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ORNL/TM-12466

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MCNP Analysis of the FOEHN Critical Experiment

October 1993

Advanced Neutron Source

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DEPARTMENT OF ENERGY**

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MCNP ANALYSIS OF THE FOEHN CRITICAL EXPERIMENT

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October 1993

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U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ACKNOWLEDGEMENTS

We would like to thank Oak Ridge National Laboratory personnel C. D. West, Advanced Neutron Source (ANS) project director, and D. L. Selby, ANS research and development manager, for encouraging this work and providing the necessary funding. We also thank D. L. Selby and B. A. Worley for reviewing the draft report.

P. Ageron of the Institut Laue-Langevin in Grenoble, France, and K. Böning and A. Rohrmoser of the Technische Universität München, in Munich, Germany, provided J. M. Ryskamp with valuable insights that were not included in the original FOEHN report. In addition, Rohrmoser spent one week in Idaho assisting on the FOEHN model. We sincerely appreciate the help these scientists provided on this project.

EXECUTIVE SUMMARY

In the research and development plan of the Advanced Neutron Source (ANS) reactor, the second phase planned for neutronics design methods validation is to compare computational model results and experimental results for a critical facility exhibiting similarities to the ANS reactor.¹ One such facility is the FOEHN experiment.² In this report, an MCNP model of the FOEHN experiment is developed, and its results are compared to experimental data from the literature. The MCNP³ model reproduces measured quantities of interest with a high level of agreement.

FOEHN is a critical experiment performed in the course of the design of the Franco-German High Flux Reactor [Institut Laue-Langevin (ILL)]. The experiment was conducted at CEN-Cadarache in the French EOLE reactor, which was modified for this purpose. The reactor core is a hollow cylinder made of 90% enriched uranium-aluminum (U-Al) alloy circular involute fuel plates. The plates have a thickness of ~1.27 mm. The core is heavy water moderated and reflected. Other components in the FOEHN experiment include loops, beam tubes, and boron axial end plates. Many of these features are similar to the currently envisioned design of the ANS reactor.⁴ Design methods capable of properly modeling FOEHN would be well suited for the design and analysis of the ANS reactor.

The core effective multiplication factor (k_{eff}), the thermal flux in the reflector, and the core power distribution were measured in FOEHN. In addition, the rendement, a neutron efficiency defined as the ratio of the maximum thermal flux in the reflector to the total power, was evaluated. All of these quantities are compared to their MCNP-computed equivalents. The fluxes and the spectrum were measured using foil activation. They correspond to MCNP F4:n tallies. The power distribution was measured using fission probes of the same material as the reactor fuel plates, yielding a quantity that essentially mirrors the core fission power production shape. This is compared to MCNP F7:n tallies. The effective multiplication factors were measured via the stable period, the continuous run, and the neutron pulse damping methods.² The MCNP KCODE option is used to estimate k_{eff} .

In the FOEHN report² estimates of the errors associated with the measured quantities are given without detailed justification. In the present work, the error estimates are reassessed. Thermal flux measurement errors are believed to range from 3.3% to as much as 22.8% vs the 2% claimed in the FOEHN report. The power distribution measurement error is believed to be 4–8% vs the 1% claimed in the FOEHN report. A major omission in the FOEHN report is the nearly 4% uncertainty on the fission probe volume.

The MCNP model developed here represents the reactor with a very high level of geometric fidelity. Since the thickness of the fuel plates and intervening heavy water channels is very small in terms of neutron mean-free paths, the core is modeled as a homogenous region. This is verified, a posteriori, to be a good approximation. The reflector internals⁵ (loops, beam tubes, hot and cold sources) are modeled explicitly. The material compositions are defined in ref. 5. The nuclear data are those included in the MCNP ENDF/B-V library.

The effective multiplication factor was computed for all three configurations² of FOEHN for a large number of control rod positions and corresponding experimental critical boron concentrations. In the simplest configuration (no boron end caps, no reflector internals), the agreement between the MCNP-computed k_{eff} and the experimental value of 1.0 is achieved within two MCNP standard deviations (2σ) for two experimental situations and within three standard deviations (3σ) for five more. In the intermediate configuration (with boron end caps, no reflector internals), four cases agree with the experimental value within 2σ and the two other cases within 3σ . In the most complex configuration (with boron end caps and reflector internals), the agreement is still remarkably good, with three matches within 2σ and all the other cases displaying matches within 3σ .

The MCNP-computed power distribution was normalized to the same average core power density of 1.0 as the FOEHN data. Typical of the results obtained, the normalized axial power distribution at three radial positions is shown in Fig. ES-1. The experimental error bars of 4% are based on the discussion presented above. The bars on the computational curve assume errors of 2σ . Similar curves were generated for radial power distributions. In this way, every experimental data point was plotted at least once. The graphs show that nearly all the computational results coincide with their experimental counterparts within the error bounds established above. In the simple reactor configuration, only two points, <2% of the total number (122), do not display any overlap. This is remarkably compatible with the statistical interpretation that 95% of the points lie within the $\pm 2\sigma$ "error band." A similar high level of agreement is observed for the thermal fluxes and for the rendement. This work shows that the use of MCNP for the neutronics design of a reactor with features similar to the FOEHN experiment can be achieved successfully.

Fig. ES-1. Computed vs measured axial power distribution at three radial positions of the FOEHN critical experiment.

ABSTRACT

A very high fidelity MCNP model of the Franco-German FOEHN critical experiment has been developed. The results obtained show a high degree of agreement with each of the three configurations of the experiment. In particular, it is shown that the model reproduces the power density production distribution for all but a few of the experimental points internal to the core. Agreement for points of the axial ends at the core is less comprehensive. In the configurations that include boron axial core end covers, the agreement is similar within the core, but a few additional disagreement points arise at the axial ends of the core. The results remain consistent, however, with the statistical interpretation of MCNP tallies. The quantities computed also include the thermal flux in the reflector and the core multiplication factor for various critical configurations. It is found that the fluxes agree with the experiment within the experimental error bounds and two computational standard deviations. Most of the core multiplication results agree within three MCNP standard deviations. The overall conclusion of this study is that MCNP is an appropriate and valid computational tool for the static neutronic design of plate-fueled, heavy-water-moderated reactors, such as FOEHN or the Advanced Neutron Source.

1. INTRODUCTION

1.1 MOTIVATION

In the research and development plan of the Advanced Neutron Source (ANS) reactor, the second phase of validation for the neutronics design methods is to compare model (i.e., computational) results and experimental (i.e., measured) results for a critical facility exhibiting similarities with the ANS reactor.¹ One such facility is FOEHN,² a critical experiment performed in the course of the design of the Franco-German High Flux Reactor (FGHFR) at the Institut Laue-Langevin (ILL) in Grenoble, France. The experiment was conducted in the French EOLE reactor, which was modified for this purpose. FGHFR is a heavy water reactor with many features similar to those of the proposed ANS reactor. In particular, they both use (or would use) heavy water as moderator and coolant, and they both use (or would use) highly enriched uranium with aluminum plate fuel. The similarity between the two reactors can be seen further from the description of the FOEHN experiment in Chap. 2 and by a graphic rendition of their respective MCNP models in Chap. 3. These similarities in the characteristics of the two reactors suggest that benchmarking MCNP³ calculations against FOEHN experimental results will enhance the current level of confidence in the computational results and will contribute to the validation of the computational approach chosen for the neutronics design of the ANS reactor.

1.2 SCOPE AND LIMITATIONS OF THE STUDY

In this work, an MCNP model of the FOEHN experiment is developed and its results are compared to experimental data from the literature. It is found that the MCNP model reproduces measured quantities of interest with a high level of agreement. A validation of the method used for computing power generation in the ANS reactor is inferred from the successful comparison of computational results using this method and experimental results in the case of the FOEHN² experiment. The extent to which this validation is achieved is limited only by the lack of availability of comprehensive documentation on the details of the experimental setup and on the experimental results. The main sources of differences between the experiment and the model developed in this work stem from the lack of some geometric data about the reactor and in the lack of more detailed information about the materials used than that supplied in the FOEHN report (e.g., impurities information). The results obtained in the course of this study show that the omission of these data leads to no significant difference from the experimental results.

The MCNP model developed here is extensive. It conforms to a high level of fidelity in the representation of the various features of the reactor. The approximations made, when not dictated by the lack of information on the experiment, are explained and their justifications given in Chap. 3. The main items of comparison in the current work are (1) the core multiplication factor for several soluble boron concentration/control rod position combinations, (2) the thermal flux, (3) the core power distribution, and (4) the rendement (neutron efficiency).⁴

1.3 ORGANIZATION OF THE REPORT

In Chap. 2, a review of the FOEHN experiment is presented. Following a brief description of the experiment, a survey of the measured quantities is given. The method of data normalization used in the FOEHN report is explained, and a compatible one for the MCNP computational results is

presented. Finally, the error analysis of the FOEHN experiment is reviewed and complemented. In Chap. 3, the MCNP model developed in this work is presented. In Sect. 3.2, the approximations made are discussed. In Sect. 3.3, the modeling of the reactor features is presented. In Sect. 3.4, the choice of tallies and the methods for computing the elements of the comparison with the experiment are given. Chapter 4 documents the results of the comparisons between the experiment and the model. In Chap. 5, the main results and conclusions of this study are summarized. The references cited in this work are listed in Chap. 6.

2. THE FOEHN EXPERIMENT

2.1 INTRODUCTION

The FOEHN experiment was conducted with three levels of complexity. The first level involves mock-up of only the core surrounded by a reflector, without boron end caps and without the reflector internal structures (internals). The second includes boron end caps (top and bottom of core) but no reflector internals. The third level includes the boron end caps and mock-ups of the features internal to the reflector. A description of the experimental setup (core, reflector, and experimental facilities of the reactor), the method used in reporting the results, and an analysis of the experimental error estimates are presented in this chapter.

2.2 DESCRIPTION OF THE FOEHN EXPERIMENT

2.2.1 Reactor Components and Geometry

The components and geometry of the FOEHN experiment are described in the report by Scharmer and Eckert.² A brief review of the elements necessary to the construction of an MCNP model is given in this section.

2.2.1.1 Reactor Core

The fuel zone is a hollow cylinder of height 0.80 m, with outer and inner radii of 0.195 and 0.14 m, respectively. The fuel plates were fabricated out of a uranium-aluminum alloy and shaped as circular involutes with a 134.855-mm generating radius. The fuel plates did not have any cladding along their outer edges. A gap of 1.8 mm is maintained between the assembled plates. Other characteristics of the fuel plates are summarized in Table 2.1. The core structures were all fabricated from the AG3-NE aluminum alloy described in Sect. 3.2.2.

Table 2.1. FOEHN experiment fuel plates characteristics

Fuel	U-A1 alloy (90% ²³⁵ U)
Load (kg ²³⁵ U/m ²)	0.568
Total ²³⁵ U mass (kg)	8.556
Number of plates in core	276
Plate length (mm)	800.0 ± 0.5
Plate width (mm)	68.3 ± 0.2
Plate thickness (mm)	1.27 ± 0.05
Thickness of lateral A1 cladding (mm)	0.1

The coolant channel volume in the fuel zone was determined in ref. 2 on the basis of the dimensions of the fuel plates and the core structures as measured after fabrication. The borated heavy water volume thus contained in the core was 0.027 m^3 (ref. 2). The total free column volume in the core barrel, including the gaps around the fuel zone, was reported as 0.02885 m^3 (ref. 2).

2.2.1.2 Reflector and Internal Stack Geometry

The core is located in the center of a cylindrical tank of 2.30-m diam and 2.21-m height. The tank is filled with D_2O . A stack passes through the tank axially. The stack extends to the upper rotating plug and has the function of isolating the core and preventing the entire heavy water inventory in the reflector from being contaminated by boron in the event of a leak in the core barrel.

2.2.1.3 Control Elements and Safety System

The excess reactivity of the reactor is compensated for partly by the boron dissolved in the moderator and partly by a control rod that is inserted from below into the central flux trap. The absorber section of this control rod is a nickel tube 5-mm thick, 1.0-m long, and of outer radius 0.126 m.

2.2.1.4 Safety Rods

Six dummy safety rods were used. They were supported by upright aluminum guide tubes of 0.04-m diam and a wall thickness of 4 mm. The safety rods consisted of 2-mm thick cadmium tubes of 90-mm OD and 1.50-m length, clad in 0.5-mm stainless steel.

2.2.1.5 Solid Boron End Zones

A portion of the excess reactivity is compensated for by boron plates above and below the fuel zone. The boron end zones consist of horizontal, 1-mm thick, borated aluminum plates and pure aluminum plates.

2.2.2 Experimental Facilities

A variety of experimental components are included in the reflector of the FOEHN critical facility. These include 16 beam tubes, a hot source, a cold source, and pneumatic tubes for material irradiations. These assemblies closely resemble the facilities originally designed for the FGHFR and are described more fully in the FOEHN report and in ref. 6. A brief description of the main reflector components is given below.

2.2.2.1 Reflector Internal Components

Sixteen beam tubes comprise the bulk of the reflector components. These are used for functions ranging from isotope production and neutron extraction for scattering experiments to conversion electron and/or photon extraction. The beam tubes in FOEHN are of three main shapes: cylindrical, rectangular, and truncated conical. Beam tube orientations range from horizontal to vertical. All beam tube walls are composed of the AG3-NE aluminum alloy and are evacuated within. Two pneumatic tubes for material irradiations are also present in the reflector. These vertical cylindrical tubes are 0.04-m diam and made of the AG3-NE aluminum alloy. One tube nose is located at the core midplane,

and the other is 0.2-m above the midplane. The beta spectrometry vertical channel has an ID of 0.20 m and a wall thickness of 2 mm. It passes through the full height of the reflector. The pneumatic transport systems are simulated by vertical aluminum tubes with 0.04-m ID and 2-mm wall thickness.

2.2.2.2 Cold Source Facility Mock-up

The cold source is simulated by an aluminum vessel of 0.40-m ID and 0.50-m height. The wall thickness is 5 mm. The effect of the cold moderator on neutron absorption in the wall is simulated via an increase in the wall thickness. In the experiment, this was achieved using an aluminum bell 3-mm thick that fit over the cold source.

2.2.2.3 Hot Source Facility Mock-up

The FOEHN hot source mock-up consisted of a cylindrical block of graphite inside a Zircaloy-4 vessel, surrounded by an AG3-NE tube. Two probe holes, one horizontal and one vertical, extend through the center of the graphite block to provide access for measurements within the hot source. The hot source mock-up was located at a radius of 0.496 m from the core centerline, and its centerline was 0.1-m below the core midplane.

2.2.2.4 Loops

The FOEHN critical facility contains three separate loops. The core loop serves to isolate the core region and allows for addition of borated heavy water to the core for reactivity control. The stack loop seals off the primary coolant loop from the reflector. The reflector loop provides cooling for the reflector components. Both the stack and reflector loops can be independently heated and cooled.

2.2.3 Materials

The materials used in the FOEHN experiment are described in great detail in ref. 2, and some of their properties are summarized in Sect. 2.2.1.1 above. The description of the materials does not include quantification of any impurity content. In Sect. 3.2.2, the differences between experiment and model materials are enumerated.

2.3 RESULTS OF THE FOEHN EXPERIMENT

The FOEHN experiment is summarized in a report by Scharmer and Eckert.² The main results of interest to the current study are those related to benchmarking an MCNP simulation against the experiment. These results are the spatial distribution of power production, the fluxes, the effective core multiplication factor (k_{eff}), and the rendement. The quantities of interest (limited to the static parameters) are reviewed below, and their actual meanings in the FOEHN experiment are clarified. The actual results of the FOEHN experiment are reviewed in Chap. 4 in conjunction with their comparison to the model.

2.3.1 Quantities Measured

2.3.1.1 Core Multiplication Factor (k_{eff})

The reactivity was measured in the FOEHN experiment via three methods: (1) the stable period method for slightly supercritical states, (2) the continuous reactivity measurement method for cases with large reactivity, and (3) the pulsed neutron source method for subcritical states. The experimental results reported include both critical and off-critical states.

2.3.1.2 Fluxes and Spectrum

The fluxes and the spectrum were measured in the FOEHN experiment using the well known method of foil activation. For the thermal flux measurements, the cadmium ratio, R_{Cd} , was evaluated using a manganese (Mn) probe irradiated at the same location in the experiment and at the same power, once without a cover (Mn) and once under a thick cadmium (Cd) cover (Mn/Cd). From R_{Cd} and the total activity (Mn case), the thermal flux can be computed. The epithermal flux was measured using gold (Au) and indium (In) resonance probes under Cd covers. The fast flux was measured using the threshold reactions of sulfur (S) and phosphorus (P) probes.

The flux spectrum in the FOEHN experiment was measured using paired probes of uranium-plutonium (U/Pu) and lutetium-manganese (Lu/Mn) in addition to the manganese and Mn/Cd probes used for R_{Cd} . The activation ratios obtained from these pairs were then used to obtain a discrete neutron spectrum (thermal, epithermal, and fast neutron energy groups).

2.3.1.3 Flux Efficiency (Rendement)

The rendement is defined in the FOEHN report as the ratio of the maximum thermal flux in the reflector to the total power produced in the core,

$$r = \frac{\phi_{\theta}^{\max}}{P_{tot}} \quad (1)$$

For experimental determination, this expression is rewritten in terms of experimentally available quantities,

$$r = \frac{A_{Mn, \max}}{A_{Mn, R}} \cdot \frac{v}{v_0} \cdot \frac{A_{U, R}}{A_{U, C}} \cdot \frac{1}{\sum_{f, \theta}^U V_c Q} \quad (2)$$

where $A_{Mn, \max}$, $A_{Mn, R}$, $A_{U, R}$, and $A_{U, C}$ are measured activations, respectively, of manganese at the maximum of the flux, of manganese in the reflector, of uranium in the reflector, and of uranium in the core. V_c is the core volume, v is the mean neutron velocity at the location of the maximum of the flux, and v_0 is

$$v_0 = \frac{2}{(\pi)^{1/2}} \cdot 2200 \text{ m/s} \quad (3)$$

The ratio v/v_0 and the effective microscopic fission cross section $\sigma_{f,eff}$ (503 barns at the point of the measurement located at a radius of 0.50 m from the centerline of the reactor) were evaluated using the code THERMOS. The evaluation of r in the FOEHN report also assumes that the recoverable energy released per fission event, Q , is 199.73 MeV.

2.3.1.4 Power Distribution

In the FOEHN report, it is claimed that the power distribution is measured. In reality, the fission power production density (understood to include all the recoverable energy, then normalized to a unit average power density throughout the core) is measured and reported. The fission power production is measured using fission probes of composition similar to that of the reactor material (fuel plates) and cut right into the plates. This choice has the advantage of not significantly disturbing the system studied. The fission foils are irradiated; then the gamma activity above 511 keV is measured. The measured activity is deemed proportional to the power released in the probe during irradiation. The measurements necessarily include all gammas above 511 keV and, hence, may include activity contributed by nonfission events. The results reported do not describe the power distribution as it would result from the combined effects of power production, transport, and deposition. Gamma heating is also reported and is discussed in the next subsection.

2.3.1.5 Gamma Heating in the Reflector

Gamma heating of structural and other materials is the result of the transfer of energy via gamma radiation and the subsequent deposition of the gamma radiation. It is measured in the FOEHN experiment using glass dosimeters and an ionization chamber. The glass dosimetry technique relies on the measurement of the fluorescence induced by the formation of optical centers (i.e., defects) in the glass as a consequence of irradiation by the gamma rays. The effect of the neutron-induced centers is subtracted by comparison to activation measurements. The method is suitable for the measurement of the photon flux and of the energy deposition in the glass probe. A prediction for the energy deposition in other materials (e.g., reflector materials) can be inferred from their respective energy absorption coefficients. The ionization chamber method is fully described in classical references, such as *The Atomic Nucleus* by R. D. Evans.⁷ The chamber used in the FOEHN experiment has a sensitivity to gammas of 1200 W/g-A. The FOEHN report does not give a sensitivity to gammas for the glass probes.

2.3.2 Normalization of Tabulated Results

The flux and power data obtained in the FOEHN experiment were reported normalized to an average power density (or flux density) of 1.0 over the core of the reactor. The report did not describe the normalization method in sufficient detail to make it easily reproducible. In this section, the normalization method used in the FOEHN report is explained. A simple and more practical alternative, which is shown to be compatible with that of the experimental report, yet easier to implement, is proposed and described.

2.3.2.1 FOEHN Experiment Normalization Method

The powers reported for the FOEHN experiment are normalized to an average density of 1.0 over the whole reactor core. The procedure followed by the FOEHN experiment authors is described in Sect. 5.1.4 of their report. They used both a "mechanical" (i.e., semigraphical) and a "mathematical"

(i.e., semi-analytical numerical) integration approach to evaluate the total core power for use in normalization. In the mechanical approach, the measured radial power distribution is plotted at each value of the axial variable, then graphically integrated. An axial power distribution results that is then integrated to yield a total core power. The normalized power is then determined by multiplying each experimental value by the volume of the core and dividing it by the total power. The resulting distribution has the advantage of consisting of numbers close to 1.0 when the power density measurements are close to the core average power density. The second normalization method used by the authors of the FOEHN experiment differs only in the way the total power integral is obtained. In this second method, the entire set of measurements is fitted by polynomials, and the resulting two-dimensional curve is used in a computational integration procedure. In the next two subsections, an alternative method is introduced that works well when a sufficient number of data points are available.

2.3.2.2 Single Table Normalization

The integration and normalization methods used in the FOEHN experiment should be expected to work well, but they are not fully rigorous from a mathematical point of view. Indeed, the measurements were made with probes of finite dimensions ($3 \text{ mm} \times 5 \text{ mm} \times 1.27 \text{ mm}$) that are not negligible with respect to the distance over which the flux changes significantly (in some regions at a rate of 3%/mm). The reported measurement values are actually average values over the probe and not point values. The correct curve fitting procedure taking this fact into account is a complicated one, involving considerations of functional analysis.⁸ This method is beyond the scope of this study. A procedure that errs in the opposite direction may be as legitimate as the one used by the authors of the FOEHN experiment, especially when dealing with a large number of experimental points. This procedure is outlined below.

The normalization procedure proposed here differs from those of the FOEHN report only in the use of an r, H trapezoidal integration procedure. In this approach, it is assumed that the data from a given probe applies to the domain surrounding it up to the middle of the distance separating it from the center of the closest adjacent probes in the r and H directions (or up to the edge of the fuel plate if applicable). The integration is then carried out by multiplying the power (or power density) by the volume of the region and summing over all probes. This integration procedure was applied to the data of Table 5.1.5 of the FOEHN report. The average power density is found to be 1.014. The difference of 1.4% between our computations and the expected value of 1.0 shows that the two normalization procedures (FOEHN report and ours) are compatible and confirms the fact that the table in the FOEHN report is normalized to an average density of 1.0.

2.3.2.3 Multiple Tables with Missing Data

It is desirable to obtain an average from multiple tables of similar data (such as Tables 5.3.6, 5.3.7, 5.3.8, and 5.3.9 of the FOEHN report). It is in fact necessary to combine the data from these tables because they cannot be reproduced computationally without precise data on the azimuthal position of the experimental fuel plates that carry the probes. In addition, for the sake of better statistics, the tally cells are actually annuli. The computational results, therefore, correspond to an average of a large number of probes distributed around the core. The averaging of the data from the four experimental plates is the best option available for a comparison.

The construction of a proper average of the experimental data could be achieved in two ways:
 (1) renormalize the experimental data to 1.0; then form a point-to-point average according to

$$(T)_av = \frac{1}{N_i} \sum_p (T)_p ; \quad (4)$$

or (2) perform a point-to-point average according to the formula shown above without first renormalizing the data. In the equation, $(T)_av$ stands for the average tally for the i -th position (defined by its radial and axial coordinates), $(T)_p$ is the i -th position tally in the p -th experimental plate, and N_i is the number of (nonmissing) entries for tallies in the i -th position. These two options should both work well if the number of data points is large in each table (i.e., there are enough data points for the integration procedure to be accurate), and the initial tables are found to be normalized to 1.0 (or very close to 1.0) following the method proposed in Sect. 2.3.2.2. If there are many missing data points, or if the tables are not found to be normalized to an average density close enough to 1.0, then the second procedure must be used. The rationale for this choice is that the reported data are already normalized to an average power density of 1.0 according to the method used in the FOEHN experiment. Such data can then be averaged without further transformation. The resulting combined table should be expected to be more closely approximated by the tallies over annuli that are used in this study. The combined table, having a larger number of points than any of its constituent tables, should also be expected to be normalized to a value closer to 1.0 than (at least some of) the individual tables. The combined data from Tables 5.3.6–5.3.9 of the FOEHN report are shown in Table 2.2. It was verified that the entries of this new table are normalized to an average core power density of ~ 1.006 according to the procedure in Sect. 2.3.2.2.

2.3.2.4 Normalization of Fluxes

The fluxes in the FOEHN experiment are reported normalized to a total core power of 1.0 W. The MCNP tallies are normalized "per fission neutron." The MCNP tallies must be renormalized to make a direct comparison with experimental values possible. The fluxes are renormalized by multiplying the MCNP tallies by the power normalization factor PN given by⁹

$$PN = P \cdot v \cdot \frac{1}{Q} \cdot \frac{1}{k_{eff}} , \quad (5)$$

where P is the reactor power, v is the average number of neutrons per fission, Q is the fission energy, and k_{eff} is the effective multiplication factor from the MCNP run that yielded the flux tallies to be renormalized. The normalization to 1.0 W is achieved by setting P equal to 1.0. In this work, v is computed within MCNP for each reactor configuration and is reported along with the results that use it. When a value for v is not reported, the value 2.44175 is assumed. The energy per fission used in this work, Q , is 202.47 MeV/fission, except in the evaluation of the rendement where the value 199.73 MeV was used in order to conform with the practice adopted in the FOEHN report.

Table 2.2. Experimental power production distribution in FOEHN^a

H/r (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0.5033	0.4701	0.4529	0.4492	0.4462	0.4908	0.5958	0.7363	0.8162	0.9236	1.2140
5.0											1.1739
9.4	0.6978										1.1654
14.5	0.4629					0.4437					1.1657
19.4	0.4880					0.4295					1.1697
28.5	0.4920					0.4270					1.1787
50.0	0.5061	0.4655	0.4540	0.4359	0.4214	0.4560	0.5526	0.6827	0.7796	0.8979	1.2395
75.0	0.5441					0.4965					1.3249
100.0	0.6163					0.5283					1.4047
175.0	0.7386	0.6832	0.6508	0.6328	0.6002	0.6410	0.7650	0.9542	1.0744	1.2272	1.6764
250.0	0.8609					0.7408					1.8965
325.0	0.9626					0.8191					2.0636
400.0	1.0555	0.9788	0.9144	0.8984	0.8473	0.8850	1.0357	1.2898	1.4189	1.6113	2.2120
475.0	1.3656					0.9684					2.2314
550.0	1.4596					0.9621					2.1906
625.0	1.3661	1.2192	1.0878	1.0273	0.9211	0.9003	1.0106	1.2300	1.3538	1.5147	2.0550
700.0	1.2275					0.8055					1.8327
725.0	1.1729					0.7442					1.7600
750.0	1.1257	0.9867	0.8775	0.8289	0.7265	0.7100	0.7993	1.0039	1.0851	1.2325	1.7150
771.5	1.1000					0.6721					1.6685
780.6	1.1352					0.7285					1.6806
785.5	1.1344					0.7188					1.6985
790.6	1.1528										1.7021
795.0											1.7183
797.5	1.2958	1.1534	1.0572	1.0238	0.9171	0.8625	0.9632	1.1537	1.2353	1.3559	1.8193

^aCombines Tables 5.3.6–5.3.9 of ref. 2.

2.4 ERROR ANALYSIS OF FOEHN RESULTS

2.4.1 Error Reporting in the FOEHN Experiment

The measurement errors on the ratios related to the flux spectrum are reported as 1% for R_{Cd} and $R_{Pu/U}$, and 2% for $R_{LW/Mn}$ respectively.² The errors claimed by the authors of the FOEHN experiment are 2% for the relative thermal flux measurements, 3% for the absolute thermal flux measurements, 4–15% for the relative epithermal fluxes, and 13% for fast flux measurements near the core. They attributed most of the experimental error in the thermal flux measurements to the error in positioning the probes. They claim that the flux varies by 30%/cm on the tank surface at the reactor midplane. The error on the powers is reported to be <1%.² In the critical states experiments, the error on the positioning of the control rod is reported as <1 mm, whereas the error on the corresponding boron concentration is not reported. With very little analysis, the errors on the determinations of the reactivity are reported in the FOEHN report as ± 2 , ± 2 , and $\pm 3\%$, respectively, for the simple, the intermediate, and the full complexity reactor configurations.

2.4.2 Sources of Errors

2.4.2.1 Geometric Tolerances

The occurrence of geometric inaccuracies leads to errors in the experimentally measured data. Some of the geometric sources of error are the positioning error of foils and probes in the experiment, the error on the dimension of plates and other structures during fabrication, and the tolerance in the positioning of rods. Other geometric sources of error may include the effect of accidental deformation of the fuel plates as well as deformation caused by the actual operation of the reactor.

2.4.2.2 Materials Data

The composition of the various materials used in the FOEHN experiment are not known unequivocally. In particular, no information on the impurity contents was given in the FOEHN report. Another possible (though very likely small) source of error is the undocumented uncertainty on the boron concentration used for criticality experiments. The FOEHN report is ambiguous in its description of the material used for fabrication of the reflector internals. Whereas it is stated that the standard beam tube is made of the AG3-NE aluminum alloy referred to simply as aluminum in the report, the material of other structures is not explicitly described as AG3-NE, but rather only as aluminum.

2.4.2.3 Counting Geometry, Statistics, and Times

The counting statistics and consequent errors of the various measurements were not explicitly reported by the authors of the FOEHN experiment. It is unclear whether the errors they quote relate only to the counting or to the entire experiment. For example, the error of <1% reported for the power measurements is not assigned to any particular aspect of the experimental procedure. It is reasonable to assume that it is related solely to the counting time, geometry, and statistics.

2.4.3 Estimates of the Error on Select Quantities

The errors discussed in the previous section may be viewed as having two types of sources: statistical and systematic. In combining and propagating the two types of errors, care must be taken to use the proper applicable rules. The uncertainty in the measurements of activation associated with the probe positioning constitutes an unknown error of unknown sign. It was estimated by the authors of the experiment at approximately $\pm 3\%$. This error is random, but since this error is associated to fewer than three measurements for each sample, confidence bounds in the statistical sense cannot be defined for it, and the error cannot be treated like a statistical error. This error also affects all the measurements equally, so it is treated like a systematic error in this work, except that its sign is not known. It is therefore not combined statistically with the other errors. Instead, the corresponding uncertainties are combined conservatively, as if they were known errors. In contrast, the counting errors are of statistical nature. The activities of two probes irradiated at the same location, although under modified conditions, are correlated. It follows that the combination of errors should ideally take the correlation into account. Since the precise way in which the activations are correlated is not known, limiting situations have to be identified. The actual errors would then fall within the range thus determined. Such limiting ranges are defined below for the cadmium ratio, the thermal flux, and the powers. The resulting estimates for the statistical and systematic errors are then combined conservatively in a nonstatistical way.

2.4.3.1 Cadmium Ratio, R_{Cd}

The cadmium ratio, R_{Cd} , is obtained as the ratio of two activities. If a foil is positioned with an error of the order of 1 mm, as claimed in the FOEHN report, the systematic error on its activation would be of the order of 3%. It follows that the error on R_{Cd} would be $\sim 6\%$ from the compounding of the errors on two foils. The contribution of the counting error to the total relative error ranges from 0 to $\sqrt{2}$. These two figures assume the activities to be fully positively correlated and uncorrelated, respectively. The assumption of positive correlation is plausible for activations of foils at the same location in the reactor. If the correlation was negative, the contribution would have been bound by a maximum value of 2%. Other errors, such as the sample-size error, may also be present but are ignored in this analysis. The total error for the cadmium ratio ranges, therefore, between 6 and 7.4%.

2.4.3.2 Thermal Flux

The thermal flux is computed in the FOEHN experiment according to

$$\phi_{th} = B \cdot (v/v_0) \cdot A \cdot (1 - 1/R_{Cd}), \quad (6)$$

where B is a normalization constant and A is the activation of the thermal probe. It is not clear from the FOEHN report how the cadmium ratio was determined for a given thermal flux measurement. Specifically, it is not clear whether R_{Cd} was measured once at some location in the reflector and used for all thermal flux determinations at that and other locations or if R_{Cd} was reevaluated separately for each location. From the report, it seems that the former approach was adopted. If this is the case, the error on the thermal flux would follow from the error on B , the error on A (comprising at least $\sim 3\%$ for positioning and 1% for counting), and the error on R_{Cd} (comprising the combined errors on two activity measurements, about 6–7.4%). In the present analysis, it is assumed that R_{Cd} was determined

only once, and hence the logic stated at the beginning of Sect. 2.4.3 applies. In the converse, the error on the flux would entail only the errors on the two correlated measurements of the activities under cadmium cover and without cadmium cover.

Contributions to the error on ϕ_{th} arise from each of the factors in the right side of Eq. (6). The first term is the normalization constant B . In the FOEHN report, it is claimed that this normalization is performed using the measured value of the rendement. Such an approach would imply that the factor B would be either proportional or inversely proportional to the rendement and, consequently, that the corresponding relative error would have to be added to the above estimates. In Sect. 2.4.3.4, it is shown that the error on the rendement ranges from 2.2%, when only the error on the ratio v/v_0 is accounted for, to 16.2%, when the positioning errors, the counting errors, and the error on v/v_0 are taken into consideration. The second factor, v/v_0 , was shown by Rohrmoser¹⁰ to entail an error of about 2.2%. The last two factors, A and $(1 - 1/R_{Cd})$, contain errors resulting from positioning and counting. If it is assumed that all the statistical errors (i.e., counting errors) and the error on v/v_0 from B and from its explicit occurrence in Eq. (6) cancel out, then the error on ϕ_{th} would be of the order of 15.3% for a value of R_{Cd} of 20. This would decrease toward 15% as R_{Cd} increases and would be reduced to 3.3% if the positioning errors are assumed to cancel out in the evaluation of the rendement. If the errors on v/v_0 do not cancel out, and the cancellation of statistical error is minimal, then the error would be of the order of 22.8%, (10.8% if positioning error is ignored in determination of the rendement). If it is assumed that the error of 2% (to 3%) on the measured rendement claimed in the FOEHN report is correct, then the error on the thermal flux would be between 8.5 and 8.6% (to between 9.5 and 9.6%), depending on the extent of statistical error cancellation.

From the above, it can be seen that estimates of the error on the thermal flux can range from 3.3–22.8%, with a more plausible minimum of the order of 9.6%. If no other sources of error are present, then the error on the thermal flux measurements should be taken to be at least 10%. Since this is unlikely, error bars resulting from the lower estimate based on the claims of the FOEHN experiment report should be regarded as a minimum width for the error, that is, a nonconservative estimate.

2.4.3.3 Powers

In the FOEHN report, the claimed error of 1% on the powers is attributed mainly to the uncertainty in positioning the plates with respect to one another (i.e., distance between adjacent plates). In another part of the report, it is claimed that a positioning error of 1 mm induces an error of up to 3% in the activation (i.e., the flux or the power). It can be expected that the positioning of the fuel plates is known to be about 0.1 mm (the distance between plates is given as 1.8 mm) and hence that the corresponding error would be only as high as 0.3%. To this, the error related to the dimensions of the fission probes proper and the counting must also be accounted for in the calculation. If the counting error (i.e., measurement error) is the same as that for the flux measurements, then it should be taken to be ~1%. The error on the dimensions of the probes cannot be known with any degree of certainty since they are not documented in the report. It can be guessed, however, that they can be related to the errors made on measurements of some of the features of the EOLE reactor. For example, the error on the thickness of the fuel plate is 0.05 mm. If a similar error is made for each of the dimensions of the fission probes, the resulting relative error on the area of a given probe would be ~2.7%. The implied error on the power measurement resulting from this would be the same (i.e., 2.7%). In addition, the error on the dimension of 0.05 mm for each side of the rectangular shapes would induce a positioning error on the flux (or power) similar to that caused by four positioning errors by distances half the dimension error and hence add up to 0.3% for the two sides of the rectangle (or to 0.45% if a thickness positioning error is assumed). The sum of all the errors discussed here ranges from 1–4.15%. The relative error on the thickness of the probes (0.05 mm for a 1.27-mm

thickness) would affect the counting and hence would contribute an additional 3.94% to the power error estimate. A grand total of up to 8% is therefore plausible. Other possible errors resulting from the actual location (i.e., positioning error) of the probes and from deformation (resulting from cutting and use) are not accounted for in this scenario. The upper bound of 4% chosen in the remainder of this work as the error on the power (for use in comparisons to MCNP results) is a lowest estimate and is similar to the estimate of the error on the flux arrived at in Sect. 2.4.3.2 by reanalyzing the FOEHN report data and claims.

2.4.3.4 Rendement

The computation of the rendement in the FOEHN experiment uses four measured activations, an estimate of the energy and core volume averaged fission cross section, an estimate of the ratio v/v_0 , and an estimate of the energy released per fission event. Each of these can be known only approximately and, hence, is a source of error. Assuming a relative error on each constituent term in the equation for r , the nonstatistical component of the relative error on r is

$$\begin{aligned} \frac{\Delta r}{r} = & \frac{\Delta A_{Mn,max}}{A_{Mn,max}} + \frac{\Delta A_{Mn,R}}{A_{Mn,R}} + \frac{\Delta(v/v_0)}{v/v_0} + \\ & \frac{\Delta A_{U,R}}{A_{U,R}} + \frac{\Delta A_{U,C}}{U_{U,C}} + \frac{\Delta \Sigma_{f,th}^U}{\Sigma_{f,th}^U} + \frac{\Delta V_c}{V_c} + \frac{\Delta p}{p} . \end{aligned} \quad (7)$$

The statistical error on the activities has to be added. The error on the ratio v/v_0 was shown by Rohrmoser to be 2.2%. If the errors on the fission cross section and on the core volume V_c are ignored, and if the error on the activations is taken to be 1% (following the claims in the FOEHN report) to 4% (3% positioning and 1% counting), then the error on r should be between 2.2% (assuming positioning error cancellation, hence ignoring all but the error on v/v_0 , and with the counting error contributing 0% for full positive correlation, when maximum cancellation occurs) and 16.2% (positioning errors taken into account and with statistical error contributing 2% in the uncorrelated case). The error sources omitted here may or may not be negligible and might have to be accounted for in the analysis.

2.5 SUMMARY

The FOEHN experiment has been reviewed and its salient features described. The quantities that were measured have been identified. A method for normalizing model data that is compatible with the normalization method used in the FOEHN report has been proposed. The reported estimates of the experimental errors were discussed. It is concluded here that, as given in ref. 2, the error estimates of the FOEHN experiment are significantly underestimated. It is shown, in particular, that the errors on the fluxes should be taken to be at least of the order of 10%, while the errors on the powers should be taken to be at least 4% of the reported values.

3. MCNP MODEL OF THE FOEHN EXPERIMENT

3.1 INTRODUCTION

MCNP models that correspond to the three configurations of the FOEHN experiment have been developed and are described in this chapter. The assumptions and approximations made are outlined in Sect. 3.2. In Sect. 3.3, the geometry and modeled features of the reactor are described. The choice of MCNP tallies and methods for computation of nontally quantities are described in Sect. 3.4. The full MCNP model (i.e., input file) is included as Appendix A.

3.2 MAJOR APPROXIMATIONS AND ASSUMPTIONS

The highest possible degree of geometric fidelity was systematically sought in the modeling of the FOEHN critical experiment. Whenever possible, the exact geometry of the component was used. The reactor core was modeled with some approximations justified in the next section. The reflector internal components were modeled explicitly and in full accordance with the specifications of the FOEHN experiment report. The next two subsections describe geometry and materials approximations made in the development of the MCNP model, respectively.

3.2.1 Homogenous Core, Geometry Details, and Fidelity

The FOEHN core, described in Sect. 2.2.1.1, was modeled as a homogenous hollow cylinder of fuel, cladding and structural materials, and borated heavy water. The dimensions are those specified in the FOEHN report. In the experiment, the power measurements were conducted on individual fuel plates. The highest fidelity description would hence require the explicit modeling of the plates and of the individual fission probes. This is an unpractical option, however, since the fuel plates are shaped as circular involutes, a shape not available in the MCNP geometry modules. In addition, since the fuel plates are much smaller than the mean free path of neutrons in the fuel material, the fuel can be homogenized with no significant loss of accuracy.¹¹ Another major reason for avoiding explicit treatment of the fission probes is the fact that computing tallies over such small volumes would make obtaining satisfactory statistics prohibitively expensive.

The only other geometric approximations made involve some structural and control materials of the axial end zones separating the core region from the heavy water moderator. In the actual experimental facility, in the simplest reactor configuration, an AG3-NE alloy "plug" plate isolates the borated heavy water in the core region from the surrounding unborated heavy water. It is followed (on the outside) by unborated D₂O and, much farther, by the axial portion of the reactor core barrel. In the intermediate and full complexity configurations, the boron end caps follow the inner AG3-NE alloy plug, replacing some of the D₂O between the axial plug and the axial portion of the core barrel. These boron end caps are constructed as alternate layers of borated and unborated AG3-NE plates in a B/U/B pattern repeated four times (for a total of eight Borated layers and four Unborated ones). In the MCNP model, only the inner AG3-NE seal (plug) is modeled explicitly. The boron end caps are modeled as homogenous regions 30-mm thick. The axial portion of the core barrel (exact location and thickness undocumented), having little neutronic impact, is simply ignored. The modeling of the borated end caps as homogenous regions allows the use of the boron end zone homogenized material description from the FOEHN report. Little effect on global core parameters is anticipated, and only minor perturbations in the core power distribution are expected.

The MCNP model of the radial description of the reactor follows closely the information provided in the FOEHN report. Such information is, however, not complete, and assumptions have to be made. A summary of the description of the core region starting at the reactor centerline and moving outward is given in Sect. 3.3.1.

In some critical states, the control rod top was at a height <1.0 m position in the MCNP coordinate system. In these cases, a portion of the rod was below the bottom of the reflector tank, which is the lower boundary of the MCNP model. In the model, the portion of the rod protruding below the tank floor was neglected. This should not produce any significant problem since the distance of this portion of the rod from the active core is large. In these states, dissolved boron is the primary source of reactivity control, and, hence, the protruding section of the control rod has negligible worth. Further discussion of this phenomenon is included in Sect. 4.2.1.

3.2.2 Assumptions on Materials Data

The materials used in the MCNP model of the FOEHN critical facility mirror as closely as possible the actual materials used in the facility. This was accomplished by using the material compositions given in Table 3.1 of the FOEHN report for the fueled region of the core and for the boron end plates. The atomic contents of all other material compositions (e.g., borated and unborated D_2O , AG3-NE, etc.) were calculated in this work. Where gaps appear in the table, approximations and best guesses had to be used. These are explained below.

Table 3.1. Composition of Zircaloy-4 used in the model^a

Element	Weight percent
Zr	Balance
Sn	1.5
Fe	0.20
Cr	0.10
Ni	0.007

^aFrom S. Glasstone and A. Sesonske, *Nuclear Reactor Engineering*, 3rd Ed., p. 460, Van Nostrand Reinhold, 1981.

The hot source graphite and the cadmium in the safety rods were modeled as elemental graphite and cadmium at full theoretical density with no impurities. This produces an overestimate of the atomic densities for these materials and is expected to produce some local effects, especially in the hot source flux calculations. However, since the safety rods were not included in any of the FOEHN experiments used in these calculations, the cadmium density had no effect on the results.

In several reflector internal components, the zirconium alloy Zircaloy-4 and stainless steel type 304 (SS-304) were used. Compositions for these alloys were not available, so the material composition for SS-304 was taken from a standard handbook,¹² and that of Zircaloy-4 was assumed to be the same as the one used in the MCNP model of the ANS reactor. The composition used for Zircaloy-4 is shown in Table 3.1. Since there is a large range of possible nuclide contents for these alloys, there ensues a consequent degree of uncertainty about the fidelity of the model. This will again produce mainly local effects, with insignificant global consequences. The composition data used for the

AG3-NE aluminum alloy are given in Table 3.2. All heavy water is assumed to be contaminated by 0.25 at. % light water. This value is very close to the values quoted in the FOEHN report.

Table 3.2. Composition of the AG3-NE aluminum alloy

Element	10^{30} atoms/m ³	Element	10^{30} atoms/m ³
Al	0.031673	FE	6.9681×10^{-5}
Co	2.1221×10^{-8}	Ni	6.6513×10^{-7}
Cr	6.493×10^{-5}	Cu	6.3346×10^{-7}
Mn	1.1323×10^{-4}	Ga	4.4342×10^{-6}
Th	4.751×10^{-9}	Ta	3.1673×10^{-6}

3.3 MCNP MODEL DESCRIPTION

The FOEHN experiment incorporates many of the features found in the current design of the ANS reactor. The comparison is illustrated by SABRINA¹³ printouts of the MCNP models for the ANS reactor and FOEHN in Figs. 3.1a and 3.1b, respectively. As can be seen from Fig. 3.1b, the MCNP model of the FOEHN critical experiment incorporates a full description of the entire experiment, including all reflector internals and the boron end zones. The cases that did not require either the reflector internals or boron end zones are modeled by substituting heavy water for the actual material in the appropriate zones. The approximations used in developing the model are described in the previous section. The complete model is described below. Additional details of the model can be seen in Figs. 3.1b–3.6. These are SABRINA printouts of six views of the experiment as modeled in MCNP. The views are front, left, right, top, bottom, and rear, respectively.

3.3.1 The Core and Surrounding Structures

The core is modeled as a hollow cylinder 0.8-m tall, with inner and outer radii of 0.14 and 0.195 m, respectively. Figures 3.7a and 3.7b show, respectively, a diagram of an axial and a radial (top view) of the core and the surrounding barrel. The core region is modeled as a homogenous mixture of the uranium fuel, borated heavy water, and aluminum cladding material. The choice of a homogenous core model was justified in Sect. 3.2.1. An additional reason for using a homogenous core model is the fact that the actual plate locations are not documented in the FOEHN report, and their spacings could vary since the fuel plates were not welded to the inner and outer core barrel walls. The core material properties are those of Table 3.1 of the FOEHN report. Dissolved boron in the heavy water was added to the mixture as required for each case, with the appropriate corrections made to the material description and overall atom density. The boron end zones were modeled as homogenous regions at the top and bottom of the core, 30-mm thick, with the same radius as the core.

Figure 3.8 shows an axial diagram of the core region and its surrounding structures. The control rod was modeled as a nickel annulus 5-mm thick and 1-m long. The dimensions for the heavy water regions and surrounding core barrel and isolation cask were derived from detailed figures of these regions (ref. 6). The structures above and below the core were modeled according to Fig. 3.3 in the FOEHN report. Since no exact dimensions were provided, best estimates from the diagram were used.

Fig. 3.1a. SABRINA printout of the current ANS reactor design MCNP model.

Fig. 3.1b. SABRINA printout of the FOEHN experiment MCNP model (front view).

Fig. 3.2. SABRINA printout of the FOEHN experiment MCNP model (left view).

Fig. 3.3. SABRINA printout of the FOEHN experiment MCNP model (right view).

Fig. 3.4. SABRINA printout of the FOEHN experiment MCNP model (top view).

Fig. 3.5. SABRINA printout of the FOEHN experiment MCNP model (lower view).

Fig. 3.6. SABRINA printout of the FOEHN experiment MCNP model (back view).

Not to Scale

H192-AMD-0393-00

Fig. 3.7a. Axial view of the FOEHN core and its surrounding cask.

M192-AMO-0393-04

Fig. 3.7b. Radial view of the FOEHN core and its surrounding cask.

M192-AMO-0393-03

Fig. 3.8. Axial diagram of the FOEHN core and surrounding structures.

In modeling the core, the control cylinder, and the core barrel, a number of assumptions had to be made. Referring to Figs. 3.7a and 3.7b, the core is now described starting from the centerline and moving outward. The central region is occupied by unborated heavy water up to a radius of 121 mm. The following cylindrical shell is the control rod (5-mm thick). Following the control rod is a layer of unborated heavy water extending 7.6 mm. After this heavy water comes the inner wall of the core barrel. The outside surface of this wall, facing the inner reflector and control shell, is smooth. The inside surface, facing the core, is grooved (comb teeth) to hold the fuel plates in place. It is not clear from the FOEHN report whether the inner side combs cover the entire length of the core. In that report, pictures of the external combs show that they do not fully cover the core. The comb region may have gaps containing borated D_2O . In the model, the geometric details of the gaps are ignored; the entire shell (solid portion and comb region) is modeled as a single, solid, 6.1-mm thick AG3-NE shell followed by a 0.3-mm layer of borated D_2O . The fuel lies immediately after this heavy water layer. The thickness of the fuel region is 55.0 mm. This region is assumed to contain a homogenous mixture of borated D_2O , aluminum, and ^{235}U . A borated D_2O -filled gap of 1.1 mm separates the fuel region from the external comb region (also used to hold the fuel plates in place). The remarks made about the inside comb region are applicable to the outside one. The region is also modeled as a solid AG3-NE shell 6.1-mm thick. The water contained in the comb region is modeled as a separate layer of borated D_2O located between the comb shell and the outer wall of the core barrel. This layer also accounts for the fact that the fit between the comb shell and the core barrel wall cannot be exact, and that some tolerance is to be expected. The thickness of the borated D_2O layer is chosen to be 0.5481 mm. This choice accommodates the balance of borated D_2O contained within the core barrel and otherwise not accounted for in the "free" (nonfuel) volume within the core. The outside wall of the core barrel is 5-mm thick. The core barrel is surrounded by the external nonborated D_2O reflector.

The above description contains an assumption pertaining to the distribution of borated heavy water within the core/core barrel region. It is assumed that some of the borated heavy water is not located in the fuel region and instead constitutes a shell within the outer core barrel region. A similar assumption is not made, however, for the inner core barrel region. With these assumptions, the core and core barrel regions are modeled to contain 28.85 L of borated D_2O . This is the measured borated D_2O content of the core/core barrel in FOEHN, and it is different from the design content of 27.0 L.

3.3.2 Reflector Internals

The description and placement of the reflector internals were done according to Fig. 2 and Table 2 of ref. 5. The beam tubes and other assorted channels were modeled as evacuated AG3-NE tubes using material 40 from Table 3.1 of the FOEHN report. The hot and cold sources geometry and materials were modeled exactly as described in Figs. 3 and 4 of ref. 8. The beam tubes were modeled as AG3-NE alloy tubes. The interior of the beam tubes was modeled as a vacuum.

3.3.3 Safety Rods

The safety rods were modeled as described in Sect. 2.2.1.4. Locations for the safety rods were based on Sect. 5.5.2.2 of the FOEHN report with the rod centers located 0.33 m from the core center. The safety rods were not included in any of the experiments modeled. They were replaced, therefore, with heavy water in all model cases.

3.3.4 The Coordinate System

The coordinate system used in the FOEHN model was the same as that used to describe most of the structures in the experiment. The origin was at the core centerline and at the bottom of the reflector tank. The use of this coordinate system allowed direct translation of the core structures and reflector internals to the MCNP geometry model. Figure 3.8 shows the origin and coordinate system used. A different coordinate system was used for the control rod, and, thus, some translation to the MCNP geometry model was required. In the FOEHN report, the origin for the control rod system was 0.1-m above the top of the core, with the positive direction being downward. The top of the control rod was considered to be the zero point on the rod. Thus, when the top of the control rod was 0.1-m above the top of the core, the control rod was said to be inserted to 0.0 m, and downward motion was positive insertion. This system was translated to the MCNP geometry model, which put the zero point at 1.61 m. This created some minor problems when the control rod was at a height of <1.0 m, as the bottom of the rod was then outside the MCNP model. In these cases, the portion of the rod below the tank bottom was neglected.

3.3.5 Materials

The materials used in the model are described in Sect. 3.2.2 of this report. The core and the boron end caps were taken from Table 3.1 of the FOEHN report. The data for graphite, cadmium, Zircaloy-4, and stainless steel 304 (SS-304) were not included in the FOEHN report. The assumptions used in selecting data for these materials are also discussed in Sect. 3.2.2. The actual nuclide concentrations used can be found in Appendix A, which lists the entire input file for the MCNP model. The compositions used for Zircaloy-4 and SS-304 are the same as those previously used in a model of the ANS reactor and a model of the High Flux Reactor of ILL. Figures 3.7 and 3.8 show the MCNP materials used to model the individual core regions. The beam tubes were modeled using the AG3-NE alloy. The core, borated heavy water, and aluminum core structural material compositions were altered as needed to reflect changes in the dissolved boron concentration in the core.

3.4 MCNP TALLIES AND COMPUTATION OF k_{eff} AND RENDEMENT

The choices of MCNP tallies to be used in the comparison between the FOEHN experiment and the computational model are shown, and the reasons for their selection are summarized in this section. In addition, the methods used to compute k_{eff} and the rendement are discussed.

3.4.1 Fluxes

The thermal fluxes reported in the FOEHN experiments are obtained by estimating the activation due to thermal neutrons (the activation is proportional to the flux). They are, therefore, best approximated by a track length estimate of the flux (i.e., a F4:n MCNP tally). The upper energy boundary of the thermal energy group should be chosen as 0.625 eV to conform with the definition of thermal flux chosen in the FOEHN experiment based on the cadmium effective cutoff energy.

3.4.2 Powers

The fission power density or fission power production density is described as power distribution in the FOEHN report. It is measured by evaluating the number of fission events that occurred in a given fission probe. The measurements yield a quantity proportional to the power released in the probe during irradiation. The MCNP tally that most closely represents this physical quantity is a F7:n tally.

3.4.3 Effective Multiplication Factor

The multiplication factor (k_{eff}) is measured via three different methods in the FOEHN experiment (see Sect. 2.3.1.1). In the present work, k_{eff} is computed via the KCODE option of MCNP.

3.4.4 Determination of Rendement

A measure of the neutron efficiency, the rendement, is defined as the ratio of the maximum thermal flux in the reflector to the total recoverable power produced in the reactor. In the MCNP model, the rendement is computed from the maximum value of F4:n tallies in the reflector renormalized using the multiplying factor

$$RN = v \cdot \frac{1}{Q} \cdot \frac{1}{k_{eff}}, \quad (8)$$

where v is the average number of neutrons per fission, Q is the fission energy, and k_{eff} is the effective multiplication factor from the MCNP run that yielded the flux tally to be renormalized. In this work, v is computed as the ratio of two separate MCNP tallies, and its value is reported whenever pertinent. When a value is not computed for v , and one is required, the number 2.44175 is used. The energy released per fission event, Q , is taken to be 202.47 MeV/fission unless otherwise specified. In order to obtain a meaningful comparison in the computational determination of the rendement, the same value of Q (199.73 MeV) as that of the FOEHN report is used in this work, but only for "rendement" computations.

3.5 SUMMARY

In this chapter, the MCNP model developed in this work has been presented. The main approximation made was the use of a homogenized fuel region and of homogenized boron axial end covers above and below the core. These approximations were justified by the fact that the neutron mean free path in these regions is much larger than any of the dimensions of the constituting components. The materials used in the model accurately represent the compositions used in the experiment. The only exceptions are the use of full theoretical density graphite (C) and cadmium (Cd) data. When Zircaloy-4 and stainless steel 304 were required, data developed for models of the ANS reactor and of the FGHFR were used. The fluxes and the power production distribution are modeled as F4:n and F7:n tallies, respectively. The rendement is computed as a particular case of a renormalized F4:n tally. The core multiplication factors are obtained via the KCODE option of MCNP.

4. RESULTS

4.1 INTRODUCTION

The results obtained in the course of this study are detailed in this chapter. The FOEHN report is consistently referred to for comparisons. The results are reported by reactor configuration. The core multiplication factor, thermal flux, rendement, and power distribution are addressed in turn. It is shown that the model and the experimental results coincide very well within the computational statistical error and experimental error bounds. The model results are reported normalized as described in the text. The MCNP error estimates (standard deviations σ) are reported as fractions of the tallies they qualify unless otherwise noted to be absolute values.

4.2 SIMPLE REACTOR MODEL

4.2.1 Core Multiplication Factors (k_{eff})

The multiplication factor has been evaluated for 11 critical control rod positions and corresponding boron concentrations for the simple FOEHN configuration (no boron end caps and no reflector internals). These computations used the KCODE option of MCNP with 40 cycles and 3000 histories per cycle. The results are given in Table 4.1 and shown in Fig. 4.1. The cases in Fig. 4.1 are defined in the table as particular combinations of control rod positions and soluble boron concentrations for which the reactor is critical. The case definitions for all reactor configurations are taken from Table 5.1.1 of ref. 2. It can be seen from Fig. 4.1 that the computational results coincide with 1.0 within a tolerance of 2σ for two cases and are very close for five other cases. The miss rate is 9/11 (i.e., nearly 82%). This rate is far greater than the theoretically expected average miss rate of about 5% for 2σ error bars. If the error bars are increased to 3σ , the miss rate drops to five, of which two would be very close misses.

An estimate of the effect of small perturbations in control rod position on the calculated critical states was obtained by moving the control rod up or down 20 mm from the critical position. This was done for each of three different critical states: rod at 1.438 m and 0.2477 g/L of boron in the core; rod at 1.009 m and 0.4509 g/L of boron in the core; and rod at 0.714 m and 0.5386 g/L of boron in the core. The results of these runs are presented in Table 4.2 and Fig. 4.2. These show that for the first critical state (rod initially at 1.438 m and 0.2477 g/L of boron), the rod position perturbation produces the expected behavior—rod withdrawal increases the core multiplication factor, whereas rod insertion reduced it. For the intermediate boron concentration (0.4509 g/L), the same behavior is observed. In the last case, the core multiplication factors of the initial critical state and of the perturbed states are within the 2σ error bars defined by the computational statistics and, thus, are not distinguishable. This can be attributed to the reduced worth of the control rod caused by the high concentration of boron in the core. For this critical state, the boron concentration in the core provides the bulk of the reactivity control, and hence small perturbations in the control rod positions have small effects, and the observed fluctuations have no statistical significance.

4.2.2 Thermal Flux

Calculated MCNP thermal fluxes (F4:n tallies, KCODE, 40 cycles, 10000 histories/cycle) were compared to the results given in Table 5.1.4 of ref. 2. The thermal flux for this comparison was

Table 4.1. MCNP computed core effective multiplication factors (k_{eff}) for various critical states of the simple reactor configuration

Case	Control rod position (m)		Boron conc. (g/L)	MCNP k_{eff}	MCNP error estimate (σ)
	MCNP	FOEHN			
1	1.438	0.172	0.2477	1.0003	0.0019
2	1.253	0.357	0.3349	1.0076	0.0029
3	1.155	0.455	0.3863	1.0092	0.0021
4	1.142	0.4673	0.3855	1.0093	0.0030
5	1.014	0.596	0.4501	1.0127	0.0023
6	1.009	0.601	0.4509	1.0080	0.0031
7	1.008	0.602	0.4536	1.0095	0.0026
8	0.949	0.661	0.4791	1.0069	0.0029
9	0.753	0.857	0.5268	1.0034	0.0033
10	0.720	0.89	0.5386	1.0104	0.0021
11	0.714	0.896	0.5386	1.0069	0.0028

defined as the flux below 0.625 eV. This cutoff energy was chosen to match the cutoff energy used in the FOEHN experiment. The F4:n tally gives the neutron flux averaged over a cell in units of particles/cm². Measured thermal fluxes in ref. 2 were reported at specific radii (r) and heights (z), but no specific azimuthal location was given in the report. To model these locations in MCNP, annuli of 0.01-m width and 0.01-m height were used. The center of the annuli were located at the coordinates (r,z) of the detector foils. The control rod height for this case was set at 1.01 m in the MCNP model. The boron-10 (¹⁰B) concentration was 0.450 g/L.

The MCNP F4:n tallies were normalized to 1 W total reactor power for a direct comparison with the experimental results. Table 4.3 shows the MCNP-calculated thermal fluxes, and Table 4.4 shows the corresponding computed error estimate (2 σ). The entries in these two tables are in units of 10¹¹ m⁻² · s⁻¹. The results in both of these tables use 2.43862 for ν and 202.47 MeV for Q . These results can be directly compared to the thermal fluxes in Table 5.1.4 of ref. 2. In Figs. 4.3, 4.4, and 4.5, experimental and computational axial flux shapes are shown at radii of 0.235 m, 0.355 m, and 0.835 m, respectively, from the center of the reactor. As discussed in Sect. 2.4.3.2, the error bars for the experimental data points are taken as $\pm 12\%$, a much more realistic figure than the $\pm 2\%$ claim in the FOEHN report. The error bars on the MCNP points are based on a $\pm 2\sigma$ error estimate. These figures show that MCNP-calculated thermal fluxes agree, within statistics and experimental error estimates, with the experimental results. Not seen from the three figures is the total number of points for which the experimental and computational results do not coincide (in the sense that their respective error bars overlap). This total number of misses is six. If the experimental bars are assumed to be

Fig. 4.1. MCNP prediction of k_{eff} for a set of critical states of the simple FOEHN reactor configuration.

Table 4.2. Effect of control rod perturbations on the core effective multiplication factor for three critical states of the simple reactor configuration

Control rod position (m)	Core boron concentration (g/L)	Core multiplication	
		k_{eff}	σ
1.478	0.2477	0.9937	0.0029
1.438 (base)	0.2477	1.0003	0.0019
1.398	0.2477	1.0068	0.0030
1.049	0.4509	1.0016	0.0025
1.009 (base)	0.4509	1.0080	0.0031
0.969	0.4509	1.0165	0.0029
0.760	0.5386	1.0030	0.0031
0.720 (base)	0.5386	1.0104	0.0021
0.680	0.5386	1.0054	0.0027

more narrow, the number of misses increases to 15 for 10% experimental error and to 38 for 8% experimental error. Since there are 158 experimental points, these misses represent miss rates of 3.8, 9.5, and 24% respectively. The 12% experimental error assumption yields results that are compatible with the statistical interpretation of the 2σ computational bars.

4.2.3 Rendement

For the simple reactor configuration, the measured rendement (r_{meas}) is 2.480×10^{11} neutrons/ $m^2 \cdot s \cdot W$. The error on this quantity ranges from at least $\pm 2.2\%$ to possibly as much as 16.2% as estimated in Sect. 2.4.3.4 (vs the FOEHN report claim of $\pm 2\%$). In the remainder, it is assumed that the error is the same as that on the flux—about 12%.

The MCNP computed rendement, r_{calc} , is found to be 2.777×10^{11} neutrons/ $m^2 \cdot s \cdot W$, with a standard deviation (σ) of 0.94% (assuming Q is 199.73 MeV, the same as the one used in the FOEHN report, and v is 2.43862). The computed value of the rendement is ~12% higher than the experimental one. A similar result (14% higher) was found independently by Rohrmoser.¹⁰ The two error bands (experimental and computational— 2σ) overlap significantly. They would overlap slightly even if the experimental error was taken to be as low as ~10%. The two estimates of the rendement can be considered to be coinciding.

4.2.4 Power

The MCNP model of the FOEHN critical experiment has been used to obtain F7:n tallies. The tallies have been normalized to the same constant (1.014239) as the data of the corresponding Table 5.1.5 of the FOEHN report, according to the procedure summarized in Sect. 2.3.2.2. The

Fig. 4.2. Control rod position perturbation effect on k_{eff} in the simple FOEHN reactor configuration.

Table 4.3. Computed thermal fluxes for the simple reactor configuration
(MCNP F4:n tallies; 0.625 eV cutoff; 1 W reactor power; units: $10^{11} \text{ m}^{-2} \cdot \text{s}^{-1}$)

<i>H/r</i> (mm)	235	255	275	295	315	335	355	395	435	515	635	755	835
525	0.6062	0.6828	0.7652	0.7298	0.7819	0.7997	0.8147	0.7878	0.7916	0.6971	0.5548	0.4008	0.3043
625	0.9433	1.0015	1.0857	1.0532	1.1355	1.1259	1.1325	1.0841	1.0632	0.9136	0.7038	0.4942	0.3714
725	0.9636	1.1321	1.3528	1.3327	1.4048	1.4777	1.4824	1.4568	1.3779	1.1713	0.8622	0.5972	0.4579
825	1.1441	1.4061	1.7076	1.5790	1.7676	1.8411	1.8447	1.8072	1.6965	1.4314	1.0106	0.7069	0.5353
925	1.3566	1.6437	2.0492	1.8655	2.1158	2.1648	2.1489	2.1101	1.9917	1.6737	1.1570	0.8019	0.6018
975	1.4740	1.7678	2.1728	2.0135	2.2842	2.3366	2.3357	2.2271	2.1308	1.7431	1.2169	0.8280	0.6295
1075	1.6401	1.9841	2.3830	2.2314	2.5320	2.5096	2.5115	2.4646	2.2986	1.8900	1.3199	0.8768	0.6564
1125	1.7087	2.0244	2.5312	2.2904	2.5933	2.6569	2.6205	2.5339	2.3806	1.9510	1.3422	0.9029	0.6707
1225	1.7296	2.1213	2.5841	2.3716	2.6410	2.6807	2.6773	2.5733	2.4249	1.9489	1.3576	0.9011	0.6574
1275	1.6828	2.1096	2.5514	2.3458	2.6393	2.6709	2.7046	2.5457	2.3463	1.8856	1.3205	0.8724	0.6429
1325	1.6915	2.0312	2.4320	2.3055	2.5459	2.5847	2.5897	2.4973	2.3164	1.8541	1.2858	0.8580	0.6446
1375	1.5896	1.9342	2.3635	2.2044	2.4702	2.4866	2.4523	2.3535	2.1798	1.7959	1.2447	0.8239	0.6251
1425	1.5401	1.8585	2.2559	2.1000	2.2881	2.3401	2.3536	2.3021	2.0707	1.7082	1.1965	0.8102	0.5820
1525	1.6926	1.8797	2.0065	1.9877	2.0685	2.0725	2.0369	1.9349	1.8237	1.5049	1.0570	0.7181	0.5280
1675	1.6369	1.6406	1.6205	1.6262	1.5828	1.5827	1.5395	1.4569	1.3349	1.1077	0.8017	0.5635	0.4370
1825	1.0853	1.0584	1.0410	1.0707	1.0461	1.0075	0.9953	0.9314	0.8624	0.7334	0.5652	0.4316	0.3054

Table 4.4. MCNP error estimate (2σ , absolute) for the thermal fluxes for the simple reactor configuration
(units: $10^{11} \text{ m}^{-2} \cdot \text{s}^{-1}$)

H/r (mm)	235	255	275	295	315	335	355	395	435	515	635	755	835
525	0.0258	0.0270	0.0282	0.0279	0.0281	0.0277	0.0272	0.0255	0.0249	0.0215	0.0173	0.0135	0.0180
625	0.0341	0.0341	0.0337	0.0345	0.0341	0.0331	0.0324	0.0301	0.0293	0.0249	0.0194	0.0147	0.0121
725	0.0335	0.0355	0.0376	0.0384	0.0374	0.0384	0.0371	0.0358	0.0331	0.0281	0.0216	0.0164	0.0136
825	0.0368	0.0405	0.0423	0.0417	0.0428	0.0427	0.0417	0.0394	0.0370	0.0312	0.0234	0.0180	0.0145
925	0.0404	0.0434	0.0467	0.0451	0.0461	0.0463	0.0447	0.0426	0.0398	0.0338	0.0250	0.0192	0.0155
975	0.0419	0.0449	0.0482	0.0471	0.0484	0.0477	0.0467	0.0441	0.0409	0.0345	0.0258	0.0194	0.0161
1075	0.0440	0.0476	0.0500	0.0495	0.0511	0.0497	0.0482	0.0458	0.0428	0.0355	0.0267	0.0198	0.0163
1125	0.0444	0.0478	0.0521	0.0499	0.0513	0.0510	0.0493	0.0466	0.0438	0.0363	0.0274	0.0202	0.0165
1225	0.0453	0.0496	0.0527	0.0512	0.0518	0.0509	0.0503	0.0473	0.0441	0.0366	0.0272	0.0204	0.0162
1275	0.0441	0.0494	0.0520	0.0511	0.0523	0.0507	0.0508	0.0468	0.0427	0.0354	0.0267	0.0197	0.0161
1325	0.0450	0.0483	0.0506	0.0507	0.0509	0.0501	0.0492	0.0464	0.0431	0.0352	0.0265	0.0196	0.0162
1375	0.0436	0.0468	0.0501	0.0498	0.0509	0.0497	0.0481	0.0447	0.0414	0.0352	0.0259	0.0190	0.0158
1425	0.0422	0.0461	0.0496	0.0483	0.0485	0.0482	0.0471	0.0447	0.0402	0.0342	0.0256	0.0190	0.0150
1525	0.0454	0.0481	0.0466	0.0473	0.0459	0.0456	0.0436	0.0410	0.0383	0.0319	0.0241	0.0181	0.0144
1675	0.0465	0.0453	0.0418	0.0436	0.0405	0.0399	0.0382	0.0358	0.0326	0.0272	0.0205	0.0159	0.0133
1825	0.0380	0.0354	0.0335	0.0351	0.0333	0.0316	0.0307	0.0279	0.0257	0.0219	0.0172	0.0035	0.0109

Fig. 4.3. Comparison of experimental and computed axial flux shapes at $r = 235 \text{ mm}$ in the simple FOEHN configuration.

Fig. 4.4. Comparison of experimental and computed axial flux shapes at $r = 355 \text{ mm}$ in the simple FOEHN configuration.

Fig. 4.5. Comparison of experimental and computed axial flux shapes at $r = 835 \text{ mm}$ in the simple FOEHN configuration.

normalized results are shown in Table 4.5. In Table 4.6, the corresponding MCNP error estimates (2σ , i.e., two times the standard deviation from the normalized entries of Table 4.5) are shown.

The tallies (from Table 4.5) and the experimental data from Table 5.1.5 of the FOEHN report are compared in Figs. 4.5–4.15. The error bars shown for the computed results correspond to the 2σ values tabulated in Table 4.6. The error bars for the experimental points correspond to the 4% estimate for the error discussed in Chap. 2.

In Figs. 4.6, 4.7, and 4.8, the power distribution is plotted as a function of the axial coordinate H for the radii of 143.5 mm, 167.5 mm, and 193.95 mm, respectively. In Figs. 4.9–4.15, the power density is plotted as a function of the radius, r , for the axial planes at 2.5, 50, 175, 400, 625, 750, and 797.5 mm, respectively. In this way, every data point featured in Table 5.1.5 of the FOEHN report is plotted at least once. It can be seen from the figures that, for most points, there is at least partial overlap of the error bars from the computational predictions and the experiment. In most cases, the overlap is significant, with the experimental point actually falling within the computational error bar (or vice versa). The only points that do not show any overlap are those given by the r, H coordinate pairs in mm (143.5, 325.0) and (143.5, 400.0).

These two points correspond to slightly <1.64% of the total number (122) of experimental points. This result is in remarkably high agreement with the statistical interpretation of the computational error bars. The bars are 2σ in width. It follows that there is a 95% probability that the physically correct value of the computed quantity lie within the band defined by such error bars. The 1.64% of the points lying outside the error band is compatible with the corresponding 5% probability that points lie outside the band. In an independent study, using the discrete ordinate transport code DOT, Rohrmoser¹⁰ obtained similar results—the same two experimental points were not reproduced by his model. The difference between models and experiment are in the same direction. The agreement between the two independent modeling efforts suggests that the experimental points might be incorrect. The difference (~3%) is not significant. The use of a homogenized representation for the fuel is known to be capable of producing local power variations as high as 5% in MCNP computations.¹¹ This effect appears not to be significant in the present case.

4.3 INTERMEDIATE COMPLEXITY REACTOR MODEL

4.3.1 Core Multiplication Factor (k_{eff})

The results of KCODE calculations (40 cycles, 3000 histories/cycle) for the intermediate complexity reactor configuration are tabulated in Table 4.7 and shown in Fig. 4.16. The cases referred to in the figure are defined in Table 4.7. For this reactor configuration, the k_{eff} predictions coincide (within 2σ) with the expected experimental value of 1.0 in four cases out of six. The two misses are within the 3σ band. These results can be interpreted as 0–33% misses.

4.3.2 Thermal Flux

Calculated MCNP thermal fluxes were compared to the results given in Table 5.2.5 of ref. 2. As stated previously, thermal fluxes for this benchmarking analysis were computed as F4:n tallies for neutron energies below 0.625 eV in a KCODE calculation using 40 cycles of 10000 particles each. Modeling of the detectors was done in the same way as described in Sect. 4.2.2. The control rod height for this case was set at 1.163 m in MCNP (corresponding to the experimental control rod height of 0.447 m given in ref. 2). The boron (^{10}B) concentration was set to 0.258 g/L.

Table 4.5. Normalized MCNP power production (F7:n tallies) for the simple reactor configuration

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
02.5	0.9140	0.9214	0.8688	0.8321	0.8763	0.9120	1.0486	1.1412	1.1877	1.3026	1.6102
09.4	0.7367										1.3728
14.5	0.6567					0.5302					
19.4	0.6551					0.5064					1.2527
28.5	0.5374					0.4774					1.2152
50.0	0.5492	0.4938	0.4541	0.4255	0.3944	0.4528	0.5227	0.6585	0.7909	0.8983	1.2714
75.0	0.5344					0.4611					1.2705
100.0	0.5565					0.4441					1.3406
175.0	0.6676	0.6066	0.5734	0.5360	0.4921	0.5390	0.6686	0.7855	0.8908	1.0792	1.4619
250.0	0.7621					0.6617					1.7424
325.0	1.1703					0.7913					2.0383
400.0	1.3068	1.1060	0.9866	0.9477	0.8592	0.8242	0.9336	1.1980	1.3518	1.5135	2.1311
475.0	1.3052					0.8577					2.1121
550.0	1.3527					0.8606					2.1074
625.0	1.3112	1.2016	1.0356	0.9174	0.8360	0.8374	0.9156	1.0927	1.2429	1.4430	2.0251
700.0	1.2340					0.7771					1.9788
725.0	1.2306					0.7680					1.9595
750.0	1.3354	1.1567	1.0637	0.9207	0.8023	0.7971	0.9368	1.1539	1.2480	1.4645	2.0040
771.5	1.6154					0.9039					2.0945
780.6	1.7211					1.0737					2.2735
785.5	1.8351					1.1864					2.4136
790.6	2.0209										2.5324
797.5	2.5715	2.3638	2.2892	2.2125	2.0568	2.0743	2.1973	2.2845	2.4287	2.5611	2.9713

Table 4.6. MCNP error estimate (2σ , absolute) for the normalized MCNP power production for the simple reactor configuration

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
02.5	0.0590	0.0617	0.0553	0.0536	0.0535	0.0529	0.0581	0.0600	0.0615	0.0659	0.0776
09.4	0.0497										0.0659
14.5	0.0475					0.0346					0.0609
19.4	0.0455					0.0351					0.0593
28.5	0.0361					0.0334					0.0651
50.0	0.0379	0.0337	0.0330	0.0328	0.0280	0.0353	0.0343	0.0412	0.0478	0.0512	0.0653
75.0	0.0340					0.0319					0.0660
100.0	0.0365					0.0283					0.0699
175.0	0.0403	0.0385	0.0346	0.0331	0.0312	0.0320	0.0397	0.0426	0.0499	0.0546	0.0725
250.0	0.0407					0.0379					0.0828
325.0	0.0620					0.0416					0.0831
400.0	0.0674	0.0551	0.0493	0.0476	0.0450	0.0425	0.0463	0.0568	0.0611	0.0657	0.0828
475.0	0.0637					0.0444					0.0830
550.0	0.0666					0.0432					0.0814
625.0	0.0645	0.0627	0.0551	0.0490	0.0426	0.0467	0.0449	0.0538	0.0562	0.0638	0.0815
700.0	0.0647					0.0401					0.0815
725.0	0.0655					0.0424					0.0814
750.0	0.0686	0.0620	0.0589	0.0516	0.0440	0.0454	0.0482	0.0554	0.0569	0.0624	0.0825
771.5	0.0821					0.0483					0.0873
780.5	0.0840					0.0543					0.0932
785.5	0.0921					0.0603					0.0942
790.6	0.0922										0.1046
797.5	0.1080	0.1040	0.1016	0.0938	0.0872	0.0888	0.0875	0.0896	0.0923	0.0942

Fig. 4.6. Comparison of normalized experimental and computed axial power distribution in the simple FOEHN configuration at $r = 143.5$ mm.

Fig. 4.7. Comparison of normalized experimental and computed axial power distribution in the simple FOEHN configuration at $r = 167.5$ mm.

Fig. 4.8. Comparison of normalized experimental and computed axial power distribution in the simple FOEHN configuration at $r = 193.95$ mm.

Fig. 4.9. Comparison of normalized experimental and computed axial power distribution in the simple FOEHN configuration at $H = 2.5$ mm.

Fig. 4.10. Comparison of normalized experimental and computed radial power distribution in the simple FOEHN configuration at $H = 50$ mm.

Fig. 4.11. Comparison of normalized experimental and computed radial power distribution in the simple FOEHN configuration at $H = 175$ mm.

Fig. 4.12. Comparison of normalized experimental and computed radial power distribution in the simple FOEHN configuration at $H = 400$ mm.

Fig. 4.13. Comparison of normalized experimental and computed radial power distribution in the simple FOEHN configuration at $H = 625$ mm.

Fig. 4.14. Comparison of normalized experimental and computed radial power distribution in the simple FOEHN configuration at $H = 750$ mm.

Fig. 4.15. Comparison of normalized experimental and computed radial power distribution in the simple FOEHN configuration at $H = 797.5$ mm.

Table 4.7. MCNP computed core effective multiplication factors (k_{eff}) for various critical states of the intermediate complexity reactor configuration

Case	Control rod position (m)		Boron conc. (g/L)	MCNP k_{eff}	MCNP error estimate (σ)
	MCNP	FOEHN			
1	1.2578	0.3522	0.210	1.0017	0.0028
2	1.163	0.447	0.258	1.0090	0.0030
3	1.153	0.457	0.270	1.0004	0.0026
4	1.001	0.609	0.350	1.0025	0.0036
5	0.946	0.664	0.371	1.0081	0.0025
6	0.795	0.815	0.419	1.0054	0.0026

The MCNP F4:n tallies were normalized to 1 W total reactor power to allow a direct comparison to the experimental thermal fluxes of Table 5.2.5 in ref. 2. Table 4.8 shows the MCNP-calculated thermal fluxes, and Table 4.9 shows their respective relative errors (2σ). The entries in these two tables are in units of $10^{11} \text{ m}^{-2} \cdot \text{s}^{-1}$. In this case, the computed value of 2.43871 was used for v . The value of Q was 202.47 MeV, except for the estimate of the rendement for which the value 199.73 MeV was used. Figures 4.17, 4.18, and 4.19 show a comparison of the MCNP-calculated and the experimental results at the radii of 0.235 m, 0.355 m, and 0.835 m. The error bars assume $\pm 2\sigma$ for the computational points and ± 4 , ± 8 , $\pm 8\%$ for the experimental points in the three figures, respectively (vs the $\pm 2\%$ claimed in the FOEHN report). These figures show that MCNP-calculated thermal fluxes and the experimental fluxes are in agreement within the bands defined by the experimental error and the statistical limits.

4.3.3 Rendement

The rendement calculated by MCNP, r_{calc} , is $2.8529 \times 10^{11} \text{ neutrons/m}^2 \cdot \text{s} \cdot \text{W}$ with a standard deviation, σ , of 0.94%. The measured rendement, reported in ref. 2, r_{meas} , is $2.56 \times 10^{11} \text{ neutrons/m}^2 \cdot \text{s} \cdot \text{W}$. As discussed in Sect. 2.4.3.4, an error of between 2.2 and 16.2% should be associated with the measured value (vs the $\pm 2\%$ claimed in ref. 2). In the following, it is assumed that the experimental error is of the order of 12% (same as for the fluxes). The difference between the computational and the experimental results is approximately +11.5%. Rohrmoser independently computed a value 13% larger than the experimental one. As in the previous case (simplest reactor configuration), the two estimates of the rendement can be considered to be coinciding since the error bands associated with them ($\pm 12\%$ and $\pm 2\sigma$) overlap significantly. It is noteworthy that the two estimates overlap even if the experimental error band is decreased to -10% .

Fig. 4.16. MCNP prediction of k_{eff} for a set of critical states of the intermediate FOEHN reactor configuration.

Table 4.8. Computed thermal fluxes for the intermediate reactor configuration*

<i>H/r</i> (mm)	235	275	315	335	355	375	395	435	515	675	755	835	915	955
510	0.5603	0.6461	0.7398	0.7621	0.7548	0.7485	0.7479	0.7136	0.6620	0.4824	0.3943	0.3082	0.2156	0.1813
610	0.8278	0.9498	1.0481	1.0725	1.0791	1.0900	1.0517	1.0041	0.9047	0.6014	0.4917	0.3746	0.2696	0.2242
710	0.8786	1.1951	1.3845	1.4176	1.4361	1.4378	1.3973	1.3660	1.1741	0.7774	0.5935	0.4518	0.3303	0.2672
810	1.1505	1.5598	1.7764	1.8310	1.8264	1.8080	1.7878	1.6916	1.4122	0.9175	0.7098	0.5300	0.3712	0.3052
910	1.4072	1.9431	2.2152	2.2280	2.2166	2.1946	2.1763	2.0602	1.6964	1.0593	0.8042	0.5922	0.4212	0.3498
1010	1.6225	2.2402	2.4869	2.5653	2.5538	2.4961	2.4833	2.2784	1.8769	1.1445	0.8766	0.6404	0.4602	0.3673
1060	1.7193	2.3355	2.6097	2.6120	2.6530	2.6175	2.5585	2.3745	1.9351	1.1672	0.8880	0.6599	0.4614	0.3788
1110	1.7867	2.4579	2.6938	2.7880	2.7620	2.7043	2.6319	2.4422	2.0041	1.1935	0.8841	0.6701	0.4598	0.3818
1160	1.7484	2.4750	2.7342	2.7930	2.7921	2.7693	2.6698	2.4847	1.9970	1.1929	0.9148	0.6738	0.4719	0.3804
1210	1.8122	2.4653	2.7421	2.8143	2.8009	2.7308	2.7065	2.4567	2.0027	1.2021	0.9094	0.6711	0.4709	0.3825
1260	1.7670	2.4378	2.6935	2.7644	2.7510	2.6683	2.6162	2.4439	1.9291	1.1699	0.8877	0.6622	0.4621	0.3773
1310	1.7220	2.3228	2.6046	2.6796	2.6408	2.5680	2.5494	2.3327	1.8961	1.1377	0.8500	0.6453	0.4491	0.3651
1410	1.5132	2.0385	2.2988	2.3106	2.3220	2.2738	2.2254	2.0807	1.7147	1.0423	0.8020	0.5976	0.4177	0.3389
1510	1.3235	1.7094	1.8858	1.9349	1.9423	1.8933	1.8538	1.7593	1.4920	0.9171	0.7079	0.5392	0.3868	0.3139
1610	1.4131	1.5393	1.5722	1.5757	1.5798	1.5135	1.4815	1.4285	1.2118	0.7973	0.6172	0.4595	0.3239	0.2781
1710	1.2452	1.2212	1.2136	1.2185	1.2026	1.1993	1.1537	1.0896	0.9507	0.6216	0.4965	0.3804	0.2812	0.2232
1810	0.9437	0.9385	0.9127	0.8981	0.8985	0.8724	0.8627	0.8218	0.7003	0.4915	0.4290	0.2994	0.2212	0.1867

*MCNP F4:n tallies; 0.625 eV cutoff; 1 W reactor power; units: $10^{11} \text{ m}^{-2} \cdot \text{s}^{-1}$.

**Table 4.9. MCNP error estimate (2σ , absolute) for the thermal fluxes for the intermediate reactor configuration
(units: $10^{11} \text{ m}^{-2} \cdot \text{s}^{-1}$)**

H/r (mm)	235	275	315	335	355	375	395	435	515	675	755	835	915	955
510	0.0252	0.0264	0.0275	0.0271	0.0261	0.0254	0.0250	0.0233	0.0211	0.0157	0.0133	0.0111	0.0087	0.0077
610	0.0320	0.0325	0.0329	0.0326	0.0319	0.0314	0.0297	0.0277	0.0246	0.0173	0.0148	0.0121	0.0097	0.0087
710	0.0320	0.0366	0.0377	0.0371	0.0365	0.0362	0.0347	0.0333	0.0282	0.0199	0.0164	0.0134	0.0109	0.0092
810	0.0364	0.0415	0.0426	0.0425	0.0413	0.0401	0.0390	0.0365	0.0308	0.0217	0.0179	0.0146	0.0115	0.0101
910	0.0405	0.0466	0.0478	0.0468	0.0457	0.0448	0.0435	0.0408	0.0343	0.0235	0.0193	0.0154	0.0123	0.0109
1010	0.0438	0.0497	0.0502	0.0503	0.0490	0.0474	0.0467	0.0428	0.0360	0.0245	0.0200	0.0163	0.0130	0.0111
1060	0.0454	0.0514	0.0517	0.0502	0.0499	0.0487	0.0471	0.0473	0.0364	0.0245	0.0202	0.0165	0.0128	0.0114
1110	0.0457	0.0526	0.0523	0.0524	0.0508	0.0498	0.0474	0.0440	0.0373	0.0251	0.0200	0.0166	0.0129	0.0113
1160	0.0451	0.0525	0.0530	0.0520	0.0508	0.0498	0.0481	0.0447	0.0367	0.0246	0.0203	0.0166	0.0130	0.0113
1210	0.0464	0.0523	0.0532	0.0529	0.0510	0.0497	0.0482	0.0442	0.0368	0.0252	0.0206	0.0166	0.0131	0.0115
1260	0.0456	0.0531	0.0528	0.0525	0.0506	0.0486	0.0471	0.0445	0.0363	0.0246	0.0202	0.0164	0.0130	0.0113
1310	0.0451	0.0506	0.0516	0.0514	0.0496	0.0478	0.0474	0.0429	0.0360	0.0241	0.0196	0.0163	0.0127	0.0110
1410	0.0430	0.0473	0.0487	0.0481	0.0474	0.0450	0.0436	0.0408	0.0343	0.0231	0.0191	0.0155	0.0123	0.0107
1510	0.0400	0.0438	0.0445	0.0441	0.0435	0.0417	0.0404	0.0376	0.0319	0.0216	0.0177	0.0149	0.0118	0.0102
1610	0.0421	0.0428	0.409	0.0400	0.0392	0.0369	0.0359	0.0343	0.0288	0.0204	0.0169	0.0136	0.0106	0.0098
1710	0.0408	0.0379	0.0357	0.0351	0.0339	0.0336	0.0316	0.0292	0.0255	0.0177	0.0150	0.0122	0.0101	0.0086
1810	0.0347	0.0332	0.0307	0.0300	0.0291	0.0279	0.0274	0.0253	0.0214	0.0157	0.0034	0.0108	0.0089	0.0079

Fig. 4.17. Comparison of experimental and computed axial flux shapes at $r = 235$ mm in the intermediate FOEHN configuration.

Fig. 4.18. Comparison of experimental and computed axial flux shapes at $r = 355$ mm in the intermediate FOEHN configuration.

Fig. 4.19. Comparison of experimental and computed axial flux shapes at $r = 835$ mm in the intermediate FOEHN configuration.

4.3.4 Power

The intermediate complexity MCNP model of the FOEHN critical experiment has been used to obtain F7:n tallies (KCODE option, 80 cycles, 10000 particles/cycle). The tallies have been normalized to the same constant (0.99781) as the data of the corresponding table of the FOEHN report (Table 5.2.6), according to the procedure summarized in Sect. 2.3.2.2. The normalized MCNP results are shown in Table 4.10. In Table 4.11, the corresponding MCNP error estimates (2σ) are shown. For the sake of completeness, the experimental data (Table 5.2.6 of ref. 2) are shown in Table 4.12.

The tallies from Table 4.10 and the experimental data from Table 5.2.6 of the FOEHN report are compared in Figs. 4.20–4.22. The error bars shown for the computed results correspond to the 2σ values tabulated in Table 4.11. The error bars for the experimental points correspond to the 4% estimate for the error discussed in Chap. 2.

In Figs. 4.20–4.22, the power distribution is plotted as a function of the axial coordinate H for the radii of 143.5, 167.5, and 193.95 mm, respectively. It can be seen from the figures that for most points in the reactor interior, there is at least partial (and most of the time significant) overlap of the error bars from the computational predictions and the experiment. In Table 4.13, all the experimental and computational results are compared in the sense of overlap of their respective error bands. In the table, an entry of 0 indicates overlap, whereas an entry of 1 indicates no overlap. There are 12 nonoverlapping points out of a total of 123 data points. This implies a nonmatching rate of 9.76%. The table shows that overlap occurs for most points internal to the reactor and that nearly all points at the top and bottom of the core show no overlap. This can be attributed to a lack of precise information about the location of the boron end caps and their modeling as homogenous rather than heterogenous regions. In addition, a possible, though probably negligible, effect might be the impact of the absence of an external AG3-NE end cover. These external covers (axial portion of the reactor tank, beyond the inner AG3-NE seals and the boron end caps) were not modeled because their size is not known, and they are expected to have little neutronic relevance, if any. If the nonmatching end points (9 points—2 at top and 7 at bottom of core) are excluded from the nonmatching count, the nonmatching rate drops to 2.44%, well within the expected nonoverlap rate of 5% predictable from the use of the $\pm 2\sigma$ error bands.

4.4 FULL COMPLEXITY REACTOR MODEL

4.4.1 Core Multiplication Factor (k_{eff})

The multiplication factor for the FOEHN experiment in the full complexity reactor configuration has been computed for several control rod positions and corresponding critical soluble boron concentrations (defined in Table 5.3.2 of ref. 2). The KCODE estimates (40 cycles, 3000 histories/cycle) of k_{eff} for the full-featured reactor configuration are tabulated in Table 4.14 and are shown in Fig. 4.23. They display three close misses and one miss by about 1σ . In three cases, the estimate of k_{eff} overlaps with the expected value of 1.0 (within 2σ). In these three cases, however, the overlap is by a very small margin. As in the previous two configurations, the small number of cases limits the statistical significance of the results.

4.4.2 Thermal Flux

For the full-complexity FOEHN configuration, the thermal flux was measured at the noses of several beam tubes, radially and axially through the hot source, axially through the cold source, and

Table 4.10. Normalized MCNP power production (F7:n tallies) for the intermediate reactor configuration

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0.4918	0.4541	0.4300	0.4241	0.3590	0.4224	0.5387	0.6491	0.7339	0.8520	1.1667
9.4	0.4905										1.1733
14.5	0.4708					0.4285					1.1304
19.4	0.4607					0.4342					1.2063
28.5	0.4858					0.4325					1.1563
50.0	0.5447	0.4788	0.4491	0.4717	0.4044	0.4271	0.5349	0.6463	0.7655	0.8724	1.2390
75.0	0.5334					0.4732					1.3318
100.0	0.6005					0.5259					1.4222
175.0	0.7687	0.7013	0.6651	0.6403	0.5809	0.6249	0.7231	0.9331	1.0298	1.1228	1.5690
250.0	0.8994					0.7783					1.9762
325.0	0.9600					0.8230					2.0875
400.0	1.0411	0.9761	0.9307	0.8933	0.8266	0.8588	1.0681	1.2665	1.4233	1.6231	2.2295
475.0	1.4025					0.9759					2.2987
550.0	1.4749					0.9592					2.2911
625.0	1.3238	1.2077	1.0794	1.0092	0.8876	0.8658	0.9922	1.1805	1.3557	1.6413	2.1978
700.0	1.1736					0.7781					1.8758
725.0	1.1740					0.7317					1.7848
750.0	1.1131	0.9953	0.8451	0.7881	0.7397	0.6913	0.7818	1.0226	1.1521	1.2781	1.7095
771.5	1.0583					0.6549					1.7299
780.6	1.1249					0.6785					1.7121
785.5	1.0787					0.6380					1.7523
790.6	1.1233										1.7326
797.5	1.1574	1.0260	0.9053	0.8431	0.7667	0.7043	0.8371	1.0455	1.1916	1.2919	1.7957

Table 4.11. MCNP error estimate (2σ , absolute) for the normalized MCNP power production for the intermediate reactor configuration

H/r (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0.0409	0.0343	0.0315	0.0327	0.0279	0.0307	0.0373	0.0439	0.0483	0.0491	0.0653
9.4	0.0344										0.0615
14.5	0.0347					0.0308					0.0619
19.4	0.0334					0.0309					0.0644
28.5	0.0345					0.0309					0.0624
50.0	0.0395	0.0338	0.0322	0.0362	0.0289	0.0296	0.0342	0.0401	0.0452	0.0508	0.0619
75.0	0.0366					0.0311					0.0666
100.0	0.0364					0.0351					0.0697
175.0	0.0423	0.0390	0.0372	0.0365	0.0345	0.0376	0.0419	0.0504	0.0505	0.0546	0.0715
250.0	0.0455					0.0405					0.0806
325.0	0.0511					0.0430					0.0843
400.0	0.0498	0.0472	0.0477	0.0481	0.0428	0.0419	0.0536	0.0580	0.0615	0.0665	0.0843
475.0	0.0679					0.0472					0.0910
550.0	0.0711					0.0468					0.0894
625.0	0.0675	0.0623	0.0555	0.0557	0.0447	0.0448	0.0488	0.0548	0.0594	0.0702	0.0870
700.0	0.0638					0.0426					0.0773
725.0	0.0664					0.0414					0.0778
750.0	0.0634	0.0569	0.0507	0.0476	0.0493	0.0411	0.0439	0.0515	0.0583	0.0649	0.0773
771.5	0.0622					0.0411					0.0758
780.6	0.0637					0.0419					0.0774
785.5	0.0613					0.0389					0.0785
790.6	0.0660					0.0000					0.0807
797.5	0.0681	0.0630	0.0581	0.0528	0.0486	0.0421	0.0487	0.0533	0.0617	0.0641	0.0787

Table 4.12. Experimental power production distribution in the intermediate reactor configuration^a

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0.5018	0.4759	0.4512	0.4397	0.4338	0.4766	0.5805	0.7211	0.8090	0.9171	1.1850
4.5											1.1990
9.4	0.4839										1.2000
14.5	0.4794					0.4238					1.1911
19.4	0.4794					0.4167					1.2224
28.5	0.4847					0.4245					1.2601
50.0	0.5110	0.4742	0.4459	0.4239	0.4093	0.4420	0.5392	0.6769	0.7785	0.8976	1.3421
75.0	0.5567					0.4770					1.4317
100.0	0.5930					0.5121					1.7123
175.0	0.7313	0.6753	0.6400	0.6051	0.5872	0.6257	0.7491	0.9407	1.0623	1.2310	1.9383
250.0	0.8502					0.7224					2.1266
325.0	0.9511					0.8000					2.2504
400.0	1.0142	0.9537	0.8855	0.8438	0.8084	0.8560	1.1200	1.2612	1.4062	1.6161	2.3172
475.0	1.3118					0.9275					2.2620
550.0	1.3564					0.9315					2.1313
625.0	1.3150	1.1794	1.0616	0.9743	0.8880	0.8800	0.9931	1.2161	1.3458	1.5414	1.9097
700.0	1.1813					0.7740					1.8183
725.0	1.1423					0.7301					1.7799
750.0	1.0947	0.9687	0.8770	0.7968	0.7082	0.6966	0.8015	0.9889	1.1146	1.2653	1.7620
771.5	1.0978					0.6885					1.7518
780.6	1.0300					0.7054					1.7609
785.5	1.1152					0.7138					1.7956
790.6	1.1577										1.8400
797.5	1.2617	1.1367	1.0807	0.9924	0.9023	0.8946	0.9708	1.1586	1.2664	1.4038	

^aTable 5.2.6 of ref. 2.

Fig. 4.20. Comparison of normalized experimental and computed axial power distribution in the intermediate FOEHN configuration at $r = 143.5$ mm.

Fig. 4.21. Comparison of normalized experimental and computed axial power distribution in the intermediate FOEHN configuration at $r = 167.5$ mm.

Fig. 4.22. Comparison of normalized experimental and computed axial power distribution in the intermediate FOEHN configuration at $r = 193.95$ mm.

Table 4.13. Points of nonmatching power production density in the intermediate reactor configuration

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0	0	0	0	1	1	0	0	0	0	0
4.5											
9.4	0										0
14.5	0					0					0
19.4	0					0					0
28.5	0					0					0
50.0	0	0	0	0	0	0	0	0	0	0	0
75.0	0					0					0
100.0	0					0					0
175.0	0	0	0	0	0	0	0	0	0	1	1
250.0	0					0					0
325.0	0					0					0
400.0	0	0	0	0	0	0	0	0	0	0	0
475.0	0					0					0
550.0	0					0					0
625.0	0	0	0	0	0	0	0	0	0	0	0
700.0	0					0					0
725.0	0					0					0
750.0	0	0	0	0	0	0	0	0	0	0	0
771.5	0					0					0
780.6	0					0					0
785.5	0					1					0
790.6	0										0
797.5	0	1	1	1	1	1	1	1	0	0	0

Table 4.14. MCNP-computed core effective multiplication factors (k_{eff}) for various critical states of the full complexity reactor configuration

Case	Control rod position (mm)		Boron conc. (g/L)	MCNP k_{eff}	MCNP error estimate (σ)
	MCNP	FOEHN			
1	0.806	0.804	0.347	0.9935	0.0027
2	0.899	0.711	0.311	0.9981	0.0024
3	1.014	0.596	0.260	0.9973	0.0027
4	1.031	0.579	0.248	0.9935	0.0027
5	1.107	0.503	0.210	0.9931	0.0027
6	1.225	0.385	0.143	0.9943	0.0028
7	1.361	0.249	0.078	0.9890	0.0028

axially on the surface of Channel 17. In an attempt to accurately model these measurements, point detector tallies (i.e., next collision estimator, MCNP F5 tallies) were used. These allowed the flux at exact locations to be calculated with better statistics than the track length tallies (F4 tally) with small volume elements. The beam tube fluxes were calculated with the control rod position set to 1.139 m and a core boron concentration of 0.177 g/L. The other flux calculations were performed with the control rod set at 1.016 m and a core boron concentration of 0.255 g/L. The results obtained displayed a very large number of significant discrepancies between the experimental and the MCNP-computed fluxes, with many points showing no overlap between the computational and experimental error bands by a large margin. These large discrepancies result mainly from the inability of MCNP point detector tallies to incorporate histories involving $S(\alpha,\beta)$ interactions with moderating materials. The computational results have no value from a benchmarking point of view and, hence, are omitted from this report. The $S(\alpha,\beta)$ effect is explained below.

The $S(\alpha,\beta)$ cross-section data correspond to the coherent and incoherent elastic and incoherent inelastic scattering cross sections for materials with significant crystalline or other lattice-dependent scattering effects. These cross-section data, incorporated in the MCNP cross-section libraries and utilized in the FOEHN MCNP models, have a large effect on the behavior of heavy-water-moderated reactors and also influence the performance of other materials, such as liquid deuterium in cold sources and graphite in hot sources.

The large quantity of heavy water in the FOEHN experiment induces nearly all thermal neutrons to undergo at least one lattice-influenced thermal interaction before reaching the reflector components. These $S(\alpha,\beta)$ interactions are not accounted for by MCNP point detector tallies. This can result in a significant discrepancy between the computed tallies and the measured values. This was made very apparent in the initial analysis of the reflector thermal fluxes for the full complexity configuration, when inclusion of the $S(\alpha,\beta)$ data produced flux results that were a factor of two to four below the experimental values. The alternative to this method is to compute the fluxes without using the $S(\alpha,\beta)$ cross-section data. This would produce global inaccuracies in the flux energy distribution since fewer

Fig. 4.23. MCNP prediction of k_{eff} for a set of critical states of the full-featured FOEHN reactor configuration.

neutrons would be scattered into the lower thermal energy ranges (<0.625 eV). However, this would allow all neutron histories to interact with the point detector tallies. This method was tried and produced a systematic underestimation of the thermal fluxes calculated. These results are also omitted from this report.

An additional effect of the lack of $S(\alpha,\beta)$ cross-section data is seen in the results for the hot source. The presence of hot (~ 2000 K) graphite in the hot source introduces another set of $S(\alpha,\beta)$ cross-section data into the calculation. These have a different effect on the flux energy distribution, as there is significantly more upscattering from interactions with hot graphite than from interactions with room-temperature heavy water. The result is a tendency to lower the thermal flux (<0.625 eV) with increasing penetration into the hot source. Since the $S(\alpha,\beta)$ treatment is absent from the simulation, there ensues a large overestimation of the radial and axial thermal flux distributions in the hot source.

4.4.3 Rendement

The MCNP computed rendement, r_{calc} , is 2.4114×10^{11} neutrons/m² · s · W. The error estimate on this, 2σ , is 4.968×10^9 neutrons/m² · s · W. The measured rendement reported in ref. 2, r_{meas} , is 2.30×10^{11} neutrons/m² · s · W. The error reported in ref. 2 is $\sim 0.05 \times 10^{11}$ neutrons/m² · s · W (i.e., $\sim 3\%$). This error may be underestimated and could be as large as $\sim 16.2\%$ (see Sect. 2.4.3.4). With a difference of only 4.84% between the center values, the two estimates of the rendement agree within statistics (even with the lowest error estimates).

4.4.4 Power

The full complexity MCNP model of the FOEHN critical experiment has been used to obtain F7:n tallies (KCODE option, 80 cycles, 10000 particles/cycle). The tallies have been normalized to the same value (1.006) as the data of Table 2.2 obtained in Sect. 2.3.2.3 by combining the results of Tables 5.3.6–5.3.9 of the FOEHN report. The normalized MCNP results are shown in Table 4.15 of this report. In Table 4.16, the corresponding MCNP error estimates (2σ) are shown. The tallies from Table 4.15 and the combined experimental data from Table 2.2 are compared in Figs. 4.24–4.26. The error bars shown for the computed results are the 2σ values tabulated in Table 4.16. The error bars for the experimental points correspond to the 4% estimate for the error discussed in Chap. 2.

In Figs. 4.24–4.26 the power distribution is plotted as a function of the axial coordinate H for the radii of 143.5, 167.5, and 193.95 mm, respectively. As in the intermediate complexity case, it can be seen from the figures that for most points in the reactor interior, there is at least partial (and, in most instances, significant) overlap of the error bars from the computational predictions and the experiment. In Table 4.17, all the experimental and computational results are compared in the sense of overlap of their respective error bands. In the table, an entry of 0 indicates overlap, whereas an entry of 1 indicates no overlap. There are 18 nonoverlapping points out of a total of 125 data points. This implies a nonmatching rate of 14.4%. The table shows that overlap occurs for most points internal to the reactor and that nearly all points at the bottom and almost half the points at the top of the core show no overlap. As in the previous configuration, this can be attributed to the lack of precise information about the location of the borated end caps, the omission of the AG3-NE end covers in the model, and possibly to the modeling of the boron end caps as homogenous rather than heterogenous regions. If the end points (14 points, top and bottom of core) are excluded from the nonmatching count, the nonmatching rate drops to 3.20%, well within the expected nonoverlap rate of 5% predictable from the use of the $\pm 2\sigma$ error bands. Aside from the axial end points, two of the remaining four nonoverlap points occur at the inner radius of the core near the tip of the inserted control rod, where flux gradients are sharp and the discrepancy between MCNP F7:n tallies and the measured power

Table 4.15. Normalized MCNP power production (F7:n tallies) for the full complexity reactor configuration

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0.5044	0.4600	0.4189	0.4090	0.4294	0.4340	0.5167	0.6771	0.7065	0.7916	1.1002
9.4	0.4881										1.1871
14.5	0.4829					0.4092					1.2219
19.4	0.4854					0.4351					1.1927
28.5	0.5392					0.4283					1.2167
50.0	0.5305	0.4931	0.4392	0.4430	0.4566	0.4293	0.5406	0.6496	0.7680	0.9189	1.3222
75.0	0.5806					0.5034					1.3701
100.0	0.6347					0.5593					1.5916
175.0	0.7294	0.6678	0.6653	0.6339	0.6275	0.6528	0.7472	0.9301	1.0398	1.2076	1.9029
250.0	0.9000					0.7454					2.0977
325.0	0.9773					0.8130					2.2091
400.0	1.0904	1.0323	0.9687	0.9121	0.8414	0.8904	1.0201	1.2561	1.4289	1.6747	2.2745
475.0	1.5061					1.0533					2.1995
550.0	1.6064					0.9873					2.0027
625.0	1.3510	1.2273	1.1075	1.0047	0.8925	0.9016	1.0031	1.2251	1.3244	1.5141	1.8211
700.0	1.3155					0.8339					1.7019
725.0	1.1976					0.7740					1.7236
750.0	1.1100	0.9172	0.8365	0.7941	0.7155	0.7349	0.8652	1.0136	1.1565	1.2903	1.6379
771.5	1.0874					0.6835					1.6754
780.6	1.1191					0.7063					1.5936
785.5	1.1037					0.6727					1.6444
790.6	1.1370										1.6124
797.5	1.2027	1.0695	0.9411	0.8474	0.7471	0.7574	0.8243	0.0116	1.0783	1.2262	

Table 4.16. MCNP error estimate (2σ , absolute) for the normalized MCNP power production for the full complexity reactor configuration

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0.0377	0.0353	0.0318	0.0316	0.0327	0.0317	0.0372	0.0437	0.0455	0.0477	0.0607
9.4	0.0344										0.0651
14.5	0.0356					0.0300					0.0689
19.4	0.0335					0.0329					0.0656
28.5	0.0418					0.0322					0.0638
50.0	0.0383	0.0346	0.0299	0.0327	0.0383	0.0288	0.0375	0.0433	0.0501	0.0535	0.0677
75.0	0.0383					0.0342					0.0680
100.0	0.0410					0.0366					0.0754
175.0	0.0398	0.0369	0.0379	0.0350	0.0438	0.0377	0.0427	0.0484	0.0526	0.0599	0.0784
250.0	0.0468					0.0404					0.0856
325.0	0.0481					0.0429					0.0844
400.0	0.0497	0.0508	0.0469	0.0440	0.0406	0.0459	0.0492	0.0575	0.0634	0.0693	0.0873
475.0	0.0723					0.0518					0.0845
550.0	0.0774					0.0486					0.0793
625.0	0.0676	0.0631	0.0571	0.0508	0.0469	0.0445	0.0488	0.0590	0.0615	0.0669	0.0772
700.0	0.0687					0.0484					0.0735
725.0	0.0651					0.0430					0.0782
750.0	0.0666	0.0532	0.0478	0.0483	0.0454	0.0428	0.0495	0.0545	0.0601	0.0614	0.0737
771.5	0.0642					0.0421					0.0754
780.6	0.0642					0.0436					0.0739
785.5	0.0640					0.0398					0.0779
790.6	0.0664										0.0735
797.5	0.0702	0.0640	0.0574	0.0534	0.0466	0.0457	0.0465	0.0542	0.0552	0.0601

Fig. 4.24. Comparison of normalized experimental and computed axial power distribution in the full-featured FOEHN configuration at $r = 143.5$ mm.

Fig. 4.25. Comparison of normalized experimental and computed axial power distribution in the full-featured FOEHN configuration at $r = 167.5$ mm.

Fig. 4.26. Comparison of normalized experimental and computed axial power distribution in the full-featured FOEHN configuration at $r = 193.95$ mm.

Table 4.17. Points of nonmatching power production density in the full complexity reactor configuration^a

<i>H/r</i> (mm)	143.5	146.5	149.5	152.5	159.0	167.5	176.0	182.5	185.5	188.5	193.95
2.5	0	0	0	0	0	1	1	0	1	1	1
5.0											0
9.4	1										0
14.5	0					0					1
19.4	0					0					0
28.5	0					0					0
50.0	0	0	0	0	0	0	0	0	0	0	0
75.0	0					0					0
100.0	0					0					0
175.0	0	0	0	0	0	0	0	0	0	0	0
250.0	0					0					0
325.0	0					0					0
400.0	0	0	0	0	0	0	0	0	0	0	0
475.0	1					0					0
550.0	1					0					0
625.0	0	0	0	0	0	0	0	0	0	0	0
700.0	0					0					0
725.0	0					0					0
750.0	0	0	0	0	0	0	0	0	0	0	0
771.5	0					0					0
780.6	0					0					0
785.5	0										0
790.6	0										0
795.0											0
797.5	0	0	1	1	1	1	1	1	1	1	1

^a125 data points, 18 misses (14.40%), 4 misses excluding top and bottom rows (3.20%).

production (based on gamma activity counting) is expected to be the greatest. The existence of a sharp flux gradient may also imply, for the measurement, a higher error than the $\pm 4\%$ used for the comparison performed in this work.

4.5 SUMMARY

In this chapter, the results of the MCNP simulations of all three FOEHN experiment configurations have been presented and discussed. It has been shown that all three models agree consistently with the experimental results within the limits of interpretation of the statistics inherent to the Monte Carlo approach. It was shown that the computed spatial distribution of the power production in the cores, the thermal flux distribution in the reflector, and the rendement agree very well with the corresponding experimental values. Where discrepancies between the models and the experiment occurred, they were fully correlated to (and explained by) the approximations made, the lack of precise information about the experimental setup, or the limitations of the version of the MCNP code used in this work.

5. CONCLUSIONS

Phase II of the validation of the neutronic design methods of the ANS reactor has been completed and presented in this report. The use of MCNP as a neutronics design code has been benchmarked against the FOEHN critical experiment. Many quantities of interest to the safe and efficient operation of a high-intensity neutron source reactor were computed and compared to their experimental counterparts. It was shown that for all quantities of importance (core power distribution, reflector fluxes, effective multiplication factor, and rendement figure of merit), the computational results reproduced the experimental ones within the error bounds defined by the statistics and the experimental errors. A notable exception pertains to the use of point detector tallies in MCNP for estimating fluxes in small regions. These MCNP tallies have been found to be inadequate for the design estimation of fluxes.

The results presented in this report document a successful benchmarking of the MCNP computer code against the FOEHN critical experiments and a significant, positive contribution to the validation of the neutronics design methodology for the ANS reactor.

In addition to the validation of the neutronics design methodology, the testing of the robustness of the design to small changes in some materials specifications was performed. Specifically, the AG3-NE alloy used as a structural material was replaced entirely by pure aluminum for some runs. It was found that changes in the effective multiplication factor and in some powers were larger than the computed statistical errors. It follows from this study that small changes in materials could have important effects on the neutronics of a reactor sharing some of the design characteristics of the FOEHN experiment. It is therefore recommended that, for a design for which requirements are rigid (such as the ANS reactor), a range of material compositions and of geometric specifications for which the performance remains within the ranges defined by the statistical bands (or by performance specifications) should be identified. Such a sensitivity analysis of the design would be a crucial step in the design effort, both to ensure a safe reactor and to contribute to reducing the cost of the project by identifying acceptable tolerance limits. An example of the type of artifacts that may arise in the design of the ANS reactor can be illustrated by one encountered inadvertently. It was found that small perturbations in some critical parameters significantly affect the performance of the reactor. Specifically, it was found that the mechanical tolerances within the core (i.e., fuel plate sizes, fit of core barrel components) affect the actual borated water content of the core. The improper distribution of this borated water was found to significantly distort the spatial distribution of the power production density. The knowledge of acceptable bounds for the mechanical tolerances may have important consequences on the safe and economical operation of the reactor. For example, the correlation of fuel manufacturing tolerances to power distribution would allow the definition of fuel manufacturing bounds for which the resulting reactor loading and power distribution would remain within the acceptable operational range. This would affect every reload and could result in recurrent savings.

A second issue that must be addressed in the design of the various facilities of the ANS reactor is the use of a version of MCNP capable of treating the $S(\alpha,\beta)$ interactions. It is recommended that for future models, the newest version of MCNP be used after it is quality-assurance certified.

The lack of complete and precise information about the FOEHN experiment caused a number of difficulties, of which many were resolved by experimenting with several plausible options. However, there still remain uncertainties about the positions of certain components in the core. Among the remaining unknowns are the exact location of the borated end caps, the azimuthal positions of the various fuel plates, and the thickness and exact location of the AG3-NE axial portion of the reactor bucket. One of these (the borated end caps location) may be the cause of the larger than average

discrepancy between experiment and model observed at the axial ends of the core. The use of a homogenized core was dictated by the lack of precise information about the azimuthal position of the fuel plates and the lack of a circular involute geometry option in the MCNP code. The potential error arising from this approximation has been previously quantified in the case of the ANS design for which the core D_2O is not borated. The effect in the presence of boron is uncertain. A short study aimed at quantifying the difference between a homogenous and an explicit heterogenous model in the presence of borated heavy water is currently under way.

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6. REFERENCES

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Appendix A. MCNP MODEL INPUT FILE

APPENDIX A

MCNP MODEL INPUT FILE

A full listing of the input for the MCNP model of the full complexity FOEHN configuration is given below.

message: outp=frn800.o runtpe=frn800.r srctp=frn800.s mctal=frn800.m

FRN800 - Complete model of the FOEHN reactor (the complete experiment)

c

c Cell cards

c

c The model was derived from information gathered from Glaser, et al.,
 c "Verifizierung des dreidimensionalen Rechencodes MORSE-K durch
 c nachrechnen des kritischen Experimentes FOEHN", dated Jan. 16, 1991,
 c and ORNL/TR-91/23 "FOEHN: The Critical Experiment for the Franco-German
 c High Flux Reactor", English version, (Dec. 1971).

c

c

c

c Structures below the core

c

1	1	0.099753	-1	12	-14	imp:n=1	\$ D2o region
2	1	0.099753	4	-8	12 -13	imp:n=1	\$ D2o region
3	12	0.047175	1	-2	12 -14	imp:n=1	\$ Structural material - Al
4	12	0.047175	-2	14	-16	imp:n=1	\$ Structural material - Al
5	12	0.047175	3	-10	13 -16	imp:n=1	\$ Structural material - Al
6	12	0.047175	8	-10	12 -13	imp:n=1	\$ Structural material - Al
7	12	0.047175	3	-4	12 -13	imp:n=1	\$ Structural material - Al
8	12	0.047175	2	-3	12 -15	imp:n=1	\$ Structural material - Al
9	1	0.099753	-2	16	-17	imp:n=1	\$ D2o region
10	10	9.13e-2	2	-3	15 -18	imp:n=1	\$ Control rod - Nickel
11	1	0.099753	3	-8	16 -163	imp:n=1	\$ D2o region
12	12	0.047175	8	-10	16 -17	imp:n=1	\$ Structural material - Al

c

c

c

Structures even with the core

c

13	1	0.099753	-2	17	-19	imp:n=1	\$ D2o region
14	1	0.099753	2	-3	18 -195	imp:n=1	\$ Control rod - nickel
15	1	0.099753	3	-4	163 -19	imp:n=1	\$ D2o region
16	12	0.047175	4	-5	163 -19	imp:n=1	\$ Inner core tube - Al
17	2	0.099763646	5	-6	163 -19	imp:n=1	\$ Borated d2o
19	2	0.099763646	7	-8	163 -19	imp:n=1	\$ Borated d2o
20	12	0.047175	8	-9	17 -19	imp:n=1	\$ Inner tube w/borated d2o
21	2	0.099763646	9	-900	17 -19	imp:n=1	\$ borated d2o
221	12	0.047175	900	-10	17 -19	imp:n=1	\$ outer tank - Al
1131	12	0.047175	-7	6	151 -1138	imp:n=1	\$ Top Al seal
1132	12	0.047175	-7	6	1164 -17	imp:n=1	\$ Bottom Al seal

c
c The beam tubes
c

22	0	-20 21 -22	imp:n=1	\$ Inside of beam tube1
23	12 0.047175	-23 20 21 -22	imp:n=1	\$ Outside of beam tube1
24	0	-24 25 -26	imp:n=1	\$ Inside of beam tube2
25	12 0.047175	-27 24 25 -26	imp:n=1	\$ Outside of beam tube2
26	0	-28 29 -30	imp:n=1	\$ Inside of beam tube3
27	12 0.047175	-31 28 29 -30	imp:n=1	\$ Outside of beam tube3
28	0	-32 33 -34	imp:n=1	\$ Inside of beam tube4
29	12 0.047175	-35 32 33 -34	imp:n=1	\$ Outside of beam tube4
30	0	-36 37 -38 (43:-41:42:-40)	imp:n=1	\$ Inside of beam tube6
31	12 0.047175	-39 36 37 -38 (43:-41:42)	imp:n=1	\$ Outside of beam tube6
32	0	-40 41 -42	imp:n=1	\$ Inside of beam tube7
33	12 0.047175	-43 40 41 -42	imp:n=1	\$ Outside of beam tube7
34	0	-44 45 -46	imp:n=1	\$ Inside of beam tube8
35	12 0.047175	-47 44 45 -46	imp:n=1	\$ Outside of beam tube8
36	0	-48 49 -50	imp:n=1	\$ Inside of beam tube9
37	12 0.047175	-51 48 49 -50	imp:n=1	\$ Outside of beam tube9
38	0	-52 53 -54	imp:n=1	\$ Inside of beam tube10
39	12 0.047175	-55 52 53 -54	imp:n=1	\$ Outside of beam tube10
40	0	-56 57 -58	imp:n=1	\$ Inside of beam tube11
41	12 0.047175	-59 56 57 -58	imp:n=1	\$ Outside of beam tube11
42	0	-60 61 -62	imp:n=1	\$ Inside of beam tube13
43	12 0.047175	-63 60 61 -62	imp:n=1	\$ Outside of beam tube13

c
c Cold source - cell 14
c

44	12 0.047175	-68 67 71 -75	imp:n=1	\$ Outer bell covering
45	12 0.047175	-67 66 71 -74	imp:n=1	\$ Vessel
46	0	-66 65 72 -73	imp:n=1	\$ Vacuum inside vessel
47	12 0.047175	-65 64 72 -73	imp:n=1	\$ Rod inside vessel
48	0	-64 72 -73	imp:n=1	\$ Vacuum w/i rod w/i vessel
49	12 0.047175	-66 71 -72	imp:n=1	\$ Bottom of vessel
50	12 0.047175	-69 70 -71	imp:n=1	\$ Plug on bottom of vessel
51	12 0.047175	-78 77 75 -195	imp:n=1	\$ Outer tube on top of vessel
52	0	-77 65 75 -195	imp:n=1	\$ Vacuum between tube & rod
53	12 0.047175	-65 64 75 -195	imp:n=1	\$ Rod inside tube
54	0	-64 75 -195	imp:n=1	\$ Vacuum w/i rod w/i tube
55	12 0.047175	-67 74 -75	imp:n=1	\$ Top of outer bell covering
56	12 0.047175	-66 73 -74	imp:n=1	\$ Top of vessel
57	12 0.047175	-79 80 -195 (-75:78) (69:-70:71) (68:-71:75)	imp:n=1	\$ Rest of cold source

c
c Hot source - cell 15
c

58	12 0.047175	-82 83 -195 85	imp:n=1	\$ Outer guide tube
59	12 0.047175	-85 87 -88	imp:n=1	\$ Top lid of hot cell
60	1 0.099753	-85 89 86 -87	imp:n=1	\$ Between tube & cylinder
61	9 0.0428042	-89 92 90 -91	imp:n=1	\$ Inner cylinder

62	0	-92	95	93	-94	imp:n=1	\$ Void between cyl. & graphite
63	7 1.67e-2	-95	96	-98	(100)	imp:n=1	\$ Bottom half of graphite
64	1 0.099753	88	-85	-195		imp:n=1	\$ D2o region on top of lid
65	7 1.67e-2	-95	99	-97	(100)	imp:n=1	\$ Top half of graphite
66	0	-95	98	-99		imp:n=1	\$ Horizontal split in graphite
67	0	-100	96	-98		imp:n=1	\$ Vertical split in graphite
68	12 0.047175	-85	83	-86		imp:n=1	\$ Bottom lid of hot cell
69	9 0.0428042	-92	90	-93		imp:n=1	\$ Bottom lid of inner cylinder
70	9 0.0428042	-92	-91	94		imp:n=1	\$ Top lid of inner cylinder
71	0	-95	93	-96		imp:n=1	\$ Bottom of void
72	0	-95	97	-94		imp:n=1	\$ Top of void
73	1 0.099753	-89	86	-90		imp:n=1	\$ Bottom - outer/inner tubes
74	1 0.099753	-89	91	-87		imp:n=1	\$ Top - outer/inner tubes
75	0	-100	99	-97		imp:n=1	\$ Vertical split in graphite
c							
c							
c							
		Rest of the beam tubes					
76	0	-101	102	-103		imp:n=1	\$ Inside of beam tubel6
77	12 0.047175	-104	101	102	-103	imp:n=1	\$ Outside of beam tubel6
78	0	-105	106	-103		imp:n=1	\$ Inside of beam tubel7
79	12 0.047175	-108	105	106	-103	imp:n=1	\$ Outside of beam tubel7
80	0	-109	110	-111		imp:n=1	\$ Inside of beam tubel9
81	12 0.047175	-112	109	110	-111	imp:n=1	\$ Outside of beam tubel9
82	0	-113	114	-115		imp:n=1	\$ Inside of beam tube21
83	12 0.047175	-116	113	114	-115	imp:n=1	\$ Outside of beam tube21
84	0	-117	118	-119		imp:n=1	\$ Inside of beam tube22
85	12 0.047175	-120	117	118	-119	imp:n=1	\$ Outside of beam tube22
86	0	-121	122	-195		imp:n=1	\$ Inside of beam tube23
87	12 0.047175	-124	121	122	-195	imp:n=1	\$ Outside of beam tube23
88	0	-125	126	-127		imp:n=1	\$ Inside of beam tube24
89	12 0.047175	-128	125	126	-127	imp:n=1	\$ Outside of beam tube24
c							
c							
c							
		Safety rods					
90	1 0.099753	-129	12	-135	164	imp:n=1	\$ Safety rod 1
91	1 0.099753	-130	12	-135	169	imp:n=1	\$ Safety rod 2
92	1 0.099753	-131	12	-135	174	imp:n=1	\$ Safety rod 3
93	1 0.099753	-132	12	-135	179	imp:n=1	\$ Safety rod 4
94	1 0.099753	-133	12	-135	184	imp:n=1	\$ Safety rod 5
95	1 0.099753	-134	12	-135	189	imp:n=1	\$ Safety rod 6
c							
c							
c							
		Area outside the safety rods and the core up to 40cm radius					
96	1 0.099753	198	-11	12	-19 (129:-12:135) (130:-12:135)		
					(133:-12:135) (132:-12:135) (131:-12:135)(10)		
					(134:-12:135) (31:-29) (108:-106) (35:-33)		
					(82:-83)	imp:n=1	
c							
c							
c							
		The four quarters of the reactor-everything outside the tubes/cells					

97 1 0.099753 137 138 -194 12 -195 (11:19) (120:-118:119)
 (82:-83) (39:-37) (108:-106) (43:-41) (55:-53:54)
 (47:46) (51:-49:50) (63:-62:62) (116:-114) (39:-37)
 (-2:197:195) imp:n=1
 98 1 0.099753 137 -138 -194 12 -195 (11:19) (47:-45) (63:62)
 (-2:197:195) (124:-122) (35:34) (112:111) (43:42)
 (116:115) (39:38) imp:n=1
 99 1 0.099753 -137 -138 -194 12 -195 (11:19) (35:-33:34) (-2:197:195)
 (23:-21:22) (128:127) (27:-25) (31:30) (112:-110:111)
 (63:-61) imp:n=1
 100 1 0.099753 -137 138 -194 12 -195 (11:19) (27:26) (128:-126)
 (-2:197:195) (59:-57:58) (120:-118) (31:-29)
 (104:-102) (79:-80) imp:n=1
 101 0 136 imp:n=0

c

c

Top borated zone

c

102 14 0.0830797 -7 6 1138 -139 imp:n=1 \$ top Aluminum seal
 103 14 0.0830797 -7 6 139 -140 imp:n=1 \$ Al plate
 104 14 0.0830797 -7 6 140 -141 imp:n=1 \$ Boron plate
 105 14 0.0830797 -7 6 141 -142 imp:n=1 \$ Al plate
 106 14 0.0830797 -7 6 142 -143 imp:n=1 \$ Al plate
 107 14 0.0830797 -7 6 143 -144 imp:n=1 \$ B plate
 108 14 0.0830797 -7 6 144 -145 imp:n=1 \$ Al plate
 109 14 0.0830797 -7 6 145 -146 imp:n=1 \$ Al plate
 110 14 0.0830797 -7 6 146 -147 imp:n=1 \$ B plate
 111 14 0.0830797 -7 6 147 -148 imp:n=1 \$ Al plate
 112 14 0.0830797 -7 6 148 -149 imp:n=1 \$ Al plate
 113 14 0.0830797 -7 6 149 -150 imp:n=1 \$ B plate
 114 14 0.0830797 -7 6 150 -19 imp:n=1 \$ Al plate

c

c

Bottom borated zone

c

115 14 0.0830797 -7 6 -1164 152 imp:n=1 \$ Al plate
 116 14 0.0830797 -7 6 -152 153 imp:n=1 \$ B plate
 117 14 0.0830797 -7 6 -153 154 imp:n=1 \$ Al plate
 118 14 0.0830797 -7 6 -154 155 imp:n=1 \$ Al plate
 119 14 0.0830797 -7 6 -155 156 imp:n=1 \$ B plate
 120 14 0.0830797 -7 6 -156 157 imp:n=1 \$ Al plate
 121 14 0.0830797 -7 6 -157 158 imp:n=1 \$ Al plate
 122 14 0.0830797 -7 6 -158 159 imp:n=1 \$ B plate
 123 14 0.0830797 -7 6 -159 160 imp:n=1 \$ Al plate
 124 14 0.0830797 -7 6 -160 161 imp:n=1 \$ Al plate
 125 14 0.0830797 -7 6 -161 162 imp:n=1 \$ B plate
 126 14 0.0830797 -7 6 -162 163 imp:n=1 \$ Al plate

c

c

The inner rings of the safety rods

c

c

Safety rod 1

c

127 1 0.099753 -164 165 12 -135 imp:n=1 \$ cadmium region
 128 1 0.099753 -165 166 12 -135 imp:n=1 \$ inner cladding

129	1	0.099753	-166	167	12	-135	imp:n=1	\$ d2o channel
130	1	0.099753	-167	168	12	-135	imp:n=1	\$ Al guide tube
131	1	0.099753	-168	-135	12		imp:n=1	\$ d2o inside guide tube
C								
C	Safety rod 2							
C								
132	1	0.099753	-169	170	12	-135	imp:n=1	\$ cadium region
133	1	0.099753	-170	171	12	-135	imp:n=1	\$ inner cladding
134	1	0.099753	-171	172	12	-135	imp:n=1	\$ d2o channel
135	1	0.099753	-172	173	12	-135	imp:n=1	\$ Al guide tube
136	1	0.099753	-173	-135	12		imp:n=1	\$ d2o inside guide tube
C								
C	Safety rod 3							
C								
137	1	0.099753	-174	175	12	-135	imp:n=1	\$ cadium region
138	1	0.099753	-175	176	12	-135	imp:n=1	\$ inner cladding
139	1	0.099753	-176	177	12	-135	imp:n=1	\$ d2o channel
140	1	0.099753	-177	178	12	-135	imp:n=1	\$ Al guide tube
141	1	0.099753	-178	-135	12		imp:n=1	\$ d2o inside guide tube
C								
C	Safety rod 4							
C								
142	1	0.099753	-179	180	12	-135	imp:n=1	\$ cadium region
143	1	0.099753	-180	181	12	-135	imp:n=1	\$ inner cladding
144	1	0.099753	-181	182	12	-135	imp:n=1	\$ d2o channel
145	1	0.099753	-182	183	12	-135	imp:n=1	\$ Al guide tube
146	1	0.099753	-183	-135	12		imp:n=1	\$ d2o inside guide tube
C								
C	Safety rod 5							
C								
147	1	0.099753	-184	185	12	-135	imp:n=1	\$ cadium region
148	1	0.099753	-185	186	12	-135	imp:n=1	\$ inner cladding
149	1	0.099753	-186	187	12	-135	imp:n=1	\$ d2o channel
150	1	0.099753	-187	188	12	-135	imp:n=1	\$ Al guide tube
151	1	0.099753	-188	-135	12		imp:n=1	\$ d2o inside guide tube
C								
C	Safety rod 6							
C								
152	1	0.099753	-189	190	12	-135	imp:n=1	\$ cadium region
153	1	0.099753	-190	191	12	-135	imp:n=1	\$ inner cladding
154	1	0.099753	-191	192	12	-135	imp:n=1	\$ d2o channel
155	1	0.099753	-192	193	12	-135	imp:n=1	\$ Al guide tube
156	1	0.099753	-193	-135	12		imp:n=1	\$ d2o inside guide tube
C								
C	The reflector tank							
C								
157	12	0.047175	-196	194	12	-195 (104) (108)		
			(120:-118:119)	(112:-110:111)				
			(116:-114:115)			imp:n=1		
C								
C	The encompassing sphere - outside the reflector tank							
C								

158 0 -136 (196:-12:195) (104:-102:103)
 (108:-102:103) (120:-118:119) (112:-110:111)
 (116:-114:115) imp:n=1

c

c

The structures above the core

c

159	12	0.047175	4	-5	19	-201	imp:n=1	\$ structure above core
160	1	0.099753	5	-9	19	-199	imp:n=1	\$ d20 region core
161	1	0.099753	10	-197	19	-195	imp:n=1	\$ structure above core
162	12	0.047175	5	-10	199	-200	imp:n=1	\$ structure above core
163	1	0.099753	5	-10	200	-201	imp:n=1	\$ d20 region above core
164	1	0.099753	3	-10	201	-195	imp:n=1	\$ d20 region above core
165	1	0.099753	10	-198	17	-19	imp:n=1	\$ outer tank
166	12	0.047175	9	-10	19	-199	imp:n=1	\$ outer tank
167	1	0.099753	10	-198	12	-17	imp:n=1	\$ d20 outside lower core

c

c

Cells used for core power distribution tallies

c

614	6	0.083382617	6	-306	17	-151	imp:n=1	\$ radius 14.20cm
615	6	0.083382617	306	-307	17	-261	imp:n=1	\$ radius 14.50 z=71.50 - tally
616	6	0.083382617	306	-307	261	-262	imp:n=1	
617	6	0.083382617	306	-307	262	-263	imp:n=1	\$ z=71.69 - tally
618	6	0.083382617	306	-307	263	-264	imp:n=1	
619	6	0.083382617	306	-307	264	-265	imp:n=1	\$ z=72.70 - tally
620	6	0.083382617	306	-307	265	-267	imp:n=1	\$ z=73.20 - tally
621	6	0.083382617	306	-307	267	-268	imp:n=1	
622	6	0.083382617	306	-307	268	-269	imp:n=1	\$ z=74.10 - tally
623	6	0.083382617	306	-307	269	-270	imp:n=1	
624	6	0.083382617	306	-307	270	-271	imp:n=1	\$ z=76.25 - tally
625	6	0.083382617	306	-307	271	-272	imp:n=1	
626	6	0.083382617	306	-307	272	-273	imp:n=1	\$ z=78.75 - tally
627	6	0.083382617	306	-307	273	-274	imp:n=1	
628	6	0.083382617	306	-307	274	-275	imp:n=1	\$ z=81.25 - tally
629	6	0.083382617	306	-307	275	-276	imp:n=1	
630	6	0.083382617	306	-307	276	-277	imp:n=1	\$ z=88.75 - tally
631	6	0.083382617	306	-307	277	-278	imp:n=1	
632	6	0.083382617	306	-307	278	-279	imp:n=1	\$ z=96.75 - tally
633	6	0.083382617	306	-307	279	-280	imp:n=1	
634	6	0.083382617	306	-307	280	-281	imp:n=1	\$ z=100.75 - tally
635	6	0.083382617	306	-307	281	-282	imp:n=1	
636	6	0.083382617	306	-307	282	-283	imp:n=1	\$ z=111.25 - tally
637	6	0.083382617	306	-307	283	-284	imp:n=1	
638	6	0.083382617	306	-307	284	-285	imp:n=1	\$ z=118.25 - tally
639	6	0.083382617	306	-307	285	-286	imp:n=1	
640	6	0.083382617	306	-307	286	-287	imp:n=1	\$ z=126.25 - tally
641	6	0.083382617	306	-307	287	-288	imp:n=1	
642	6	0.083382617	306	-307	288	-289	imp:n=1	\$ z=133.75 - tally
643	6	0.083382617	306	-307	289	-290	imp:n=1	
644	6	0.083382617	306	-307	290	-291	imp:n=1	\$ z=141.25 - tally
645	6	0.083382617	306	-307	291	-292	imp:n=1	
646	6	0.083382617	306	-307	292	-293	imp:n=1	\$ z=143.75 - tally
647	6	0.083382617	306	-307	293	-294	imp:n=1	

648	6	0.083382617	306	-307	294	-295	imp:n=1	\$ z=146.25 - tally
649	6	0.083382617	306	-307	295	-296	imp:n=1	
650	6	0.083382617	306	-307	296	-297	imp:n=1	\$ z=148.40 - tally
651	6	0.083382617	306	-307	297	-298	imp:n=1	
652	6	0.083382617	306	-307	298	-299	imp:n=1	\$ z=149.31 - tally
653	6	0.083382617	306	-307	299	-300	imp:n=1	\$ z=149.81 - tally
654	6	0.083382617	306	-307	300	-303	imp:n=1	\$ z=150.31 - tally
655	6	0.083382617	306	-307	303	-304	imp:n=1	
656	6	0.083382617	306	-307	304	-151	imp:n=1	\$ z=151.00 - tally

c

657	6	0.083382617	307	-308	17	-261	imp:n=1	\$ radius 14.80 z=71.50 - tally
658	6	0.083382617	307	-308	261	-262	imp:n=1	
659	6	0.083382617	307	-308	262	-263	imp:n=1	\$ z=71.69 - tally
660	6	0.083382617	307	-308	263	-264	imp:n=1	
661	6	0.083382617	307	-308	264	-265	imp:n=1	\$ z=72.70 - tally
662	6	0.083382617	307	-308	265	-267	imp:n=1	\$ z=73.20 - tally
663	6	0.083382617	307	-308	267	-268	imp:n=1	
664	6	0.083382617	307	-308	268	-269	imp:n=1	\$ z=74.10 - tally
665	6	0.083382617	307	-308	269	-270	imp:n=1	
666	6	0.083382617	307	-308	270	-271	imp:n=1	\$ z=76.25 - tally
667	6	0.083382617	307	-308	271	-272	imp:n=1	
668	6	0.083382617	307	-308	272	-273	imp:n=1	\$ z=78.75 - tally
669	6	0.083382617	307	-308	273	-274	imp:n=1	
670	6	0.083382617	307	-308	274	-275	imp:n=1	\$ z=81.25 - tally
671	6	0.083382617	307	-308	275	-276	imp:n=1	
672	6	0.083382617	307	-308	276	-277	imp:n=1	\$ z=88.75 - tally
673	6	0.083382617	307	-308	277	-278	imp:n=1	
674	6	0.083382617	307	-308	278	-279	imp:n=1	\$ z=96.75 - tally
675	6	0.083382617	307	-308	279	-280	imp:n=1	
676	6	0.083382617	307	-308	280	-281	imp:n=1	\$ z=103.75 - tally
677	6	0.083382617	307	-308	281	-282	imp:n=1	
678	6	0.083382617	307	-308	282	-283	imp:n=1	\$ z=111.25 - tally
679	6	0.083382617	307	-308	283	-284	imp:n=1	
680	6	0.083382617	307	-308	284	-285	imp:n=1	\$ z=118.25 - tally
681	6	0.083382617	307	-308	285	-286	imp:n=1	
682	6	0.083382617	307	-308	286	-287	imp:n=1	\$ z=126.25 - tally
683	6	0.083382617	307	-308	287	-288	imp:n=1	
684	6	0.083382617	307	-308	288	-289	imp:n=1	\$ z=133.75 - tally
685	6	0.083382617	307	-308	289	-290	imp:n=1	
686	6	0.083382617	307	-308	290	-291	imp:n=1	\$ z=141.25 - tally
687	6	0.083382617	307	-308	291	-292	imp:n=1	
688	6	0.083382617	307	-308	292	-293	imp:n=1	\$ z=143.75 - tally
689	6	0.083382617	307	-308	293	-294	imp:n=1	
690	6	0.083382617	307	-308	294	-295	imp:n=1	\$ z=146.25 - tally
691	6	0.083382617	307	-308	295	-296	imp:n=1	
692	6	0.083382617	307	-308	296	-297	imp:n=1	\$ z=148.40 - tally
693	6	0.083382617	307	-308	297	-298	imp:n=1	
694	6	0.083382617	307	-308	298	-299	imp:n=1	\$ z=149.31 - tally
695	6	0.083382617	307	-308	299	-300	imp:n=1	\$ z=149.81 - tally
696	6	0.083382617	307	-308	300	-303	imp:n=1	\$ z=150.31 - tally
697	6	0.083382617	307	-308	303	-304	imp:n=1	
698	6	0.083382617	307	-308	304	-151	imp:n=1	\$ z=151.00 - tally

c

699	6	0.083382617	308	-309	17	-261	imp:n=1	\$ radius 15.10 z=71.50 - tally
700	6	0.083382617	308	-309	261	-262	imp:n=1	
701	6	0.083382617	308	-309	262	-263	imp:n=1	\$ z=71.69 - tally
702	6	0.083382617	308	-309	263	-264	imp:n=1	
703	6	0.083382617	308	-309	264	-265	imp:n=1	\$ z=72.70 - tally
704	6	0.083382617	308	-309	265	-267	imp:n=1	\$ z=73.20 - tally
705	6	0.083382617	308	-309	267	-268	imp:n=1	
706	6	0.083382617	308	-309	268	-269	imp:n=1	\$ z=74.10 - tally
707	6	0.083382617	308	-309	269	-270	imp:n=1	
708	6	0.083382617	308	-309	270	-271	imp:n=1	\$ z=76.25 - tally
709	6	0.083382617	308	-309	271	-272	imp:n=1	
710	6	0.083382617	308	-309	272	-273	imp:n=1	\$ z=78.75 - tally
711	6	0.083382617	308	-309	273	-274	imp:n=1	
712	6	0.083382617	308	-309	274	-275	imp:n=1	\$ z=81.25 - tally
713	6	0.083382617	308	-309	275	-276	imp:n=1	
714	6	0.083382617	308	-309	276	-277	imp:n=1	\$ z=88.75 - tally
715	6	0.083382617	308	-309	277	-278	imp:n=1	
716	6	0.083382617	308	-309	278	-279	imp:n=1	\$ z=96.75 - tally
717	6	0.083382617	308	-309	279	-280	imp:n=1	
718	6	0.083382617	308	-309	280	-281	imp:n=1	\$ z=103.75 - tally
719	6	0.083382617	308	-309	281	-282	imp:n=1	
720	6	0.083382617	308	-309	282	-283	imp:n=1	\$ z=111.25 - tally
721	6	0.083382617	308	-309	283	-284	imp:n=1	
722	6	0.083382617	308	-309	284	-285	imp:n=1	\$ z=118.25 - tally
723	6	0.083382617	308	-309	285	-286	imp:n=1	
724	6	0.083382617	308	-309	286	-287	imp:n=1	\$ z=126.25 - tally
725	6	0.083382617	308	-309	287	-288	imp:n=1	
726	6	0.083382617	308	-309	288	-289	imp:n=1	\$ z=133.75 - tally
727	6	0.083382617	308	-309	289	-290	imp:n=1	
728	6	0.083382617	308	-309	290	-291	imp:n=1	\$ z=141.25 - tally
729	6	0.083382617	308	-309	291	-292	imp:n=1	
730	6	0.083382617	308	-309	292	-293	imp:n=1	\$ z=143.75 - tally
731	6	0.083382617	308	-309	293	-294	imp:n=1	
732	6	0.083382617	308	-309	294	-295	imp:n=1	\$ z=146.25 - tally
733	6	0.083382617	308	-309	295	-296	imp:n=1	
734	6	0.083382617	308	-309	296	-297	imp:n=1	\$ z=148.40 - tally
735	6	0.083382617	308	-309	297	-298	imp:n=1	
736	6	0.083382617	308	-309	298	-299	imp:n=1	\$ z=149.31 - tally
737	6	0.083382617	308	-309	299	-300	imp:n=1	\$ z=149.81 - tally
738	6	0.083382617	308	-309	300	-303	imp:n=1	\$ z=150.31 - tally
739	6	0.083382617	308	-309	303	-304	imp:n=1	
740	6	0.083382617	308	-309	304	-151	imp:n=1	\$ z=151.00 - tally

c

741	6	0.083382617	309	-313	17	-261	imp:n=1	\$ radius 15.40,z=71.50 - tally
742	6	0.083382617	309	-313	261	-262	imp:n=1	
743	6	0.083382617	309	-313	262	-263	imp:n=1	\$ z=71.69 - tally
744	6	0.083382617	309	-313	263	-264	imp:n=1	
745	6	0.083382617	309	-313	264	-265	imp:n=1	\$ z=72.70 - tally
746	6	0.083382617	309	-313	265	-267	imp:n=1	\$ z=73.20 - tally
747	6	0.083382617	309	-313	267	-268	imp:n=1	
748	6	0.083382617	309	-313	268	-269	imp:n=1	\$ z=74.10 - tally

749	6	0.083382617	309	-313	269	-270	imp:n=1	
750	6	0.083382617	309	-313	270	-271	imp:n=1	\$ z=76.25 - tally
751	6	0.083382617	309	-313	271	-272	imp:n=1	
752	6	0.083382617	309	-313	272	-273	imp:n=1	\$ z=78.75 - tally
753	6	0.083382617	309	-313	273	-274	imp:n=1	
754	6	0.083382617	309	-313	274	-275	imp:n=1	\$ z=81.25 - tally
755	6	0.083382617	309	-313	275	-276	imp:n=1	
756	6	0.083382617	309	-313	276	-277	imp:n=1	\$ z=88.75 - tally
757	6	0.083382617	309	-313	277	-278	imp:n=1	
758	6	0.083382617	309	-313	278	-279	imp:n=1	\$ z=96.75 - tally
759	6	0.083382617	309	-313	279	-280	imp:n=1	
760	6	0.083382617	309	-313	280	-281	imp:n=1	\$ z=103.75 - tally
761	6	0.083382617	309	-313	281	-282	imp:n=1	
762	6	0.083382617	309	-313	282	-283	imp:n=1	\$ z=111.25 - tally
763	6	0.083382617	309	-313	283	-284	imp:n=1	
764	6	0.083382617	309	-313	284	-285	imp:n=1	\$ z=118.25 - tally
765	6	0.083382617	309	-313	285	-286	imp:n=1	
766	6	0.083382617	309	-313	286	-287	imp:n=1	\$ z=126.25 - tally
767	6	0.083382617	309	-313	287	-288	imp:n=1	
768	6	0.083382617	309	-313	288	-289	imp:n=1	\$ z=133.75 - tally
769	6	0.083382617	309	-313	289	-290	imp:n=1	
770	6	0.083382617	309	-313	290	-291	imp:n=1	\$ z=141.25 - tally
771	6	0.083382617	309	-313	291	-292	imp:n=1	
772	6	0.083382617	309	-313	292	-293	imp:n=1	\$ z=143.75 - tally
773	6	0.083382617	309	-313	293	-294	imp:n=1	
774	6	0.083382617	309	-313	294	-295	imp:n=1	\$ z=146.25 - tally
775	6	0.083382617	309	-313	295	-296	imp:n=1	
776	6	0.083382617	309	-313	296	-297	imp:n=1	\$ z=148.40 - tally
777	6	0.083382617	309	-313	297	-298	imp:n=1	
778	6	0.083382617	309	-313	298	-299	imp:n=1	\$ z=149.31 - tally
779	6	0.083382617	309	-313	299	-300	imp:n=1	\$ z=149.81 - tally
780	6	0.083382617	309	-313	300	-303	imp:n=1	\$ z=150.31 - tally
781	6	0.083382617	309	-313	303	-304	imp:n=1	
782	6	0.083382617	309	-313	304	-151	imp:n=1	\$ z=151.00 - tally
c								
783	6	0.083382617	313	-314	17	-151	imp:n=1	\$ radius 15.75
784	6	0.083382617	314	-315	17	-261	imp:n=1	\$ radius 16.05,z=71.50 - tally
785	6	0.083382617	314	-315	261	-262	imp:n=1	
786	6	0.083382617	314	-315	262	-263	imp:n=1	\$ z=71.69 - tally
787	6	0.083382617	314	-315	263	-264	imp:n=1	
788	6	0.083382617	314	-315	264	-265	imp:n=1	\$ z=72.70 - tally
789	6	0.083382617	314	-315	265	-267	imp:n=1	\$ z=73.20 - tally
790	6	0.083382617	314	-315	267	-268	imp:n=1	
791	6	0.083382617	314	-315	268	-269	imp:n=1	\$ z=74.10 - tally
792	6	0.083382617	314	-315	269	-270	imp:n=1	
793	6	0.083382617	314	-315	270	-271	imp:n=1	\$ z=76.25 - tally
794	6	0.083382617	314	-315	271	-272	imp:n=1	
795	6	0.083382617	314	-315	272	-273	imp:n=1	\$ z=78.75 - tally
796	6	0.083382617	314	-315	273	-274	imp:n=1	
797	6	0.083382617	314	-315	274	-275	imp:n=1	\$ z=81.25 - tally
798	6	0.083382617	314	-315	275	-276	imp:n=1	
799	6	0.083382617	314	-315	276	-277	imp:n=1	\$ z=88.75 - tally

800	6	0.083382617	314	-315	277	-278	imp:n=1	
801	6	0.083382617	314	-315	278	-279	imp:n=1	\$ z=96.75 - tally
802	6	0.083382617	314	-315	279	-280	imp:n=1	
803	6	0.083382617	314	-315	280	-281	imp:n=1	\$ z=103.75 - tally
804	6	0.083382617	314	-315	281	-282	imp:n=1	
805	6	0.083382617	314	-315	282	-283	imp:n=1	\$ z=111.25 - tally
806	6	0.083382617	314	-315	283	-284	imp:n=1	
807	6	0.083382617	314	-315	284	-285	imp:n=1	\$ z=118.25 - tally
808	6	0.083382617	314	-315	285	-286	imp:n=1	
809	6	0.083382617	314	-315	286	-287	imp:n=1	\$ z=126.25 - tally
810	6	0.083382617	314	-315	287	-288	imp:n=1	
811	6	0.083382617	314	-315	288	-289	imp:n=1	\$ z=133.75 - tally
812	6	0.083382617	314	-315	289	-290	imp:n=1	
813	6	0.083382617	314	-315	290	-291	imp:n=1	\$ z=141.25 - tally
814	6	0.083382617	314	-315	291	-292	imp:n=1	
815	6	0.083382617	314	-315	292	-293	imp:n=1	\$ z=143.75 - tally
816	6	0.083382617	314	-315	293	-294	imp:n=1	
817	6	0.083382617	314	-315	294	-295	imp:n=1	\$ z=146.25 - tally
818	6	0.083382617	314	-315	295	-296	imp:n=1	
819	6	0.083382617	314	-315	296	-297	imp:n=1	\$ z=148.40 - tally
820	6	0.083382617	314	-315	297	-298	imp:n=1	
821	6	0.083382617	314	-315	298	-299	imp:n=1	\$ z=149.31 - tally
822	6	0.083382617	314	-315	299	-300	imp:n=1	\$ z=149.81 - tally
823	6	0.083382617	314	-315	300	-303	imp:n=1	\$ z=150.31 - tally
824	6	0.083382617	314	-315	303	-304	imp:n=1	
825	6	0.083382617	314	-315	304	-151	imp:n=1	\$ z=151.00 - tally
C								
826	6	0.083382617	315	-316	17	-151	imp:n=1	\$ radius 16.60
827	6	0.083382617	316	-317	17	-261	imp:n=1	\$ radius 16.90 z=71.50 - tally
828	6	0.083382617	316	-317	261	-262	imp:n=1	
829	6	0.083382617	316	-317	262	-263	imp:n=1	\$ z=71.69 - tally
830	6	0.083382617	316	-317	263	-264	imp:n=1	
831	6	0.083382617	316	-317	264	-265	imp:n=1	\$ z=72.70 - tally
832	6	0.083382617	316	-317	265	-267	imp:n=1	\$ z=73.20 - tally
833	6	0.083382617	316	-317	267	-268	imp:n=1	
834	6	0.083382617	316	-317	268	-269	imp:n=1	\$ z=74.10 - tally
835	6	0.083382617	316	-317	269	-270	imp:n=1	
836	6	0.083382617	316	-317	270	-271	imp:n=1	\$ z=76.25 - tally
837	6	0.083382617	316	-317	271	-272	imp:n=1	
838	6	0.083382617	316	-317	272	-273	imp:n=1	\$ z=78.75 - tally
839	6	0.083382617	316	-317	273	-274	imp:n=1	
840	6	0.083382617	316	-317	274	-275	imp:n=1	\$ z=81.25 - tally
841	6	0.083382617	316	-317	275	-276	imp:n=1	
842	6	0.083382617	316	-317	276	-277	imp:n=1	\$ z=88.75 - tally
843	6	0.083382617	316	-317	277	-278	imp:n=1	
844	6	0.083382617	316	-317	278	-279	imp:n=1	\$ z=96.75 - tally
845	6	0.083382617	316	-317	279	-280	imp:n=1	
846	6	0.083382617	316	-317	280	-281	imp:n=1	\$ z=103.75 - tally
847	6	0.083382617	316	-317	281	-282	imp:n=1	
848	6	0.083382617	316	-317	282	-283	imp:n=1	\$ z=111.25 - tally
849	6	0.083382617	316	-317	283	-284	imp:n=1	
850	6	0.083382617	316	-317	284	-285	imp:n=1	\$ z=118.25 - tally

851	6	0.083382617	316	-317	285	-286	imp:n=1	
852	6	0.083382617	316	-317	286	-287	imp:n=1	\$ z=126.25 - tally
853	6	0.083382617	316	-317	287	-288	imp:n=1	
854	6	0.083382617	316	-317	288	-289	imp:n=1	\$ z=133.75 - tally
855	6	0.083382617	316	-317	289	-290	imp:n=1	
856	6	0.083382617	316	-317	290	-291	imp:n=1	\$ z=141.25 - tally
857	6	0.083382617	316	-317	291	-292	imp:n=1	
858	6	0.083382617	316	-317	292	-293	imp:n=1	\$ z=143.75 - tally
859	6	0.083382617	316	-317	293	-294	imp:n=1	
860	6	0.083382617	316	-317	294	-295	imp:n=1	\$ z=146.25 - tally
861	6	0.083382617	316	-317	295	-296	imp:n=1	
862	6	0.083382617	316	-317	296	-297	imp:n=1	\$ z=148.40 - tally
863	6	0.083382617	316	-317	297	-298	imp:n=1	
864	6	0.083382617	316	-317	298	-299	imp:n=1	\$ z=149.31 - tally
865	6	0.083382617	316	-317	299	-300	imp:n=1	\$ z=149.81 - tally
866	6	0.083382617	316	-317	300	-303	imp:n=1	\$ z=150.31 - tally
867	6	0.083382617	316	-317	303	-304	imp:n=1	
868	6	0.083382617	316	-317	304	-151	imp:n=1	\$ z=151.00 - tally
c								
859	6	0.083382617	317	-318	17	-151	imp:n=1	\$ radius 17.45
870	6	0.083382617	318	-319	17	-261	imp:n=1	\$ radius 17.75 z=71.50 - tally
871	6	0.083382617	318	-319	261	-262	imp:n=1	
872	6	0.083382617	318	-319	262	-263	imp:n=1	\$ z=71.69 - tally
873	6	0.083382617	318	-319	263	-264	imp:n=1	
874	6	0.083382617	318	-319	264	-265	imp:n=1	\$ z=72.70 - tally
875	6	0.083382617	318	-319	265	-267	imp:n=1	\$ z=73.20 - tally
876	6	0.083382617	318	-319	267	-268	imp:n=1	
877	6	0.083382617	318	-319	268	-269	imp:n=1	\$ z=74.10 - tally
878	6	0.083382617	318	-319	269	-270	imp:n=1	
879	6	0.083382617	318	-319	270	-271	imp:n=1	\$ z=76.25 - tally
880	6	0.083382617	318	-319	271	-272	imp:n=1	
881	6	0.083382617	318	-319	272	-273	imp:n=1	\$ z=78.75 - tally
882	6	0.083382617	318	-319	273	-274	imp:n=1	
883	6	0.083382617	318	-319	274	-275	imp:n=1	\$ z=81.25 - tally
884	6	0.083382617	318	-319	275	-276	imp:n=1	
885	6	0.083382617	318	-319	276	-277	imp:n=1	\$ z=88.75 - tally
886	6	0.083382617	318	-319	277	-278	imp:n=1	
887	6	0.083382617	318	-319	278	-279	imp:n=1	\$ z=96.75 - tally
888	6	0.083382617	318	-319	279	-280	imp:n=1	
889	6	0.083382617	318	-319	280	-281	imp:n=1	\$ z=103.75 - tally
890	6	0.083382617	318	-319	281	-282	imp:n=1	
891	6	0.083382617	318	-319	282	-283	imp:n=1	\$ z=111.25 - tally
892	6	0.083382617	318	-319	283	-284	imp:n=1	
893	6	0.083382617	318	-319	284	-285	imp:n=1	\$ z=118.25 - tally
894	6	0.083382617	318	-319	285	-286	imp:n=1	
895	6	0.083382617	318	-319	286	-287	imp:n=1	\$ z=126.25 - tally
896	6	0.083382617	318	-319	287	-288	imp:n=1	
897	6	0.083382617	318	-319	288	-289	imp:n=1	\$ z=133.75 - tally
898	6	0.083382617	318	-319	289	-290	imp:n=1	
899	6	0.083382617	318	-319	290	-291	imp:n=1	\$ z=141.25 - tally
900	6	0.083382617	318	-319	291	-292	imp:n=1	
901	6	0.083382617	318	-319	292	-293	imp:n=1	\$ z=143.75 - tally

902	6	0.083382617	318	-319	293	-294	imp:n=1	
903	6	0.083382617	318	-319	294	-295	imp:n=1	\$ z=146.25 - tally
904	6	0.083382617	318	-319	295	-296	imp:n=1	
905	6	0.083382617	318	-319	296	-297	imp:n=1	\$ z=148.40 - tally
906	6	0.083382617	318	-319	297	-298	imp:n=1	
907	6	0.083382617	318	-319	298	-299	imp:n=1	\$ z=149.31 - tally
908	6	0.083382617	318	-319	299	-300	imp:n=1	\$ z=149.81 - tally
909	6	0.083382617	318	-319	300	-303	imp:n=1	\$ z=150.31 - tally
910	6	0.083382617	318	-319	303	-304	imp:n=1	
911	6	0.083382617	318	-319	304	-151	imp:n=1	\$ z=151.00 - tally
c								
912	6	0.083382617	319	-320	17	-151	imp:n=1	\$ radius 18.10
913	6	0.083382617	320	-321	17	-261	imp:n=1	\$ radius 18.40 z=71.50 - tally
914	6	0.083382617	320	-321	261	-262	imp:n=1	
915	6	0.083382617	320	-321	262	-263	imp:n=1	\$ z=71.69 - tally
916	6	0.083382617	320	-321	263	-264	imp:n=1	
917	6	0.083382617	320	-321	264	-265	imp:n=1	\$ z=72.70 - tally
918	6	0.083382617	320	-321	265	-267	imp:n=1	\$ z=73.20 - tally
919	6	0.083382617	320	-321	267	-268	imp:n=1	
920	6	0.083382617	320	-321	268	-269	imp:n=1	\$ z=74.10 - tally
921	6	0.083382617	320	-321	269	-270	imp:n=1	
922	6	0.083382617	320	-321	270	-271	imp:n=1	\$ z=76.25 - tally
923	6	0.083382617	320	-321	271	-272	imp:n=1	
924	6	0.083382617	320	-321	272	-273	imp:n=1	\$ z=78.75 - tally
925	6	0.083382617	320	-321	273	-274	imp:n=1	
926	6	0.083382617	320	-321	274	-275	imp:n=1	\$ z=81.25 - tally
927	6	0.083382617	320	-321	275	-276	imp:n=1	
928	6	0.083382617	320	-321	276	-277	imp:n=1	\$ z=88.75 - tally
929	6	0.083382617	320	-321	277	-278	imp:n=1	
930	6	0.083382617	320	-321	278	-279	imp:n=1	\$ z=96.75 - tally
931	6	0.083382617	320	-321	279	-280	imp:n=1	
932	6	0.083382617	320	-321	280	-281	imp:n=1	\$ z=103.75 - tally
933	6	0.083382617	320	-321	281	-282	imp:n=1	
934	6	0.083382617	320	-321	282	-283	imp:n=1	\$ z=111.25 - tally
935	6	0.083382617	320	-321	283	-284	imp:n=1	
936	6	0.083382617	320	-321	284	-285	imp:n=1	\$ z=118.25 - tally
937	6	0.083382617	320	-321	285	-286	imp:n=1	
938	6	0.083382617	320	-321	286	-287	imp:n=1	\$ z=126.25 - tally
939	6	0.083382617	320	-321	287	-288	imp:n=1	
940	6	0.083382617	320	-321	288	-289	imp:n=1	\$ z=133.75 - tally
941	6	0.083382617	320	-321	289	-290	imp:n=1	
942	6	0.083382617	320	-321	290	-291	imp:n=1	\$ z=141.25 - tally
943	6	0.083382617	320	-321	291	-292	imp:n=1	
944	6	0.083382617	320	-321	292	-293	imp:n=1	\$ z=143.75 - tally
945	6	0.083382617	320	-321	293	-294	imp:n=1	
946	6	0.083382617	320	-321	294	-295	imp:n=1	\$ z=146.25 - tally
947	6	0.083382617	320	-321	295	-296	imp:n=1	
948	6	0.083382617	320	-321	296	-297	imp:n=1	\$ z=148.40 - tally
949	6	0.083382617	320	-321	297	-298	imp:n=1	
950	6	0.083382617	320	-321	298	-299	imp:n=1	\$ z=149.31 - tally
951	6	0.083382617	320	-321	299	-300	imp:n=1	\$ z=149.81 - tally
952	6	0.083382617	320	-321	300	-303	imp:n=1	\$ z=150.31 - tally

953	6	0.083382617	320	-321	303	-304	imp:n=1	
954	6	0.083382617	320	-321	304	-151	imp:n=1	\$ z=151.00 - tally
c								
955	6	0.083382617	321	-322	17	-261	imp:n=1	\$ radius 18.70 z=71.50 - tally
956	6	0.083382617	321	-322	261	-262	imp:n=1	
957	6	0.083382617	321	-322	262	-263	imp:n=1	\$ z=71.69 - tally
958	6	0.083382617	321	-322	263	-264	imp:n=1	
959	6	0.083382617	321	-322	264	-265	imp:n=1	\$ z=72.70 - tally
960	6	0.083382617	321	-322	265	-267	imp:n=1	\$ z=73.20 - tally
961	6	0.083382617	321	-322	267	-268	imp:n=1	
962	6	0.083382617	321	-322	268	-269	imp:n=1	\$ z=74.10 - tally
963	6	0.083382617	321	-322	269	-270	imp:n=1	
964	6	0.083382617	321	-322	270	-271	imp:n=1	\$ z=76.25 - tally
965	6	0.083382617	321	-322	271	-272	imp:n=1	
966	6	0.083382617	321	-322	272	-273	imp:n=1	\$ z=78.75 - tally
967	6	0.083382617	321	-322	273	-274	imp:n=1	
968	6	0.083382617	321	-322	274	-275	imp:n=1	\$ z=81.25 - tally
969	6	0.083382617	321	-322	275	-276	imp:n=1	
970	6	0.083382617	321	-322	276	-277	imp:n=1	\$ z=88.75 - tally
971	6	0.083382617	321	-322	277	-278	imp:n=1	
972	6	0.083382617	321	-322	278	-279	imp:n=1	\$ z=96.75 - tally
973	6	0.083382617	321	-322	279	-280	imp:n=1	
974	6	0.083382617	321	-322	280	-281	imp:n=1	\$ z=103.75 - tally
975	6	0.083382617	321	-322	281	-282	imp:n=1	
976	6	0.083382617	321	-322	282	-283	imp:n=1	\$ z=111.25 - tally
977	6	0.083382617	321	-322	283	-284	imp:n=1	
978	6	0.083382617	321	-322	284	-285	imp:n=1	\$ z=118.25 - tally
979	6	0.083382617	321	-322	285	-286	imp:n=1	
980	6	0.083382617	321	-322	286	-287	imp:n=1	\$ z=126.25 - tally
981	6	0.083382617	321	-322	287	-288	imp:n=1	
982	6	0.083382617	321	-322	288	-289	imp:n=1	\$ z=133.75 - tally
983	6	0.083382617	321	-322	289	-290	imp:n=1	
984	6	0.083382617	321	-322	290	-291	imp:n=1	\$ z=141.25 - tally
985	6	0.083382617	321	-322	291	-292	imp:n=1	
986	6	0.083382617	321	-322	292	-293	imp:n=1	\$ z=143.75 - tally
987	6	0.083382617	321	-322	293	-294	imp:n=1	
988	6	0.083382617	321	-322	294	-295	imp:n=1	\$ z=146.25 - tally
989	6	0.083382617	321	-322	295	-296	imp:n=1	
990	6	0.083382617	321	-322	296	-297	imp:n=1	\$ z=148.40 - tally
991	6	0.083382617	321	-322	297	-298	imp:n=1	
992	6	0.083382617	321	-322	298	-299	imp:n=1	\$ z=149.31 - tally
993	6	0.083382617	321	-322	299	-300	imp:n=1	\$ z=149.81 - tally
994	6	0.083382617	321	-322	300	-303	imp:n=1	\$ z=150.31 - tally
995	6	0.083382617	321	-322	303	-304	imp:n=1	
996	6	0.083382617	321	-322	304	-151	imp:n=1	\$ z=151.00 - tally
c								
997	6	0.083382617	322	-323	17	-261	imp:n=1	\$ radius 19.00 z=71.50 - tally
998	6	0.083382617	322	-323	261	-262	imp:n=1	
999	6	0.083382617	322	-323	262	-263	imp:n=1	\$ z=71.69 - tally
1000	6	0.083382617	322	-323	263	-264	imp:n=1	
1001	6	0.083382617	322	-323	264	-265	imp:n=1	\$ z=72.70 - tally
1002	6	0.083382617	322	-323	265	-267	imp:n=1	\$ z=73.20 - tally

1003	6	0.083382617	322	-323	267	-268	imp:n=1	
1004	6	0.083382617	322	-323	268	-269	imp:n=1	\$ z=74.10 - tally
1005	6	0.083382617	322	-323	269	-270	imp:n=1	
1006	6	0.083382617	322	-323	270	-271	imp:n=1	\$ z=76.25 - tally
1007	6	0.083382617	322	-323	271	-272	imp:n=1	
1008	6	0.083382617	322	-323	272	-273	imp:n=1	\$ z=78.75 - tally
1009	6	0.083382617	322	-323	273	-274	imp:n=1	
1010	6	0.083382617	322	-323	274	-275	imp:n=1	\$ z=81.25 - tally
1011	6	0.083382617	322	-323	275	-276	imp:n=1	
1012	6	0.083382617	322	-323	276	-277	imp:n=1	\$ z=88.75 - tally
1013	6	0.083382617	322	-323	277	-278	imp:n=1	
1014	6	0.083382617	322	-323	278	-279	imp:n=1	\$ z=96.75 - tally
1015	6	0.083382617	322	-323	279	-280	imp:n=1	
1016	6	0.083382617	322	-323	280	-281	imp:n=1	\$ z=103.75 - tally
1017	6	0.083382617	322	-323	281	-282	imp:n=1	
1018	6	0.083382617	322	-323	282	-283	imp:n=1	\$ z=111.25 - tally
1019	6	0.083382617	322	-323	283	-284	imp:n=1	
1020	6	0.083382617	322	-323	284	-285	imp:n=1	\$ z=118.25 - tally
1021	6	0.083382617	322	-323	285	-286	imp:n=1	
1022	6	0.083382617	322	-323	286	-287	imp:n=1	\$ z=126.25 - tally
1023	6	0.083382617	322	-323	287	-288	imp:n=1	
1024	6	0.083382617	322	-323	288	-289	imp:n=1	\$ z=133.75 - tally
1025	6	0.083382617	322	-323	289	-290	imp:n=1	
1026	6	0.083382617	322	-323	290	-291	imp:n=1	\$ z=141.25 - tally
1027	6	0.083382617	322	-323	291	-292	imp:n=1	
1028	6	0.083382617	322	-323	292	-293	imp:n=1	\$ z=143.75 - tally
1029	6	0.083382617	322	-323	293	-294	imp:n=1	
1030	6	0.083382617	322	-323	294	-295	imp:n=1	\$ z=146.25 - tally
1031	6	0.083382617	322	-323	295	-296	imp:n=1	
1032	6	0.083382617	322	-323	296	-297	imp:n=1	\$ z=148.40 - tally
1033	6	0.083382617	322	-323	297	-298	imp:n=1	
1034	6	0.083382617	322	-323	298	-299	imp:n=1	\$ z=149.31 - tally
1035	6	0.083382617	322	-323	299	-300	imp:n=1	\$ z=149.81 - tally
1036	6	0.083382617	322	-323	300	-303	imp:n=1	\$ z=150.31 - tally
1037	6	0.083382617	322	-323	303	-304	imp:n=1	
1038	6	0.083382617	322	-323	304	-151	imp:n=1	\$ z=151.00 - tally
c								
1039	6	0.083382617	323	-324	17	-151	imp:n=1	\$ radius 19.20
1040	6	0.083382617	324	-7	325	-262	imp:n=1	\$ radius 19.50 z=71.50 - tally
1041	6	0.083382617	324	-7	17	-325	imp:n=1	
1042	6	0.083382617	324	-7	262	-263	imp:n=1	\$ z=71.69 - tally
1043	6	0.083382617	324	-7	263	-264	imp:n=1	
1044	6	0.083382617	324	-7	264	-265	imp:n=1	\$ z=72.70 - tally
1045	6	0.083382617	324	-7	265	-267	imp:n=1	\$ z=73.20 - tally
1046	6	0.083382617	324	-7	267	-268	imp:n=1	
1047	6	0.083382617	324	-7	268	-269	imp:n=1	\$ z=74.10 - tally
1048	6	0.083382617	324	-7	269	-270	imp:n=1	
1049	6	0.083382617	324	-7	270	-271	imp:n=1	\$ z=76.25 - tally
1050	6	0.083382617	324	-7	271	-272	imp:n=1	
1051	6	0.083382617	324	-7	272	-273	imp:n=1	\$ z=78.75 - tally
1052	6	0.083382617	324	-7	273	-274	imp:n=1	
1053	6	0.083382617	324	-7	274	-275	imp:n=1	\$ z=81.25 - tally

1054	6	0.083382617	324	-7	275	-276	imp:n=1	
1055	6	0.083382617	324	-7	276	-277	imp:n=1	\$ z=88.75 - tally
1056	6	0.083382617	324	-7	277	-278	imp:n=1	
1057	6	0.083382617	324	-7	278	-279	imp:n=1	\$ z=96.75 - tally
1058	6	0.083382617	324	-7	279	-280	imp:n=1	
1059	6	0.083382617	324	-7	280	-281	imp:n=1	\$ z=103.75 - tally
1060	6	0.083382617	324	-7	281	-282	imp:n=1	
1061	6	0.083382617	324	-7	282	-283	imp:n=1	\$ z=111.25 - tally
1062	6	0.083382617	324	-7	283	-284	imp:n=1	
1063	6	0.083382617	324	-7	284	-285	imp:n=1	\$ z=118.25 - tally
1064	6	0.083382617	324	-7	285	-286	imp:n=1	
1065	6	0.083382617	324	-7	286	-287	imp:n=1	\$ z=126.25 - tally
1066	6	0.083382617	324	-7	287	-288	imp:n=1	
1067	6	0.083382617	324	-7	288	-289	imp:n=1	\$ z=133.75 - tally
1068	6	0.083382617	324	-7	289	-290	imp:n=1	
1069	6	0.083382617	324	-7	290	-291	imp:n=1	\$ z=141.25 - tally
1070	6	0.083382617	324	-7	291	-292	imp:n=1	
1071	6	0.083382617	324	-7	292	-293	imp:n=1	\$ z=143.75 - tally
1072	6	0.083382617	324	-7	293	-294	imp:n=1	
1073	6	0.083382617	324	-7	294	-295	imp:n=1	\$ z=146.25 - tally
1074	6	0.083382617	324	-7	295	-296	imp:n=1	
1075	6	0.083382617	324	-7	296	-297	imp:n=1	\$ z=148.40 - tally
1076	6	0.083382617	324	-7	297	-298	imp:n=1	
1077	6	0.083382617	324	-7	298	-299	imp:n=1	\$ z=149.31 - tally
1078	6	0.083382617	324	-7	299	-300	imp:n=1	\$ z=149.81 - tally
1079	6	0.083382617	324	-7	300	-303	imp:n=1	\$ z=150.31 - tally
1080	6	0.083382617	324	-7	326	-151	imp:n=1	
1081	6	0.083382617	324	-7	303	-326	imp:n=1	\$ z=151.00 - tally

c
c Surface cells
c

1	cz	9.0
2	cz	12.1
3	cz	12.6
4	cz	13.36
5	cz	13.97
6	cz	14.0
7	cz	19.5
8	cz	19.61
9	cz	20.22
900	cz	20.28
10	cz	20.78
11	cz	40.0
12	pz	0.0
13	pz	35.0
14	pz	40.0
15	pz	13.9
16	pz	53.0
17	pz	71.0
18	pz	113.9
19	pz	154.629

C
C
C

Beam tube 1

20 gq 1.2842759e-1 8.7157241e-1 1.0 6.6913061e-1 1.439452e-15
-3.7499006e-15 3.9392669e1 1.0262141e2 -1.72e2 1.0360484e4
21 p -9.3358043e-1 3.5836795e-1 -2.0083436e-15 8.6802007
22 p -9.3358043e-1 3.5836795e-1 -2.0083436e-15 9.1680201e1
23 gq 1.2842759e-1 8.7157241e-1 1.0 6.6913061e-1 1.439452e-15
-3.7499006e-15 3.9392669e1 1.0262141e2 -1.72e2 1.0357444e4

C
C
C

Beam tube 2

24 gq 3.126967e-1 6.873033e-1 1.0 9.2718385e-1 1.0536957e-15
-1.5621681e-15 5.1328843e1 7.609814e1 -1.72e2 9.4773943e3
25 p -8.2903757e-1 5.591929e-1 -9.4215763e-16 2.4408518e1
26 p -8.2903757e-1 5.591929e-1 -9.4215763e-16 1.0090852e2
27 gq 3.126967e-1 6.873033e-1 1.0 9.2718385e-1 1.0536957e-15
-1.5621681e-15 5.1328843e1 7.609814e1 -1.72e2 9.4753543e3

C
C
C

Beam tube 3

28 gq 9.9969541e-1 3.048649e-4 1.0 3.4899497e-2 -6.858948e-15
1.1972403e-16 8.5588899e1 1.4939598 -2.72e2 2.0302923e4
29 p 1.7452406e-2 -9.998477e-1 -3.4300148e-15 -6.047901
30 p 1.7452406e-2 -9.998477e-1 -3.4300148e-15 9.5152099e1
31 gq 9.9969541e-1 3.0458649e-4 1.0 3.4899497e-2 -6.858948e-15
1.1972403e-16 8.5588899e1 1.4939598 -2.72e2 2.0300883e4

C
C
C

Beam tube 4

32 gq 7.9389263e-1 2.0610737e-1 1.0 8.0901699e-1 -2.7190548e-15
1.3854276e-15 8.0036531e1 4.0780649e1 -2.22e2 1.4313227e4
33 p 4.539905e-1 -8.9100652e-1 -1.5258333e-15 1.5821156
34 p 4.539905e-1 -8.9100652e-1 -1.5258333e-15 9.2582116e1
35 gq 7.9389263e-1 2.0610737e-1 1.0 8.0901699e-1 -2.7190548e-15
1.3854276e-15 8.0036531e1 4.0780649e1 -2.22e2 1.4311187e4

C
C
C

Beam tube 6

36 gq 6.3781868e-1 3.6218132e-1 1.0 9.612617e-1 -1.0976368e-15
8.2712862e-16 -7.8218928e1 -5.894219e1 -2.42e2 1.7014096e4
37 p 6.0181502e-1 -7.9863551e-1 -6.8719506e-16 1.3111231e1
38 p 6.0181502e-1 -7.9863551e-1 -6.8719506e-16 1.0111123e2
39 gq 6.3781868e-1 3.6218132e-1 1.0 9.612617e-1 -1.0976368e-15
8.2712862e-16 -7.8218928e1 -5.894219e1 -2.42e2 1.7012056e4

C
C
C

Beam tube 7

40 gq 9.1451879e-1 8.5481214e-2 1.0 5.591929e-1 -4.433639e-15
1.3554995e-15 -8.59927e1 -2.6290607e1 -2.52e2 1.7872485e4
41 p 2.923717e-1 -9.5630476e-1 -2.3181099e-15 5.4849705
42 p 2.923717e-1 -9.5630476e-1 -2.3181099e-15 1.0298497e2

```

43  gq  9.1451879e-1 8.5481214e-2 1.0 5.591929e-1 -4.433639e-15
      1.3554995e-15 -8.59927e1 -2.6290607e1 -2.52e2 1.7870445e4
c
c  Beam tube 8
c
44  gq  4.1317591e-1 5.8682409e-1 1.0 -9.8480775e-1 -6.3236299e-15
      -7.5362086e-15 -6.086621e1 7.2537524e1 -1.72e2 9.612597e3
45  p   7.6604444e-1 6.4278761e-1 4.9189108e-15 -8.264593e-1
46  p   7.6604444e-1 6.4278761e-1 4.9189108e-15 8.747354e1
47  gq  4.1317591e-1 5.8682409e-1 1.0 -9.8480775e-1 -6.3236299e-15
      -7.5362086e-15 -6.086621e1 7.2537524e1 -1.72e2 9.610557e3
c
c  Beam tube 9
c
48  gq  2.2040355e-1 7.7959645e-1 1.0 -8.2903757e-1 -4.433639e-15
      -8.3384622e-15 1.0625745e1 -1.998412e1 -2.52e2 1.5979068e4
49  p   8.8294759e-1 4.6947156e-1 4.7219463e-15 6.4344558e1
50  p   8.8294759e-1 4.6947156e-1 4.7219463e-15 1.1314456e2
51  gq  2.2040355e-1 7.7959645e-1 1.0 -8.2903757e-1 -4.433639e-15
      -8.3384622e-15 1.0625745e1 -1.998412e1 -2.52e2 1.5977028e4
c
c  Beam tube 10
c
52  gq  9.9513403e-1 4.8659656e-3 1.0 1.391731e-1 -6.4630636e-15
      4.5194143e-16 -8.3130253e1 -5.8130336 -2.52e2 1.7587108e4
53  p   -6.9756474e-2 9.9756405e-1 3.2394228e-15 4.6807504e1
54  p   -6.9756474e-2 9.9756405e-1 3.2394228e-15 1.000075e2
55  gq  9.9513403e-1 4.8659656e-3 1.0 1.391731e-1 -6.4630636e-15
      4.5194143e-16 -8.3130253e1 -5.8130336 -2.52e2 1.7585068e4
c
c  Beam tube 11
c
56  gq  7.1658198e-1 2.7414644e-1 1.0 9.0712729e-1 -1.9013903e-15
      1.1881205e-15 -8.6309466 -6.0130121 -1.82e2 8.3011438e3
57  p   -5.2991926e-1 8.480481e-1 1.1107409e-15 4.9544795e1
58  p   -5.2991926e-1 8.480481e-1 1.1107409e-15 1.0834479e2
59  gq  7.1658198e-1 2.7414644e-1 1.0 9.0712729e-1 -1.9013903e-15
      1.1881205e-15 -8.6105367 -6.0456754 -1.82e2 8.3000121e3
c
c  Beam tube 13
c
60  gq  2.5e-1 7.5e-1 1.0 -8.660254e-1 -4.7694522e-15
      -8.2609336e-15 -5.8232221e1 1.0086117e2 -1.62e2 9.9269916e3
61  p   8.660254e-1 5.0e-1 4.7694522e-15 -8.9738835e1
62  p   8.660254e-1 5.0e-1 4.7694522e-15 8.8661165e1
63  gq  2.5e-1 7.5e-1 1.0 -8.660254e-1 -4.7694522e-15
      -8.2609336e-15 -5.8232221e1 1.0086117e2 -1.62e2 9.9249516e3
c
c  Cold source - cell 14
c
64  c/z -6.18e1 3.28e1 1.5
65  c/z -6.18e1 3.28e1 1.6

```

66 c/z -6.18e1 3.28e1 1.95e1
 67 c/z -6.18e1 3.28e1 2.0e1
 68 c/z -6.18e1 3.28e1 2.04e1
 69 c/z -6.18e1 3.28e1 4.5
 70 pz 1.065e2
 71 pz 1.105e2
 72 pz 1.11e2
 73 pz 1.6e2
 74 pz 1.605e2
 75 pz 1.609e2
 77 c/z -6.18e1 3.28e1 9.25
 78 c/z -6.18e1 3.28e1 9.5
 79 c/z -6.18e1 3.28e1 2.05e1
 80 pz 1.064e2

c

c Hot source - cell 15

c

82 c/z 3.75e1 3.25e1 1.55e1
 83 pz 1.01e2
 85 c/z 3.75e1 3.25e1 1.5e1
 86 pz 1.02e2
 87 pz 1.44e2
 88 pz 1.45e2
 89 c/z 3.75e1 3.25e1 1.35e1
 90 pz 1.03e2
 91 pz 1.43e2
 92 c/z 3.75e1 3.25e1 1.32e1
 93 pz 1.033e2
 94 pz 1.427e2
 95 c/z 3.75e1 3.25e1 1.0e1
 96 pz 1.08e2
 97 pz 1.38e2
 98 pz 1.22e2
 99 pz 1.24e2
 100 c/z 3.75e1 3.25e1 1.00

c

c Beam tube 16

c

101 c/z -5.22e1 7.45e1 2.0
 102 pz 1.11e2
 103 pz 2.31e2
 104 c/z -5.22e1 7.45e1 2.2

c

c Beam tube 17

c

105 c/z 3.9 3.73e1 2.0
 106 pz 1.31e2
 108 c/z 3.9 3.73e1 2.2

c

c Beam tube 19 - from 19a results

c

109 gq 8.9755635e-1 1.5267081e-1 9.4977284e-1 5.8924867e-1 4.1259636e-1

110 p -1.4346363e-1 1.0120434e2 -2.4350297e1 -2.4454883e2 1.7634846e4
 111 p 3.200682e-1 -9.2050485e-1 2.2411417e-1 6.1243727e1
 112 gq 3.200682e-1 -9.2050485e-1 2.2411417e-1 1.4124373e2
 8.9755635e-1 1.5267081e-1 9.4977284e-1 5.8924867e-1 4.1259636e-1
 -1.4346363e-1 1.0120434e2 -2.4350297e1 -2.4454883e2 1.7632806e4

c

c Beam tube 21 - from 21a results

c

113 gq 6.7620392e-1 4.8255025e-1 8.4124583e-1 8.1865304e-1 5.7322703e-1
 -4.5344891e-1 -2.3517413e1 -1.3604388e2 -2.1202619e2 1.5979028e4
 114 p 5.6903082e-1 -7.193398e-1 3.9843967e-1 6.7731469e1
 115 p 5.6903982e-1 -7.193398e-1 3.9843967e-1 1.6103147e2
 116 gq 6.7620392e-1 4.8255025e-1 8.4124583e-1 8.1865304e-1 5.7322703e-1
 -4.5344891e-1 -2.3517413e1 -1.3604388e2 -2.1202619e2 1.5976988e4

c

c Beam tube 22 - from 22a results

c

117 gq 6.878947e-1 4.6512176e-1 8.469777e-1 -8.1715663e-1 -5.7217923e-1
 -4.3707697e-1 1.1929125e2 1.8823231e1 -2.0555643e2 1.4184522e4
 118 p 5.5866035e-1 7.313537e-1 3.9117819e-1 8.4926917e1
 119 p 5.5866035e-1 7.313537e-1 3.9117819e-1 1.6892692e2
 120 gq 6.878343e-1 4.6512176e-1 8.469481e-1 -8.1715663e-1 -5.7217923e-1
 -4.3716155e-1 1.1930128e2 1.8823231e1 -2.0554941e2 1.4182065e4

c

c Beam tube 23

c

121 c/z 3.75e1 -6.49e1 10.0
 122 pz 1.0
 124 c/z 3.75e1 -6.49e1 1.02e1

c

c Beam tube 24 - from 24a results

c

125 gq 7.227548e-1 4.1317591e-1 8.6406929e-1 -8.0670728e-1 5.6486252e-1
 3.8825835e-1 7.0420299e1 -1.5074281e2 -2.1263661e2 1.8199186e4
 126 p -5.2654078e-1 -7.6604444e-1 3.6868783e-1 8.05063e1
 127 p -5.2654078e-1 -7.6604444e-1 3.6868783e-1 1.155063e2
 128 gq 7.227548e-1 4.1317591e-1 8.6406929e-1 -8.0670728e-1 5.6486252e-1
 3.8825835e-1 7.0420299e1 -1.5074281e2 -2.1263661e2 1.8197146e4

c

c Safety rod 1 (just the rod - bottom is surface 12 and top of the
 c safety rods is surface 134)

c

c The top and bottom of the rod is the same for all the rods.
 c These are the outer diameter of the cladding.

c

129 gq 1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15
 6.9829627e-15 -6.2019713e1 2.2573329e1 -1.3772631e-13 1.06875e3

c

c Safety rod 2

c

130 gq 1.0 1.0 2.4380884e-29 0.0 6.9829627e-15
 6.9829627e-15 -5.0558933e1 -4.2423982e1 -3.2464812e-13 1.06875e3


```

c
c   Safety rod 3
c
131  gq   1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15
        6.9829627e-15 6.2019713e1 -2.2573329e1 1.3772631e-13 1.06875e3
c
c   Safety rod 4
c
132  gq   1.0 1.0 2.4380884e-29 -5.5511151e-17 6.9829627e-15
        6.9829627e-15 1.146078e1 -6.4997312e1 -1.869218e-13 1.06875e3
c
c   Safety rod 5
c
133  gq   1.0 1.0 2.4380884e-29 0.0 6.9829627e-15
        6.9829627e-15 5.0558933e1 4.2423982e1 3.2464812e-13 1.06875e3
c
c   Safety rod 6
c
134  gq   1.0 1.0 2.4380884e-29 -5.5511151e-17 6.9829627e-15
        6.9829627e-15 -1.146078e1 6.4997312e1 1.869218e-13 1.06875e3
135  pz   100.0
c
c   The encompassing sphere around everything to check geometry
c
136  so   500
137  px   0.0
138  py   0.0
c
c   The borated regions on top and below the core
c
1138 pz   151.6
139  pz   151.833
140  pz   152.066
141  pz   152.299
142  pz   152.532
143  pz   152.765
144  pz   152.998
145  pz   153.231
146  pz   153.464
147  pz   153.697
148  pz   153.93
149  pz   154.163
150  pz   154.396
151  pz   151.00
152  pz   70.167
153  pz   69.934
154  pz   69.701
155  pz   69.468
156  pz   69.235
157  pz   69.002
158  pz   68.769
159  pz   68.536

```

160 pz 68.303
 161 pz 68.070
 162 pz 67.837
 163 pz 67.604
 1164 pz 70.4
 c
 c The inside rings of the safety rods
 c
 c Safety rod 1 (all the safety rods will follow the same pattern
 c for the surfaces as seen below)
 c
 c Inner diameter of outer cladding/outer diameter of cadum
 c
 164 gq 1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15
 6.9829627e-15 -6.2019713e1 2.2573329e1 -1.3772631e-13 1.0691975e3
 c
 c Inner diameter of cadum/outer diameter of inner cladding
 c
 165 gq 1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15
 6.9829627e-15 -6.2019713e1 2.2573329e1 -1.3772631e-13 1.0709375e3
 c
 c Inner diameter of inner cladding/outer diameter of d2o channel
 c
 166 gq 1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15
 6.9829627e-15 -6.2019713e1 2.2573329e1 -1.3772631e-13 1.07136e3
 c
 c Inner diameter of d2o channel/outer diameter of Al guide tube
 c
 167 gq 1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15
 6.9829627e-15 -6.2019713e1 2.2573329e1 -1.3772631e-13 1.085e3
 c
 c Inner diameter of Al guide tube/inner cylinder of d2o
 c
 168 gq 1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15
 6.9829627e-15 -6.2019713e1 2.2573329e1 -1.3772631e-13 1.08644e3
 c
 c Safety rod 2
 c
 169 gq 1.0 1.0 2.4380884e-29 0.0 6.9829627e-15
 6.9829627e-15 -5.0558933e1 -4.2423982e1 -3.2464812e-13 1.0691975e3
 170 gq 1.0 1.0 2.4380884e-29 0.0 6.9829627e-15
 6.9829627e-15 -5.0558933e1 -4.2423982e1 -3.2464812e-13 1.0709375e3
 171 gq 1.0 1.0 2.4380884e-29 0.0 6.9829627e-15
 6.9829627e-15 -5.0558933e1 -4.2423982e1 -3.2464812e-13 1.07136e3
 172 gq 1.0 1.0 2.4380884e-29 0.0 6.9829627e-15
 6.9829627e-15 -5.0558933e1 -4.2423982e1 -3.2464812e-13 1.085e3
 173 gq 1.0 1.0 2.4380884e-29 0.0 6.9829627e-15
 6.9829627e-15 -5.0558933e1 -4.2423982e1 -3.2464812e-13 1.08644e3
 c
 c Safety rod 3
 c
 174 gq 1.0 1.0 2.4380884e-29 1.110223e-16 6.9829627e-15

		6.9829627e-15	6.2019713e1	-2.2573329e1	1.3772631e-13	1.0691975e3
175	gq	1.0	1.0	2.4380884e-29	1.110223e-16	6.9829627e-15
		6.9829627e-15	6.2019713e1	-2.2573329e1	1.3772631e-13	1.0709375e3
176	gq	1.0	1.0	2.4380884e-29	1.110223e-16	6.9829627e-15
		6.9829627e-15	6.2019713e1	-2.2573329e1	1.3772631e-13	1.07136e3
177	gq	1.0	1.0	2.4380884e-29	1.110223e-16	6.9829627e-15
		6.9829627e-15	6.2019713e1	-2.2573329e1	1.3772631e-13	1.085e3
178	gq	1.0	1.0	2.4380884e-29	1.110223e-16	6.9829627e-15
		6.9829627e-15	6.2019713e1	-2.2573329e1	1.3772631e-13	1.08644e3

c

c

Safety rod 4

c

179	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	1.146078e1	-6.4997312e1	-1.869218e-13	1.0691975e3
180	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	1.146078e1	-6.4997312e1	-1.869218e-13	1.0709375e3
181	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	1.146078e1	-6.4997312e1	-1.869218e-13	1.07136e3
182	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	1.146078e1	-6.4997312e1	-1.869218e-13	1.085e3
183	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	1.146078e1	-6.4997312e1	-1.869218e-13	1.08644e3

c

c

Safety rod 5

c

184	gq	1.0	1.0	2.4380884e-29	0.0	6.9829627e-15
		6.9829627e-15	5.0558933e1	4.2423982e1	3.2464812e-13	1.0691975e3
185	gq	1.0	1.0	2.4380884e-29	0.0	6.9829627e-15
		6.9829627e-15	5.0558933e1	4.2423982e1	3.2464812e-13	1.0709375e3
186	gq	1.0	1.0	2.4380884e-29	0.0	6.9829627e-15
		6.9829627e-15	5.0558933e1	4.2423982e1	3.2464812e-13	1.07136e3
187	gq	1.0	1.0	2.4380884e-29	0.0	6.9829627e-15
		6.9829627e-15	5.0558933e1	4.2423982e1	3.2464812e-13	1.085e3
188	gq	1.0	1.0	2.4380884e-29	0.0	6.9829627e-15
		6.9829627e-15	5.0558933e1	4.2423982e1	3.2464812e-13	1.08644e3

c

c

Safety rod 6

c

189	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	-1.146078e1	6.4997312e1	1.869218e-13	1.0691975e3
190	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	-1.146078e1	6.4997312e1	1.869218e-13	1.0709375e3
191	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	-1.146078e1	6.4997312e1	1.869218e-13	1.07136e3
192	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	-1.146078e1	6.4997312e1	1.869218e-13	1.085e3
193	gq	1.0	1.0	2.4380884e-29	-5.5511151e-17	6.9829627e-15
		6.9829627e-15	-1.146078e1	6.4997312e1	1.869218e-13	1.08644e3

c

c

The reflector tank

c

194	cz	115	\$ inner diameter
-----	----	-----	-------------------

195	pz	221	\$ height
196	cz	116	\$ outer diameter

c

c The structures above the core

c

197	cz	21.5	\$ outer diameter of more outer tank per drawing
198	cz	21.7	\$ outer diameter of more outer tank per drawing
199	pz	175	\$ bottom of cross beam per drawing
200	pz	180	\$ top of cross beam per drawing
201	pz	185	\$ top of inner cylinder per drawing

c

c Surfaces for the core power distribution tallies

c

261	pz	71.50
262	pz	71.69
263	pz	72.19
264	pz	72.20
265	pz	72.70
267	pz	73.20
268	pz	73.60
269	pz	74.10
270	pz	75.75
271	pz	76.25
272	pz	78.25
273	pz	78.75
274	pz	80.75
275	pz	81.25
276	pz	88.25
277	pz	88.75
278	pz	95.75
279	pz	96.25
280	pz	103.25
281	pz	103.75
282	pz	110.75
283	pz	111.25
284	pz	118.25
285	pz	118.75
286	pz	125.75
287	pz	126.25
288	pz	133.25
289	pz	133.75
290	pz	140.75
291	pz	141.25
292	pz	143.25
293	pz	143.75
294	pz	145.75
295	pz	146.25
296	pz	147.90
297	pz	148.40
298	pz	148.81
299	pz	149.31
300	pz	149.81

303 pz 150.31
 304 pz 150.50
 306 cz 14.20
 307 cz 14.50
 308 cz 14.80
 309 cz 15.10
 313 cz 15.40
 314 cz 15.75
 315 cz 16.05
 316 cz 16.60
 317 cz 16.90
 318 cz 17.45
 319 cz 17.75
 320 cz 18.10
 321 cz 18.40
 322 cz 18.70
 323 cz 19.00
 324 cz 19.20
 325 pz 71.19
 326 pz 150.81

c

c

c MCNP Control Information

c

c

kcode 10000 1.0 5 80

c

prtmp 80 10 80

c

ksrc	14.2 0 79	12 12 92	0 -19.3 79	-14.2 0 131
	19.3 0 157	-19.3 0 105	0 -14.2 144	-12 -12 79
	-12 12 118	0 19.3 105	0 -19.3 157	14.2 0 92
	-12 12 79	12 -12 105	0 -14.2 92	0 -14.2 118
	12 -12 131	-19.3 0 131	0 14.2 79	0 19.3 157
	-12 12 105	19.3 0 92	12 12 144	0 -14.2 131
	19.3 0 79	0 19.3 144	12 -12 144	12 12 105
	14.2 0 157	0 -14.2 79	0 -19.3 131	-14.2 0 92
	12 -12 157	0 14.2 118	-12 12 92	19.3 0 131
	0 -19.3 118	19.3 0 144	-12 -12 105	-14.2 0 105
	0 19.3 79	12 12 131	14.2 0 118	0 14.2 157
	-12 -12 92	-19.3 0 79	0 -14.2 157	14.2 0 105
	-12 12 144	19.3 0 118	0 -19.3 92	12 12 79
	-14.2 0 157	-12 -12 118	14.2 0 144	12 -12 118
	-19.3 0 92	0 -19.3 144	-14.2 0 79	-12 12 157
	12 -12 79	14.2 0 131	-19.3 0 118	0 -14.2 105
	0 19.3 92	-19.3 0 157	-12 12 131	12 -12 92
	0 19.3 131	-12 -12 131	0 14.2 92	-12 -12 157
	-14.2 0 144	0 14.2 144	0 -19.3 105	12 12 157
	-12 -12 144	19.3 0 105	0 14.2 131	12 12 118
	-19.3 0 144	0 19.3 118	0 14.2 105	-14.2 0 118

c

```

c -----
c
c mode      n
c
c
c The material compositions were taken from the report by Glaser, et.al.
c "Verifizierung des dreidimensionalen Rechencodes MORSE-K durch
c Nachrechnen des kritischen Experimentes FOEHN", dated Jan. 16, 1991.
c
c The elements are defined by atomic density in units of barns/cm,
c Except in the case of materials 4 and 5, which are single elements.
c Therefore an atomic fraction of 1 was used.
c
c
c Material 1 - unborated d2o
c
c m1      1002.55c 0.06637      1001.50c 0.000133      8016.50c 0.03325
c mt1     hwtr.01t
c
c Material 2 - borated d2o
c
c m2      1002.55c 0.06637      1001.50c 0.000133      8016.50c 0.03325
c         5010.50c 1.0646e-5
c mt2     hwtr.01t
c
c Material 3 - element Aluminum used for structural material
c
c m3      13027.50c 0.031673      1002.55c 0.0103347      8016.50c 0.0051673
c         27059.50c 2.1221e-8      24000.50c 6.493e-5      25055.50c 1.1323e-4
c         26000.55c 6.9681e-5      28000.50c 6.6513e-7      29000.50c 6.3346e-7
c         31000.50c 4.4342e-6      73181.50c 3.1673e-10      90232.50c 4.751e-9
c mt3     hwtr.01t
c
c Material 4 - boron used for the end plates
c
c m4      5010.50c 1.0
c
c Material 5 - cadium used in the safety rods
c
c m5      48000.50c 1.0
c
c Material 6 - fuel zone - the core
c
c m6      92235.50c 0.0004736      92238.50c 0.0000468      1001.50c 0.000078
c         8016.50c 0.019432      1002.55c 0.038786      13027.50c 0.02456
c         27059.50c 1.6455e-8      24000.50c 5.0348e-5      25055.50c 8.7801e-5
c         26000.55c 5.4032e-5      28000.50c 5.1576e-7      29000.50c 4.912e-7
c         31000.50c 3.4384e-6      73181.50c 2.456e-10      90232.50c 3.684e-9
c         5010.50c 6.3578e-6
c mt6     hwtr.01t
c
c Material 7 - graphite used in the hot cell

```

```

c
m7      6000.50c 1.67e-2
mt7     grph.08t
c
c      Material 8 - aluminum with borated water-outer wall of core tube
c
m8      13027.50c 0.02654      1001.50c 0.735e-4      1002.55c 0.036682
        8016.50c 0.01838      5010.50c 5.8841e-6      27059.50c 1.6455e-8
        24000.50c 5.0348e-5      25055.50c 8.7801e-5      26000.55c 5.4032e-5
        28000.50c 5.1576e-7      29000.50c 4.912e-7      31000.50c 3.4384e-6
        73181.50c 2.456e-10      90232.50c 3.684e-9
mt8     hwtr.01t
c
c      Material 9 - zircaloy-4
c
m9      26000.55c 1.695e-4      40000.50c 4.21162e-2      50000.35c 5.185e-4
c
c      Material 10 - nickel - used in the control rod
c
m10     28000.50c 9.13e-2
c
c      Material 11 - stainless steel - safety rod cladding
c
m11     24000.50c 1.4156e-2      25055.50c 9.77323e-4      26000.55c 5.70399e-2
        28000.50c 1.09566e-2      42000.50c 1.60059e-3
c
c      Material 12 - 100% aluminum for piping/tankwalls/cells/etc.
c
m12     13027.50c 0.047175      27059.50c 4.0334e-8      24000.50c 1.2341e-4
        25055.50c 2.15215e-4      26000.55c 1.3244e-4      28000.50c 1.2642e-6
        29000.50c 1.204e-6      31000.50c 8.4280e-6      73181.50c 6.020e-10
        90232.50c 9.030e-9
c
c      Material 13 - inner core tank wall/outer tank wall w/o boron
c
m13     13027.50c 0.02654      1001.50c 0.735e-4      1002.55c 0.036682
        27059.50c 1.6455e-8      24000.50c 5.0348e-5      25055.50c 8.7801e-5
        26000.55c 5.4032e-5      28000.50c 5.1576e-7      29000.50c 4.912e-7
        31000.50c 3.4384e-6      73181.50c 2.456e-10      90232.50c 3.684e-9
        8016.50c 0.01838
mt13    hwtr.01t
c
c      Material 14 - solid boron zone - material #56 from eckert
c
m14     1002.55c 0.03867      8016.50c 0.01938      1001.50c 0.000078
        13027.50c 0.0248      5010.50c 1.517e-4      27059.50c 1.5376e-8
        24000.50c 4.7047e-5      25055.50c 8.2045e-5      26000.55c 5.0490e-5
        28000.50c 4.8195e-7      29000.50c 4.590e-7      31000.50c 3.2130e-6
        73181.50c 2.295e-10      90232.50c 3.4425e-9
mt14    hwtr.01t
c
c      TALLY INPUT

```

c

c

c

Tallies for power at radius 14.50,14.80,15.10 cm at various heights

c

f7:n

615	617	619	620	622	624	626	628	630	632	634	636	638	640	642	644	646
648	650	652	653	654	656	657	659	661	662	664	666	668	670	672	674	676
678	680	682	684	686	688	690	692	694	695	696	698	699	701	703	704	706
708	710	712	714	716	718	720	722	724	726	728	730	732	734	736	737	738
740																

c

c

Tallies for power at radius 15.4 , 16.05,16.6 cm at various heights

c

f17:n

741	743	745	746	748	750	752	754	756	758	760	762	764	766	768	770	772
774	776	778	779	780	782	784	786	788	789	791	793	795	797	799	801	803
805	807	809	811	813	815	817	819	821	822	823	825	827	829	831	832	834
836	838	840	842	844	846	848	850	852	854	856	858	860	862	864	865	866
868																

c

c

Tallies for power at radius 17.75,18.40,18.70 cm at various heights

c

f27:n

870	872	874	875	877	879	881	883	885	887	889	891	893	895	897	899	901
903	905	907	908	909	911	913	915	917	918	920	922	924	926	928	930	932
934	936	938	940	942	944	946	948	950	951	952	954	955	957	959	960	962
964	966	968	970	972	974	976	978	980	982	984	986	988	990	992	993	994
996																

c

c

Tallies for power at radius 19.0, 19.2 cm at various heights

c

f37:n

997	999	1001	1002	1004	1006	1008	1010	1012	1014	1016	1018	1020
1022	1024	1026	1028	1030	1032	1034	1035	1036	1038	1040	1042	1044
1045	1047	1049	1051	1053	1055	1057	1059	1061	1063	1065	1067	1069
1071	1073	1075	1077	1078	1079	1081						

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