS	#FS / 8 kg	gPu239/FS	#FS/6kg	
1	66.29	55.91	84.34%	2404	4 min	0 028	290137	[illegible]	257991	<-- first pass
2	112.14	79.54	70.93%	2407	4 min	0 047		0.033	181574	FS = fuel sphere
3	145.70	88.88	61.00%	2411	4 min	0 060		0.037	162763	
4	171 47	92.45	53.92%	2414	4 min	0 071		0.038	156669	
5	191.71	93.70	48.88%	2418	4 min	0.079		0 039	154832	
6	207.89	94.02	45.23%	2421	4 min	0 086		0.039	154491	
7	221 07	93.98	42.51%	2425	4 min	0 091		0 039	154825	
8	232.07	93.79	40.41%	2428	4 min	0 096		0.039	155331	
9	241.43	93 53	38.74%	2432	4 min	0 099		0.038	156010	
10	235.98	88.09	37 33%	2303	4 min	0 102	78075	0.038	156853	<-- normally discharged
					24063	23 sec				

Analysis of VSOP discharge data:

volume discarded	4.51E+05
packing fraction	6.10E-01
pebble volume	1.13E+02
# pebbles discarded	2.43E+03

	g.a.w.	1/barn-cm	g HM	gHM/peb	# peb for 6 kg HM	# peb for 8 kg HM
Pu-239	239 0522	5.19E-07	93.02	0 0382	156,935	
Pu-240	240 0538	3.87E-07	69.64	0 0286		
Pu-241	241.0568	2.55E-07	46.03	0 0189		
Pu-242	242 0587	2.21E-07	40.00	0.0164		
total			248.69	0 1022	78,266	

Fractions of plutonium isotopes in batches at bottom of core before removal:

channel	batch	PU-239	PU-240	PU-241	PU-242	total
1	89	77.74%	20.09%	2.00%	0.16%	100.00%
	90	57.68%	34.89%	6.31%	1.11%	100.00%
	91	47.13%	40.46%	9.65%	2.76%	100.00%
	92	40.47%	42.43%	12.13%	4.96%	100.00%
	93	36.02%	42.67%	13.80%	7.51%	100.00%
	94	32.89%	42.07%	14.80%	10.24%	100.00%
	95	30.60%	41.07%	15.31%	13.02%	100.00%
	96	28.85%	39.91%	15.47%	15.78%	100.00%
	97	27.45%	38.70%	15.41%	18.44%	100.00%
	98					100.00%
	99	77.74%	20.09%	2.00%	0.16%	100.00%
2	199	81.42%	16.95%	1.53%	0.09%	100.00%
	200	66.30%	28.43%	4.63%	0.64%	100.00%
	201	56.22%	34.20%	7.75%	1.83%	100.00%
	202	49.34%	36.78%	10.32%	3.56%	100.00%
	203	44.55%	37.62%	12.17%	5.65%	100.00%
	204	41.13%	37.54%	13.37%	7.96%	100.00%
	205	38.58%	36.99%	14.07%	10.36%	100.00%
	206	36.62%	36.21%	14.40%	12.77%	100.00%
	207	35.06%	35.33%	14.48%	15.13%	100.00%
	208					100.00%
	209	81.42%	16.95%	1.53%	0.09%	100.00%
3	320	85.01%	13.02%	1.89%	0.08%	100.00%
	321	72.11%	21.35%	5.99%	0.56%	100.00%
	322	62.26%	25.93%	10.23%	1.58%	100.00%
	323	55.16%	28.10%	13.66%	3.08%	100.00%
	324	50.07%	28.89%	16.10%	4.94%	100.00%
	325	46.38%	28.93%	17.67%	7.01%	100.00%
	326	43.63%	28.59%	18.58%	9.21%	100.00%
	327	41.50%	28.05%	19.01%	11.44%	100.00%
	328	39.81%	27.43%	19.12%	13.64%	100.00%
	329					100.00%
	330	85.01%	13.02%	1.89%	0.08%	100.00%
4	452	86.08%	12.19%	1.66%	0.06%	100.00%
	453	73.21%	20.69%	5.60%	0.50%	100.00%
	454	63.25%	25.46%	9.81%	1.47%	100.00%
	455	56.03%	27.77%	13.27%	2.93%	100.00%
	456	50.86%	28.65%	15.75%	4.75%	100.00%
	457	47.10%	28.74%	17.36%	6.79%	100.00%
	458	44.30%	28.43%	18.30%	8.97%	100.00%
	459	42.15%	27.92%	18.76%	11.18%	100.00%
	460	40.43%	27.32%	18.89%	13.37%	100.00%
	461					100.00%
	462	86.08%	12.19%	1.66%	0.06%	100.00%
5	617	83.21%	14.35%	2.33%	0.11%	100.00%
	618	69.52%	22.85%	6.93%	0.70%	100.00%
	619	59.64%	27.17%	11.34%	1.85%	100.00%
	620	52.64%	29.09%	14.78%	3.49%	100.00%
	621	47.67%	29.69%	17.17%	5.46%	100.00%
	622	44.08%	29.59%	18.67%	7.65%	100.00%
	623	41.40%	29.14%	19.51%	9.95%	100.00%
	624	39.34%	28.52%	19.87%	12.27%	100.00%
	625	37.69%	27.84%	19.92%	14.54%	100.00%
	626					100.00%
	627	83.21%	14.35%	2.33%	0.11%	100.00%
average	1st pass	82.69%	15.32%	1.88%	0.10%	100.00%
	discharge					100.0%