Analysis of the KUCA Type-A Experiments

Nuclear Engineering Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via DOE's SciTech Connect (<http://www.osti.gov/scitech/>)

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

Analysis of the KUCA Type-A Experiments

prepared by
G. Aliberti, J. A. Morman, J. G. Stevens, J. Roglans-Ribas
Nuclear Engineering Division, Argonne National Laboratory

January 31, 2013

SUMMARY

The Kyoto University Critical Assembly (KUCA) experiments were launched in 2000 at the Kyoto University Research Reactor Institute (KURRI) with the main objective to establish measurement techniques of neutronic parameters in subcritical systems and to investigate the accuracy of the neutronic design of an Accelerator Driven Subcritical Reactor (ADSR). Due to the continuing interest in non-proliferation issues, new studies are being performed on these assemblies with the purpose to investigate the feasibility of converting the KUCA cores to the use of low-enriched uranium (LEU) fuel.

The KUCA facility consists of the solid-moderated and -reflected type-A and -B cores, and the water-moderated and -reflected type-C core. The present document describes the analysis carried out at Argonne National Laboratory (Argonne) on the KUCA type-A cores. In particular, calculated results of the KUCA ADSR benchmark assemblies and of the feasibility studies on the conversion of the KUCA dry cores from highly-enriched uranium (HEU) to LEU are presented.

CONTENTS

SUMMARY	v
ACRONYMS	xi
1. INTRODUCTION.....	1
2. KUCA BENCHMARK ANALYSIS	1
2.1 Description of KUCA Benchmark Core	1
2.2 Calculations	4
2.2.1 Excess Reactivity and Subcriticality	4
2.2.2 Indium Reaction Rate Distributions	5
2.3 MCNP Model	6
2.4 Approximations, Assumptions and Missing Model.....	14
2.5 Calculation Results	15
2.5.1 Excess Reactivity and Subcriticality	15
2.5.2 Indium Reaction Rate Distributions	16
2.5.3 Source Multiplication Factor	20
3. CONVERSION OF THE KUCA CORES FROM HEU TO LEU	20
3.1 Use of LEU U-Al Alloy Fuel.....	21
3.1.1 Reactivity Calculations.....	24
3.1.2 Flux Spectra Calculations	25
3.2 Use of LEU U-10Mo Fuel	29
3.2.1 Reactivity Calculations.....	31
3.2.2 Flux Spectra Calculations.....	31
3.3 Feasibility Studies on the Conversion of KUCA Type-A Cores with Different Moderator-to-Fuel Volume Ratios in the Unit Cell.....	34
3.3.1 Approaches Used for the Conversion from HEU to LEU	38
3.3.2 Reactivity Calculations.....	39
3.3.3 Flux Spectra Calculations	44
4. CONCLUSIONS.....	52
5. REFERENCES.....	53
APPENDIX. MCNP INPUT FOR KUCA I-1 WITH SUBCRITICAL ROD CONFIGURATION.....	54

FIGURES

Figure 1. No Neutron Shield and No Beam Duct Core (Series-I: Case I-1).	2
Figure 2. Neutron Shield and Small Beam Duct (s') Core (Series-I: Case I-2).	2
Figure 3. Neutron Shield and Large Beam Duct (s) Core (Series-I: Case I-3).	3
Figure 4. Neutron Shield and No Beam Duct Core (Series-I: Case I-4).	3
Figure 5. No Neutron Shield, No Beam Duct and No SV Core (Series-II: Case II-1).	3
Figure 6. No Neutron Shield, No Beam Duct and SV Core (Series-II: Case II-2).	3
Figure 7. No Neutron Shield, Large Beam Duct (s) and SV Core (Series-II: Case II-3).	4
Figure 8. No Neutron Shield, Small Beam Duct (s') and SV Core (Series-II: Case II-4).	4
Figure 9. Location of the Indium (In) Wire.	6
Figure 10. Sideways View of Fuel Assembly “F”.	7
Figure 11. Sideways View of Fuel Assembly “SV” with Void.	7
Figure 12. Sideways View of Partial Fuel Assembly “26”.	7
Figure 13. Description of Fuel “F”, Partial Fuel “26” and Fuel “SV” Assemblies.	8
Figure 14. Description of Neutron Shield and Beam Duct “b”, “bs” and “bs”.	9
Figure 15. Description of Neutron Shield and Beam Duct “f”, “fs” and “fs”.	9
Figure 16. Description of Neutron Shield “fp” and “bp”.	10
Figure 17. Description of Neutron Shield “s” and “s”.	10
Figure 18. Description of Fuel Assembly at KUCA.	11
Figure 19. Description of Polyethylene (Aluminum) Reflector at KUCA.	11
Figure 20. Description of the Fuel Assembly, Polyethylene Reflector and Control Rod at KUCA.	12
Figure 21. Description of Control (Safety) Rod at KUCA.	13
Figure 22. Actual Position of Control (Safety) Rod (Actual Position = Measured Position – 11.4 cm).	13
Figure 23. Adopted Representation of Assembly “12”.	14
Figure 24. Indium Wire Location (16-17, J-W).	17
Figure 25. Calculated Indium Absorption Rate Distributions (Case I-1 to Case I-4) in MCNP Units: Rate per One Neutron and One Target Atom $\times 10^{-24}/\text{cm}^3$.	18
Figure 26. Measured Indium Wire Reaction Rate Distributions along the Vertical Direction Shown in Figures (Case I-1 to Case I-4).	18
Figure 27. Calculated Indium Absorption Rate Distributions (Case II-1 to Case II-4) in MCNP Units: Rate per One Neutron and One Target Atom $\times 10^{-24}/\text{cm}^3$.	19
Figure 28. Measured Indium Wire Reaction Rate Distributions along the Vertical Direction Shown in Figures (Case II-1 to Case II-4).	19
Figure 29. KUCA Configuration Series-I, Case I-1 with Additional Fuel Assemblies Using U-Al LEU Fuel.	21
Figure 30. KUCA Configuration Series-I, Case I-1 after Adding 56 Fuel Assemblies (KUCA I-1+56).	22
Figure 31. Configuration Series-I, Case I-2 after Adding 56 Fuel Assemblies (KUCA I-2+56).	23
Figure 32. KUCA Configuration Series-I, Case I-3 after Adding 56 Fuel Assemblies (KUCA I-3+56).	23
Figure 33. KUCA Configuration Series-I, Case I-4 after Adding 56 Fuel Assemblies (KUCA I-4+56).	24

Figure 34. Flux Spectra at the Positions A and B of KUCA I-1+56 with U-Al LEU Fuel.....	25
Figure 35. Flux Spectra at the Position B of KUCA I-1 HEU and KUCA I-1+56 with U-Al LEU Fuel.	26
Figure 36. Flux Spectra at the Positions A and B of KUCA I-2+56 with U-Al LEU Fuel.....	26
Figure 37 Flux Spectra at the Position B of KUCA I-2 HEU and KUCA I-2+56 with U-Al LEU Fuel.	27
Figure 38. Flux Spectra at the Positions A and B of KUCA I-3+56 with U-Al LEU Fuel.....	27
Figure 39. Flux Spectra at the Position B of KUCA I-3 HEU and KUCA I-3+56 with U-Al LEU Fuel.	28
Figure 40. Flux Spectra at the Positions A and B of KUCA I-4+56 with U-Al LEU Fuel.....	28
Figure 41. Flux Spectra at the Position B of KUCA I-4 HEU and KUCA I-4+56 with U-Al LEU Fuel.	29
Figure 42. Sideways View of Fuel Assembly “F” Using LEU U-10Mo Plates without Al Clad.	31
Figure 43. Sideways View of Fuel Assembly “F” Using LEU U-10Mo Plates with Al Clad.	31
Figure 44. Flux Spectra at Positions A and B of KUCA I-1 with LEU U-10Mo and No Cladding.	32
Figure 45. Flux Spectra at Positions A and B of KUCA I-1 with LEU U-10Mo and Al Cladding.	33
Figure 46. Flux Spectra at Position B of HEU and LEU KUCA I-1 Configurations.	33
Figure 47. Layouts of the Investigated KUCA cores.....	34
Figure 48. Cross Sectional View of KUCA Fuel Assembly A3/8”P36EU - ($V_m/V_f = 5.91$)	35
Figure 49. Cross Sectional View of KUCA Fuel Assembly B2/8”P48EU - ($V_m/V_f = 3.89$)	35
Figure 50. Cross Sectional View of KUCA Fuel Assembly B1/8”P80EU - ($V_m/V_f = 1.94$)	35
Figure 51. Cross Sectional View of KUCA Fuel Assembly B1/8”P60EU-EU - ($V_m/V_f = 0.97$).....	36
Figure 52. Cross Sectional View of KUCA Fuel Assembly B1/8”P48EU-EU-EU - ($V_m/V_f = 0.65$)	36
Figure 53. KUCA A3/8”P36EU: Detail of Reflector Layout Kept the Same for all Configurations.....	38
Figure 54. HEU and U-10Mo LEU fuel plate.....	39
Figure 55. Alternative LEU Fuel Loading for KUCA B1/8”P60EU-EU and B1/8”P48EU-EU-EU.....	41
Figure 56. Flux Spectra Comparison for the KUCA HEU Configurations.	45
Figure 57. Flux Spectra Comparison for the KUCA LEU Configurations with the Same H-to-U235 Atom Ratios in the Fuel Unit Cell of the Corresponding HEU Configurations.....	45
Figure 58. Flux Spectra Comparison for the KUCA A3/8”P36EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 316.45$) in the Fuel Unit Cell.	46
Figure 59. Flux Spectra Comparison for the KUCA B2/8”P48EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 206.96$) in the Fuel Unit Cell.	46
Figure 60. Flux Spectra Comparison for the KUCA B1/8”P80EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 103.48$) in the Fuel Unit Cell.	47
Figure 61. Flux Spectra Comparison for the KUCA B1/8”P60EU-EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 51.74$) in the Fuel Unit Cell.	47
Figure 62. Flux Spectra Comparison for the KUCA B1/8”P48EU-EU-EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 34.49$) in the Fuel Unit Cell.....	48
Figure 63. Flux Spectra Comparison for the KUCA A3/8”P36EU Configuration in the HEU Case and the LEU Cases with Different Thicknesses of the U-10Mo Foil.....	49
Figure 64. Flux Spectra Comparison for the KUCA B1/8”P80EU Configuration in the HEU Case and the LEU Cases with Different Thicknesses of the U-10Mo Foil.....	49

Figure 65. Flux Spectra Comparison for the LEU KUCA A3/8''P36EU Configuration With and Without Aluminum Edge Around the U-10Mo Foils.	50
Figure 66. Flux Spectra Comparison for the LEU KUCA B1/8''P80EU Configuration With and Without Aluminum Edge Around the U-10Mo Foils.	50
Figure 67. Flux Spectra Comparison for the KUCA B1/8''P60EU-EU Configuration with HEU and LEU Loadings of Same k_{eff}	51

TABLES

Table 1. Control Rod Position for the Critical States.	5
Table 2. Calculated and Measured Reactivity Values [pcm].	15
Table 3. Impact of Nuclear Data on Calculated Reactivity Values [pcm] for the KUCA I-1 Excess Reactivity Rod Configuration.	16
Table 4. Calculated Source Multiplication Factors and Eigenvalues.	20
Table 5. Calculated Reactivity [pcm] for the LEU U-Al Configurations.	24
Table 6. Number Densities [at/(barn × cm)] of High Enriched (93%) U-Al, Low Enriched (19.75%) U-Al and U-10Mo Fuel and Aluminum Clad.	30
Table 7. Calculated and Measured Reactivity (pcm, using ENDF/B-VII.0 Data).	31
Table 8. Calculated (Experimental) Multiplication Factor Values of HEU and U-10Mo LEU KUCA Configurations.	40
Table 9. Calculated Multiplication Factor Values of U-10Mo LEU KUCA Configurations.	42
Table 10. Calculated Multiplication Factor Values of HEU and LEU KUCA Cores in Reactivity Excess and Subcritical Rod Configuration.	43
Table 11. Calculated Multiplication Factor Values of the Alternative Loadings of LEU KUCA Cores with Low H/U5 in Excess Reactivity and Subcritical Rod Configuration.	43
Table 12. Location of Assemblies for Flux Spectra Determination in the KUCA Cores.	44
Table 13. Calculated Multiplication Factor Values for KUCA B1/8”P60EU-EU in the Subcritical Rod Configuration.	51

ACRONYMS

ADSR	Accelerator Driven Subcritical Reactor
DOE	U. S. Department of Energy
GTRI	Global Threat Reduction Initiative
HEU	Highly-enriched Uranium
KUCA	Kyoto University Critical Assembly
KURRI	Kyoto University Research Reactor Institute
LEU	Low-enriched Uranium
MCNP	Monte Carlo N-Particle

PRELIMINARY ANALYSIS OF THE KUCA DRY CORE EXPERIMENTS

1. INTRODUCTION

The US Department of Energy (DOE) Global Threat Reduction Initiative (GTRI) research reactor conversion program is part of the global non-proliferation effort to minimize and, to the extent possible, eliminate the use of highly-enriched uranium (HEU) in civil nuclear applications by working to convert research reactors to the use of low-enriched uranium (LEU) fuel throughout the world.

In this frame, the Kyoto University Research Reactor Institute (KURRI) and Argonne National Laboratory (Argonne) established a collaboration to explore the feasibility of converting the Kyoto University Critical Assembly (KUCA) from HEU to LEU.

A series of KUCA experiments was started in 2000 at KURRI with the main objective to establish measurement techniques for neutronics parameters in subcritical systems and to investigate the accuracy of the neutronics designs of an Accelerator Driven Subcritical Reactor (ADSR). The ADSR was primarily conceived for producing energy by transmutation of minor actinides and long-lived fission products and has attracted worldwide attention in recent years because of its safety characteristics and potential for burning plutonium and nuclear waste.

To evaluate the techniques and the ADSR concept, a benchmark was developed and reported by KURRI [1] describing the analysis of several KUCA configurations.

Due to the global interest in non-proliferation issues, new studies are being performed on these configurations with the purpose to investigate the feasibility of converting the KUCA cores to the use of LEU fuel.

The KUCA consists of the solid-moderated and -reflected type-A and -B cores, and of the water-moderated and -reflected type-C core. The present document describes results of the analyses carried out at Argonne on the KUCA type-A cores. In these assemblies, the core is reflected by polyethylene and the fuel region is obtained by stacking highly enriched (93%) uranium-aluminum (U-Al) alloy and polyethylene plates. With the use of an external pulsed neutron generator, 14 MeV neutrons produced by D-T (deuterium – tritium) reactions are injected into the subcritical core through the polyethylene reflector.

The Argonne analyses of the KUCA benchmark (benchmark specifications, requested calculations, obtained results and comparison with the measurements) are presented in Section 2 along with a detailed description of the MCNP5 model that was developed for the simulation. Section 3 presents the feasibility studies on the conversion of the KUCA dry assemblies to the use of LEU, using both U-Al alloy and U-10Mo fuel plates. Conclusions are summarized in Section 4.

2. KUCA BENCHMARK ANALYSIS

KUCA benchmark configurations were developed and reported for the analysis of the solid-moderated and -reflected type-A KUCA cores [1]. After a brief overview of the benchmark specifications and a detailed description of the adopted calculation model, results of the calculations are presented in this section for reactivity's, indium reaction rate distributions and source multiplication factors.

2.1 Description of KUCA Benchmark Core

The type-A benchmark configurations for which calculations have been performed are shown in Figures 1 through 8.

The KUCA cores under study are reflected by polyethylene and the fuel region is obtained by the stacking plates made of 93% enriched U-Al alloy and polyethylene. The desired level of subcriticality is obtained systematically by insertion of control or safety rods, or both.

A pulsed neutron generator is combined with the A-core for the purpose of injecting 14 MeV pulsed neutrons into the subcritical system through the polyethylene reflector. In some configurations, a neutron shield and a beam duct are installed in the reflector region for directing the high-energy neutrons generated in the tritium target (located outside the polyethylene reflector) to the fuel region. The deuteron beam is accelerated up to 160 keV in beam energy, 4.5 mA in beam current with a 10 μ s in pulse width and a 500 Hz pulse repetition rate. At a lower beam peak intensity of about 0.5 mA and a pulse width of up to 100 μ s, and the repetition rate can be varied from a few Hz to 30 kHz, providing up to 1×10^8 n/s.

Activation foils are located in relevant matrix positions, including (15, K) and at the tritium target (refer to Figures 1 through 8 for assembly locations) for neutron spectrum measurements. The activation foils are 45 mm $\times$ 45 mm with a thickness varying between 3 and 5 mm. Foil materials are selected to cover a range of activation energy values as wide as possible for the 14 MeV neutrons. The experimental results of the reaction rates of all irradiated activation foils are obtained by measuring the total counts of the peak energy of γ -rays emitted from specific isotopes produced by neutron capture and normalized by the counts of another irradiated foil at the location of the tritium target.

In the present calculations, only the foils contained in the 5 cm $\times$ 5 cm void region of the fuel assembly "SV" (see Section 2.3 for details) have been modeled. In the absence of specific information, no foils have been modeled at the location of the tritium target.

Figure 7. No Neutron Shield, Large Beam Duct (s) and SV Core (Series-II: Case II-3).

Figure 8. No Neutron Shield, Small Beam Duct (s') and SV Core (Series-II: Case II-4).

2.2 Calculations

The calculations performed for the KUCA benchmarks are essentially for reactivity values and indium reaction rate distributions at selected positions. Details of these calculations are presented in this section.

2.2.1 Excess Reactivity and Subcriticality

In the KUCA cores the critical state is maintained by adjusting the positions of the control rods, and the subcritical state is obtained by insertion of the control or safety rods, or both. For eigenvalue calculations, it is necessary to consider the effect of the activation foils set in the void region of the “SV” assemblies shown in Figures 6, 7 and 8.

Reactivity calculations were performed with three different control rod configurations:

1. All control and safety rods are fully withdrawn (axial rod position at $Z=120$ cm; refer to Section 2.3 for details on control and safety rods). In this document, this case is referred as the “excess reactivity” control rod configuration.
2. All safety rods are completely withdrawn and control rods C1, C2 and C3 are fully inserted (axial rod position at $Z=11.4$ cm; refer to Section 2.3 for details on control and safety rods). In this document, this case is referred as the “subcritical” control rod configuration.

3. All safety rods are completely withdrawn and the control rods are at the measured critical position as indicated in Table 1 for each configuration.

Table 1. Control Rod Position for the Critical States.

Configuration	C1 (mm)	C2 (mm)	C3 (mm)	S4-S6 (mm)
KUCA I-1	U.L. (*)	U.L.	524.34	U.L.
KUCA I-2	U.L.	U.L.	548.21	U.L.
KUCA I-3	U.L.	U.L.	745.54	U.L.
KUCA I-4	U.L.	U.L.	525.52	U.L.
KUCA II-1	U.L.	U.L.	635.94	U.L.
KUCA II-2	637.48	U.L.	U.L.	U.L.
KUCA II-3	U.L.	U.L.	742.48	U.L.
KUCA II-4	U.L.	U.L.	553.24	U.L.
(*) U.L.: Upper Limit (1200 mm)				

2.2.2 Indium Reaction Rate Distributions

Reaction rate distributions were calculated along the indium (In) wire (1.5-mm diameter and 60-cm long) that is set at the axial (vertical) position (between 16,J-W and 17,J-W) shown in Figures 1 through 8 (see details in Figure 9). The experimental results of the In wire are obtained by measuring total counts of the peak energy of γ -rays emitted from $^{115}\text{In}(n,n')^{115\text{m}}\text{In}$ reactions and normalized by the counts of another irradiated In foil ($20 \times 20 \times 1 \text{ mm}^3$) set at the location of the tritium target.

Figure 9. Location of the Indium (In) Wire.

2.3 MCNP Model

Calculations were performed using MCNP Version 5 with ENDF/B-VII.0 cross sections, plus several comparison calculations using other cross section sets. Models were developed to accurately represent each component of the fuel, control rods, safety rods and reactor structures.

The materials used in the KUCA cores are in the form of rectangular parallelepipeds, nominally 2-in. square, with thicknesses ranging between 1/16 in. and 2 in. The upper and lower parts of the fuel assemblies are polyethylene reflector layers more than 50-cm long, as shown in Figures 10 through 13. The reference fuel assemblies are formed of 2-in. x 2-in. square unit cells having one 93% enriched U-Al plate, 1/16-in. thick, and two polyethylene plates of 1/8-in. thick and 1/4-in. thick (see Figures 10 through 12). Multiple unit cells are placed together to form the core region of each assembly. In the absence of details on the axial locations, the Ni, Al, Fe and In foils used for spectrum measurements have been placed exactly at the center of the void region of the "SV" assembly (see Figure 11). The functional height of the core is approximately 40 cm. The MCNP model was developed by explicitly describing all single U-Al and polyethylene plates.

The tritium target is not located at the center of the core. To compensate for this, a neutron shield and beam duct is installed in the polyethylene radial reflector region. The main purpose of installing the neutron shield and the beam duct is to direct the largest possible number of high-energy neutrons generated in the target region to the center of the core. For shielding the high-energy and thermal neutrons, the neutron shield consists of several materials inserted into the core, as shown in Figures 14 through 17: the iron (Fe) is for shielding the high-energy neutrons generated in the target region by inelastic scattering reactions and the polyethylene containing 10 wt% boron is for shielding the thermal neutrons, moderated by scattering reactions in the reflector region. The beam duct for directing the

collimated high-energy neutrons to the core region by streaming effect is constructed as shown in Figures 13, 14, 15 and 17.

Figure 10. Sideways View of Fuel Assembly "F".

Figure 11. Sideways View of Fuel Assembly "SV" with Void.

Figure 12. Sideways View of Partial Fuel Assembly "26".

Figure 13. Description of Fuel “F”, Partial Fuel “26” and Fuel “SV” Assemblies.

Figure 14. Description of Neutron Shield and Beam Duct "b", "bs" and "bs'".

Figure 15. Description of Neutron Shield and Beam Duct "f", "fs" and "fs'".

Figure 16. Description of Neutron Shield “fp” and “bp”.

All fuel and reflector/shield rods are inserted in aluminum tubes as shown in Figures 18 and 19. These tubes are generally separated by 1-mm gap. However, referring to Figures 1 through 8, the gap separating assemblies 7-8, 13-14, 16-17, and 22-23 along the vertical direction and the gap separating assemblies F-G, I-J, and P-Q along the horizontal direction, is increased to 3 mm. These details are shown in Figure 20.

Figure 18. Description of Fuel Assembly at KUCA.

Figure 19. Description of Polyethylene (Aluminum) Reflector at KUCA.

Figure 20. Description of the Fuel Assembly, Polyethylene Reflector and Control Rod at KUCA.

According to the benchmark specifications, the control and safety rods are modeled as shown in Figure 21. Figure 22 gives a schematic representation for the specification of the control rod position. It is noted that the zero point of the measured rod position is the upper surface of the Al on the shock absorber that is 11.4 cm above the fuel assembly base.

Figure 21. Description of Control (Safety) Rod at KUCA.

Figure 22. Actual Position of Control (Safety) Rod (Actual Position = Measured Position – 11.4 cm).

2.4 Approximations, Assumptions and Missing Model

The compositions for the In wire and for the Fe parts of the assemblies f, fs, fs' and fp are missing in the benchmark report [1]. In the present calculations, these compositions are assumed to be the same as the In and Fe foils, respectively.

Compositions for the Ni foil are also missing. In the present calculations, this foil is assumed to be of pure Ni (atom density: $9.14401\text{E-}02$ at/barn-cm).

Apparently, from the benchmark specifications, all fuel and reflector assemblies (including the assemblies with the neutron shield and beam duct, such as assemblies SV, bs', fs' and s') are inserted into the aluminum tubes. By doing so, the beam duct would be obstructed by the 5-mm thick aluminum sheets that form the tube. It must be determined if any window is open in these aluminum sheets (sides of tubes) so that the beam duct would have a $5\text{ cm} \times 5\text{ cm}$ opening without any obstruction along the entire sequence of assemblies (15,U) to (15,K), and the model would be refined accordingly.

More details are needed to clarify exactly how the foils are arranged in the axial direction of the void region of assemblies "SV." Information is needed particularly on those foils at the target location that have not been modeled in the present calculations.

Since no information was provided on the assemblies containing fission chambers and UIC detectors (see Figures 1 through 8) these assemblies are assumed to be completely voided. On the other hand, assembly "N", that is apparently associated with a "neutron source" (see legends of Figures 1 through 8), has been simply replaced by polyethylene reflector. The assumptions made for the assemblies mentioned above should have zero or negligible impact on the calculated results.

The representation of the partial fuel assemblies can be based on the example of Assembly "26" given in the benchmark specifications as shown in Figure 12. However, for partial fuel assemblies with a number of fuel cells other than 26, it is not clear if one has to preserve the number of Al cells or the length of the polyethylene blocks above and below the fuel region. In the present calculations, the length of the polyethylene blocks was preserved. See for instance Figure 23 for the assumed representation of Assembly "12".

Figure 23. Adopted Representation of Assembly "12".

2.5 Calculation Results

This section presents the results of the present calculations for reactivity values and indium reaction rate distributions. Additional calculations were carried out for the analysis of the source multiplication factor, k_s , of the KUCA cores.

2.5.1 Excess Reactivity and Subcriticality

The reactivity values obtained for each configuration and for the rod positions described in Section 2.2.1 are presented in Table 2 together with the experimental results.

Table 2. Calculated and Measured Reactivity Values [pcm].

Configuration	Rod Configuration	Experiment	MCNP5*
KUCA I-1	Excess Reactivity	$+295 \pm 21$	746 ± 8
	Subcriticality	-904 ± 63	-371 ± 8
	Critical	$0 \pm$	446 ± 8
KUCA I-2	Excess Reactivity	$+293 \pm 21$	695 ± 6
	Subcriticality	-925 ± 65	-415 ± 6
	Critical	$0 \pm$	422 ± 6
KUCA I-3	Excess Reactivity	$+20 \pm 1$	445 ± 6
	Subcriticality	-1171 ± 82	-616 ± 6
	Critical	$0 \pm$	396 ± 6
KUCA I-4	Excess Reactivity	$+296 \pm 21$	746 ± 6
	Subcriticality	-907 ± 63	-368 ± 6
	Critical	$0 \pm$	441 ± 6
KUCA II-1	Excess Reactivity	143 ± 10	776 ± 6
	Subcriticality	-793 ± 56	-42 ± 6
	Critical	$0 \pm$	641 ± 6
KUCA II-2	Excess Reactivity	246 ± 17	856 ± 6
	Subcriticality	-677 ± 47	-18 ± 6
	Critical	$0 \pm$	595 ± 6
KUCA II-3	Excess Reactivity	37 ± 3	564 ± 6
	Subcriticality	-893 ± 63	-343 ± 6
	Critical	$0 \pm$	507 ± 6
KUCA II-4	Excess Reactivity	232 ± 16	934 ± 6
	Subcriticality	-702 ± 49	48 ± 6
	Critical	$0 \pm$	714 ± 6
*Calculated with ENDF/B-VII.0 data.			

There is a consistent discrepancy of approximately 400 - 500 pcm between the calculated and experimental results for all KUCA configurations from Series I and of approximately 500 - 700 pcm for all KUCA configurations from Series II. It is however important to emphasize the fact that the foils located in the void region of the fuel assemblies “SV” of the KUCA configurations II-2, II-3 and II-4 have a reactivity effect of about 800 pcm.

In an attempt to investigate the observed discrepancies in the reactivity values, calculations were also performed with different data libraries. As shown in Table 3, for the KUCA I-1 “excess reactivity” configuration (all control and safety rods fully withdrawn) the use of JEF3.1 and ENDF/B-VI.6 data lead to about the same results obtained with the ENDF/B-VII.0 library. Only with ENDF/B-VI.0 data is the obtained reactivity value about 200 pcm smaller than with the other libraries, reducing the discrepancy with the measured value to about 300 pcm. From these results it is concluded that the use of different nuclear data libraries would not have a significant impact on the discrepancies observed in Table 2 between the calculated and experimental results.

Note that ENDF/B-VII.0 data were used for all subsequent calculation results discussed in this report.

Table 3. Impact of Nuclear Data on Calculated Reactivity Values [pcm] for the KUCA I-1 Excess Reactivity Rod Configuration.

Cross Section Set	Experiment	MCNP5
ENDF/B-VII.0	$+295 \pm 21$	746 ± 8
ENDF/B-VI.6		766 ± 5
ENDF/B-VI.0		589 ± 6
JEF3.1		799 ± 6

2.5.2 Indium Reaction Rate Distributions

According to the benchmark specifications, indium reaction rate distributions were calculated along the indium wire located at the core midplane between columns 16-17 from rows J-W with a (d,t) source at the tritium target location. Figure 24 shows the exact locations between columns 16 and 17 where the reaction rates were obtained.

The reaction rate distributions were calculated for the “subcritical” control rod configuration (all control rods C1, C2 and C3 fully inserted and the safety rods completely withdrawn). For the configuration KUCA II-4 the source calculation was not possible, since even full insertion of control rods C1, C2 and C3 does not bring the calculated reactivity to a negative value (subcritical state).

For the calculation of the indium reaction rate distributions, the (d,t) neutron source was represented in the MCNP model as a 14 MeV neutron source that was uniformly distributed inside a cylinder of 2.25 cm radius and 0.30 cm height, at the location of the tritium target shown in the layouts of the KUCA configurations.

For both the Series I and II configurations, the calculated indium reaction rate distributions show a similar trend with respect to the measured ones, particularly in the fuel zone (see Figures 25 through 28). In the reflector/shield region the calculations show a depression in the distributions that in some cases is not seen in the measurements and that requires further investigations.

Figure 24. Indium Wire Location (16-17, J-W).

Figure 25. Calculated Indium Absorption Rate Distributions (Case I-1 to Case I-4) in MCNP Units: Rate per One Neutron and One Target Atom $\times 10^{-24}/\text{cm}^3$.

Figure 26. Measured Indium Wire Reaction Rate Distributions along the Vertical Direction Shown in Figures (Case I-1 to Case I-4).

Figure 27. Calculated Indium Absorption Rate Distributions (Case II-1 to Case II-4) in MCNP Units: Rate per One Neutron and One Target Atom $\times 10^{-24}/\text{cm}^3$.

Figure 28. Measured Indium Wire Reaction Rate Distributions along the Vertical Direction Shown in Figures (Case II-1 to Case II-4).

2.5.3 Source Multiplication Factor

The source multiplication factor, k_s , is commonly introduced in source driven systems to quantify the capability of the subcritical core to multiply the external source neutrons, dependent on the efficiency of the source itself. The source multiplication factor is defined as:

$$k_s = \frac{F\Phi_s}{A\Phi_s - P_{n,2n}} = \frac{F\Phi_s}{F\Phi_s + S}$$

where F is the multiplication factor, A is the loss factor (absorption plus leakage), $P_{n,2n}$ is the neutron production by (n,2n) reactions, S is the external source and Φ_s is the “source driven” flux solution of the inhomogeneous equation:

$$A\Phi_s = F\Phi_s + S + P_{n,2n}.$$

The source multiplication factor is not to be confused with k_{eff} (the multiplication factor) which is the eigenvalue of the homogeneous (source-free) equation:

$$A\Phi_0 = \frac{1}{K_{eff}} F\Phi_0$$

Table 4 shows the source multiplication factors and eigenvalues obtained for all Series I and II KUCA configurations. The amplitude of the calculated indium rate distributions is proportional to the k_s values of the different KUCA configurations; i.e., larger k_s values lead to rate distributions with larger amplitude.

Table 4. Calculated Source Multiplication Factors and Eigenvalues.

Configuration	k_{eff}	k_s
KUCA I-1	0.99630	0.83314
KUCA I-2	0.99587	0.84010
KUCA I-3	0.99388	0.86137
KUCA I-4	0.99633	0.77988
KUCA II-1	0.99958	0.93974
KUCA II-2	0.99982	0.97684
KUCA II-3	0.99658	0.90560
KUCA II-4	-	-

3. CONVERSION OF THE KUCA CORES FROM HEU TO LEU

This section describes the studies that were performed at Argonne to evaluate the feasibility of converting the KUCA assemblies to the use of LEU, using either U-Al alloy or U-10Mo fuel. Results presented in this section were partly included in Ref. 2.

The application of the U-Al alloy LEU fuel was modeled for the conversion of the KUCA I-1 to I-4 configurations that are described in the benchmark report. Conversion studies with U-10Mo fuel were initially performed for the KUCA I-1 configuration and then for other KUCA assemblies characterized by a large range of moderator-to-fuel volume ratios or hydrogen-to-U235 atom ratios in the core.

In addition to a comparison of the reactivity values, the conversion from HEU to LEU was investigated through the analysis of flux spectra in relevant locations.

3.1 Use of LEU U-Al Alloy Fuel

Calculations were initially performed for the conversion of the KUCA I-1 configuration from HEU to LEU. For this purpose, a few fuel assemblies were added to the core region as shown in Figure 29 and the uranium enrichment of the U-Al alloy plates was reduced from 93% to 19.75%, which is typically used as reference value for LEU in experimental facilities.

Figure 29. KUCA Configuration Series-I, Case I-1 with Additional Fuel Assemblies Using U-Al LEU Fuel.

The calculated multiplication factor for this LEU configuration is as low as 0.63097 with a typical U-Al density (see Table 6). It was found that for the same configuration, the uranium enrichment would need to be increased to 50% to obtain a multiplication factor of 0.92280. From the results it is obvious that the conversion of the KUCA I-1 configuration from high- to low-enriched uranium using U-Al alloy fuel would be possible only by increasing the thickness of the uranium fuel plates or by adding fuel assemblies to the core boundary or both. A series of calculations was performed to evaluate these options. No assumption was made on the constraints related to the availability of the needed materials.

As first step, the thickness of the U-Al plates in the fuel assemblies was increased from 1/16 in. to 3/16 in. This increase in thickness was achieved by replacing the 1/8-in. thick polyethylene plate of the fuel unit cell (see Figure 10) by a U-Al plate of the same thickness. The LEU U-Al fuel plates retain the same material properties as the HEU U-Al alloy, only the enrichment is reduced from 93% to 19.75%.

Calculations were performed for all KUCA series I configurations and to obtain reasonable k_{eff} values, 56 LEU fuel assemblies were added as shown in Figures 30 through 33. To ensure adequate reflection, a number of polyethylene assemblies were also added. These configurations will be referred as KUCA I-1+56, KUCA I-2+56, KUCA I-3+56 and KUCA I-4+56.

Figure 30. KUCA Configuration Series-I, Case I-1 after Adding 56 Fuel Assemblies (KUCA I-1+56).

Figure 31. Configuration Series-I, Case I-2 after Adding 56 Fuel Assemblies (KUCA I-2+56).

Figure 32. KUCA Configuration Series-I, Case I-3 after Adding 56 Fuel Assemblies (KUCA I-3+56).

Figure 33. KUCA Configuration Series-I, Case I-4 after Adding 56 Fuel Assemblies (KUCA I-1+56).

3.1.1 Reactivity Calculations

For the KUCA cores presented in Figures 30 to 33, the calculated reactivity values for both the “excess reactivity” (control rods and safety rods completely out) and “subcritical” (control rods fully inserted, safety rods completely withdrawn) rod configurations are presented in Table 5.

Table 5. Calculated Reactivity [pcm] for the LEU U-Al Configurations.

Configuration	Rod configuration	MCNP5
KUCA I-1+56	Excess Reactivity	678 ± 6
	Subcriticality	-2857 ± 6
KUCA I-2+56	Excess Reactivity	636 ± 5
	Subcriticality	-2891 ± 6
KUCA I-3+56	Excess Reactivity	351 ± 5
	Subcriticality	-3134 ± 6
KUCA I-4+56	Excess Reactivity	663 ± 6
	Subcriticality	-2870 ± 6

3.1.2 Flux Spectra Calculations

For the same configurations with U-Al LEU fuel described in Table 5, flux spectra were calculated at selected positions. Specifically, flux spectra were determined in 53 energy groups at position A, (X,Y)=(8.395 cm,-2.6 cm), along the indium wire (see Section 2.2.2 for details) and at position B, in the fuel plate of assembly (14,K) that is closest to the core midplane.

Calculations were performed in the subcritical control rod configuration. As shown in Figures 34 through 41, the flux energy distributions in the core region show two peaks, one at high energy around 2 MeV and the other at lower energies around 0.1 eV.

Figures 35, 37, 39 and 41 show the comparison of the flux spectra calculated in the same position B for the high- and low-enriched uranium configurations. It is observed that using low enriched uranium the peak at high energy decreases. This spectrum change is caused by the change in H/U ratio in the core and it is not due to the use of LEU fuel. Generally, the use of LEU results in hardening the neutron spectrum due to increased absorption by U238.

Figure 34. Flux Spectra at the Positions A and B of KUCA I-1+56 with U-Al LEU Fuel.

Figure 35. Flux Spectra at the Position B of KUCA I-1 HEU and KUCA I-1+56 with U-Al LEU Fuel.

Figure 36. Flux Spectra at the Positions A and B of KUCA I-2+56 with U-Al LEU Fuel.

Figure 37 Flux Spectra at the Position B of KUCA I-2 HEU and KUCA I-2+56 with U-Al LEU Fuel.

Figure 38. Flux Spectra at the Positions A and B of KUCA I-3+56 with U-Al LEU Fuel.

Figure 39. Flux Spectra at the Position B of KUCA I-3 HEU and KUCA I-3+56 with U-Al LEU Fuel.

Figure 40. Flux Spectra at the Positions A and B of KUCA I-4+56 with U-Al LEU Fuel.

Figure 41. Flux Spectra at the Position B of KUCA I-4 HEU and KUCA I-4+56 with U-Al LEU Fuel.

3.2 Use of LEU U-10Mo Fuel

From the previous section it is concluded that reducing the uranium enrichment of the U-Al alloy fuel plates from 93% to 19.75% gives reasonable values for the multiplication factor only by increasing the thickness of the fuel plates and the number of fuel assemblies. Obviously, use of high density fuel materials such as U-10Mo LEU fuel can reduce the required fuel plate inventory and critical core volume, but can also significantly change the core spectrum and other core characteristics.

Table 6 shows the number densities of U-Al and U-10Mo fuel with 19.75% uranium enrichment in both cases. For comparison, the HEU (93% enrichment) U-Al fuel compositions are also presented in Table 6. For the LEU fuel, it can be seen that the U-235 number density is ~20 times larger in the case of the U-10Mo plates.

Use of U-10Mo fuel plates was investigated for the KUCA I-1 configuration. As a first attempt, a calculation was performed by just replacing the 93% enriched U-Al plate by a 19.75% enriched U-10Mo plate. The thickness of fuel and polyethylene plates remains as shown in Figure 10.

Table 6. Number Densities [at/(barn × cm)] of High Enriched (93%) U-Al, Low Enriched (19.75%) U-Al and U-10Mo Fuel and Aluminum Clad.

HEU U-Al		LEU U-Al		LEU U-10Mo		Aluminum Clad	
U235	1.50694E-03	U235	3.19061E-04	U234	1.02479E-04	Al27	6.02626E-2
U238	1.08560E-04	U238	1.29644E-03	U235	7.75124E-03	B10	5.98593E-7
Al27	5.56436E-02	Al27	5.56436E-02	U236	1.79769E-04	B11	2.40941E-6
SUM	5.72591E-02	SUM	5.72591E-02	U238	3.08187E-02		
				Mo92	1.58542E-03		
				Mo94	9.88218E-04		
				Mo95	1.70080E-03		
				Mo96	1.78200E-03		
				Mo97	1.02027E-03		
				Mo98	2.57791E-03		
				Mo100	1.02881E-03		
				SUM	4.95356E-02		

As expected, the calculated reactivity value with the “subcritical” rod configuration (all safety rods completely withdrawn and control rods C1, C2 and C3 fully inserted) increased from -371 ± 8 pcm (high-enriched U-Al case) to 12341 ± 7 pcm (low-enriched U-10Mo case) indicating that the use of nominal density U-10Mo plates would keep the LEU core subcritical only by significantly reducing the thickness of the fuel plates or the number of fuel assemblies. Given these options, the thickness of the U-10Mo plates was reduced so that the U-235 mass in the fuel plate remains the same as the U-Al HEU plate. Since the XY dimensions of the plate are the same in both HEU and LEU assemblies, the thickness is changed according to the ratio of the U235 densities in the HEU and LEU configurations:

$$thickness_LEU = \frac{density_HEU}{density_LEU} \times thickness_HEU = \frac{1.50694E-03}{7.75124E-03} \times 0.1587 = 0.0309 \text{ cm}$$

Two separate approaches were used for the arrangement of the U-10Mo foils.

For the first approach, no cladding is used for the U-10Mo foils. In order to preserve the total extension (i.e. 1.0973 cm) of the fuel unit cell, the thickness of the first polyethylene plate in the unit cell was increased from 0.3086 cm to 0.4364 cm as shown in Figure 42.

The option to add Al clad to the U-10Mo foils was then considered in a separate approach (see Table 6 for the compositions of the aluminum clad used for the present studies; this composition is representative of the Al used for other U-10Mo LEU foils and contains a concentration of 20 ppm boron). In this case, the thickness of the U-10Mo plates is always fixed so that the U-235 mass in the fuel plate remains the same of the U-Al HEU core. However, with respect to the previous approach the thickness of the cladding plates is determined so that the thickness of the polyethylene plates also remains the same as in the U-Al HEU core (see Figure 43).

Figure 42. Sideways View of Fuel Assembly “F” Using LEU U-10Mo Plates without Al Clad.

Figure 43. Sideways View of Fuel Assembly “F” Using LEU U-10Mo Plates with Al Clad.

3.2.1 Reactivity Calculations

For both LEU U-10Mo KUCA I-1 configurations discussed above, calculations were performed in both “excess reactivity” and “subcritical” rod configurations. Calculated reactivity values are presented in Table 7. For comparison, the reactivity of the HEU core is also given in Table 7. It is observed that by preserving the U235 mass, the LEU U-10Mo configuration gives smaller reactivity values due to the increased H/U volume ratio. Additionally, the use of Al clad has a negative reactivity effect of about 4000 pcm.

Table 7. Calculated and Measured Reactivity (pcm, using ENDF/B-VII.0 Data).

Configuration	Rod Configuration	LEU U-10Mo Plate – No Clad	LEU U-10Mo Plate – With Clad	HEU U-Al Plate
KUCA I-1	Excess Reactivity	98 ± 6	-3629 ± 6	746 ± 8
	Subcritical	-792 ± 6	-4782 ± 6	-371 ± 8

3.2.2 Flux Spectra Calculations

Flux spectra were determined in 53 energy groups for the KUCA I-1 configurations using LEU U-10Mo fuel with and without Al clad. Calculations were performed with the “subcritical” control rod configuration characterized by the safety rods completely withdrawn and the control rods C1, C2 and C3 fully inserted.

Particularly, flux spectra were determined at position A, (X,Y)=(8.395 cm; -2.6 cm), along the indium wire (see Section 2.2.2 for details) and in position B, in the fuel plate of the assembly (14,K) that is closest to the core midplane. Results are presented in Figures 44 and 45 for the two cases without and with Al cladding, respectively. Similar to the previous KUCA configurations that have already been analyzed, flux energy distributions in the core region show two peaks, one at high energy around 2 MeV and the other at lower energies around 0.1 eV. In both cases, with or without Al clad, the flux spectra in position B show enhanced peaks at 2 MeV and 0.1 eV and a decreased distribution in the range 3 - 300 eV with respect to the neutron spectrum at position A.

Figure 46 shows the comparison of the flux spectra calculated in position B in the HEU and in the three LEU configurations, using U-Al plates (with 56 additional fuel assemblies) and U-10Mo plates with and without cladding. It is observed that the configuration using LEU U-Al fuel shows a smaller peak at 2 MeV but an enhanced distribution in the range 3 - 300 eV with respect to the other configurations. On the other hand, the LEU configuration using U-10Mo plates and Al cladding shows a smaller peak at 0.1 eV.

Figure 44. Flux Spectra at Positions A and B of KUCA I-1 with LEU U-10Mo and No Cladding.

Figure 45. Flux Spectra at Positions A and B of KUCA I-1 with LEU U-10Mo and Al Cladding.

Figure 46. Flux Spectra at Position B of HEU and LEU KUCA I-1 Configurations.

3.3 Feasibility Studies on the Conversion of KUCA Type-A Cores with Different Moderator-to-Fuel Volume Ratios in the Unit Cell

As requested by the KURRI experimentalist team, feasibility studies were performed for five “type-A” KUCA cores designated A3/8”P36EU, B2/8”P48EU, B1/8”P80EU, B1/8”P60EU-EU and B1/8”P48EU-EU-EU, which are characterized by different moderator-to-fuel volume ratios (V_m/V_f) and different H-to-U235 atom ratios (H/U5) in the fuel unit cell. In these designators, the fractional value (e.g., 1/8”) specifies the thickness of the polyethylene in the unit cell; the “P” value indicates the number of times the unit cell is repeated in the core region of the assembly (e.g., P80); and the number of times “EU” is repeated indicates the number of uranium plates in the unit cell. Results of this section were partly included in Ref. 3.

Summary descriptions of the cores of the proposed configurations were provided by KURRI. The received documentation contained pictures of the core layouts (core only, without surrounding polyethylene reflector) and fuel assemblies.

Figure 47 shows the core layouts, while Figures 48 through 52 show the cross-sectional views of the fuel assemblies and unit cells. From the first to the last configuration the V_m/V_f ratio (and consequently the H/U5 atom ratio) decreases by a factor of about 10.

Figure 47. Layouts of the Investigated KUCA cores.

P: Polyethylene Plate

EU: EU Plate

Figure 48. Cross Sectional View of KUCA Fuel Assembly A3/8''P36EU - ($V_m/V_f = 5.91$
H/U5 = 316.45).

P: Polyethylene Plate

EU: EU Plate

Figure 49. Cross Sectional View of KUCA Fuel Assembly B2/8''P48EU - ($V_m/V_f = 3.89$
H/U5 = 206.96).

P: Polyethylene Plate

EU: EU Plate

Figure 50. Cross Sectional View of KUCA Fuel Assembly B1/8''P80EU - ($V_m/V_f = 1.94$
H/U5 = 103.48).

Figure 51. Cross Sectional View of KUCA Fuel Assembly B1/8''P60EU-EU - ($V_m/V_f = 0.97$
H/U5 = 51.74).

Figure 52. Cross Sectional View of KUCA Fuel Assembly B1/8''P48EU-EU-EU - ($V_m/V_f = 0.65$
H/U5 = 34.49).

In the absence of additional details, a number of assumptions had to be made in order to perform calculations of the proposed configurations. Specifically, the following assumptions were made:

1. As mentioned above, information on the external boundary of the polyethylene reflector surrounding the core of all proposed configurations was not provided. Thus, the reflector boundary was kept as in the KUCA I-1 configuration of the benchmark report (see Figure 53 for the case of the KUCA A3/8''P36EU configuration). By doing so, some KUCA configurations have more polyethylene reflector assemblies than others (i.e. the reflector dimension is not consistent among the configurations analyzed).
2. The compositions of all materials employed (1/16'' EU plates, 1/2'', 1/4'' and 1/8'' polyethylene plates, polyethylene blocks, control and safety rods, aluminum tubes) were also taken from the KUCA benchmark specifications. It is noted that in the benchmark specifications, the compositions of the 1/16'' EU plates have no impurities (see Table 6).

3. The three control rods and the three safety rods were also modeled according to the benchmark specifications. Additionally, in the absence of any indication of the control rod position, calculations were performed for the two states that were considered in the benchmark report, i.e. the “excess reactivity” rod configuration with all control and safety rods completely withdrawn and the “subcritical” rod configuration with all safety rods completely withdrawn and control rods C1, C2 and C3 fully inserted.
4. The documentation provided by KURRI for the KUCA A3/8’’P36EU, B2/8’’P48EU, B1/8’’P80EU, B1/8’’P60EU-EU and B1/8’’P48EU-EU-EU configurations include a table with the experimental reactivity values. Since no indication was found, it is assumed that those reactivity values were obtained in the “excess reactivity” rod configuration.
5. The gaps between the assemblies for flux wire arrangements were also kept as described in the KUCA benchmark report. Additionally, the indium wire located at the core midplane between the assemblies (16,17–J,W) was kept in the present KUCA configurations as well.

Certainly, the changes that the actual configurations would imply for reflector boundary, material compositions, assembly gaps, etc., can be considered of negligible interest for the scope of the present studies on the feasibility of the conversion of the KUCA cores from high- to low-enriched uranium. However, for a better comparison of experimental and calculated k_{eff} values, the following additional information would be needed:

1. Exact position of control and safety rods for the determination of the measured k_{eff} values;
2. Detailed description of non uniform gaps for flux wires;
3. Impurities of the HEU plates.

Then, for the feasibility studies on the conversion of the proposed KUCA cores from HEU to LEU it would be advisable to know if there are any constraints on the LEU fuel to be used (fuel type, dimension of the plates, material inventory, etc.). For the present analysis, the LEU KUCA cores were loaded with U-10Mo foils (see Section 3.3.1. for more details).

The feasibility studies on the conversion of the proposed KUCA cores from HEU to LEU included analysis of the flux spectra. In this case it was not known if there are any specifications or preferences by the KUCA team on the exact position where flux spectra should be tallied and which group structure is to be used. For the present work, flux spectra were obtained in 53 energy groups and in the positions described in Section 3.3.3.

Figure 53. KUCA A3/8''P36EU: Detail of Reflector Layout Kept the Same for all Configurations.

3.3.1 Approaches Used for the Conversion from HEU to LEU

For the conversion of the proposed KUCA cores from HEU to LEU, each 1/16-in. HEU plate was replaced with a single LEU foil of U-10Mo clad by aluminum on both sides (see Case A in Figure 54). All polyethylene plates remain exactly the same as the HEU configuration. In a more sophisticated approach, one may also consider having an aluminum edge all around the LEU foil in order to prevent cracking (see Case B in Figure 54). Concerning the dimensions, it seems there are no constraints officially imposed by the fabricators, however it was assumed that the thickness of both the U-10Mo foil and Al clad cannot be less than 10 mils. Less well defined are the recommendations on the width of the aluminum edge that was fixed to a minimum of 100 mils for the present study. The compositions that were used for the U-10Mo foils and aluminum clad are the same as those given in Table 6.

Figure 54. HEU and U-10Mo LEU fuel plate.

3.3.2 Reactivity Calculations

The arrangements of both cases A and B were considered. All control and safety rods were assumed to be fully withdrawn (“excess reactivity” rod configuration).

The goal of the study was to determine the dimensions of the U-10Mo foils necessary to keep the same reactivity as the corresponding HEU configuration. For this purpose, the reactivity of the LEU configurations was first determined with conditions of maximum fuel loading, i.e., the thickness of the Al clad is reduced to the minimum allowed (10 mils), and consequently the thickness of the U-10Mo foils is fixed to the maximum value of 42.5 mils, so that the total extension of 1/16 in.’ (i.e., 62.5 mils) of the HEU fuel plate being replaced is preserved. Calculations were performed with no aluminum edge (condition of maximum loading in Case A described above) and with an aluminum edge of 100 mils (condition of maximum loading in the Case B described above). The results obtained using MCNP5 and ENDF/B-VII.0 data are presented in Table 8 for each configuration. For comparison, the reactivity values (both calculated and measured) of the corresponding HEU configurations are also presented in Table 8.

It can be seen that for the KUCA A3/8’’P36EU and B2/8’’P48EU max-loading configurations with and without the aluminum edge, the multiplication factor (k_{eff}) values obtained in the LEU case are larger than the k_{eff} values obtained in the HEU cases, as would be desirable. An excess reactivity, in fact, would allow one to reduce the thickness of the U-10Mo foils in order to get the same k_{eff} as the HEU configuration and eventually would also leave the option to adjust the dimensions of the U-10Mo foil for the purpose of improving other neutronic features, such as the neutron spectra, etc.

Table 8. Calculated (Experimental) Multiplication Factor Values of HEU and U-10Mo LEU KUCA Configurations.

Configuration	Loading Type	Plate Dimensions (mils); V_m/V_f ; H/U5	k_{eff} : Calculation (Experiment)
KUCA A3/8''P36EU	HEU	$T=62.5$; $V_m/V_f=5.91$; $H/U5=316.45$	1.00402 ± 0.00006 (1.0008)
	LEU no Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=0$ $V_m/V_f=8.69$ $H/U5=90.47$	1.10934 ± 0.00007
	LEU no Al Edge: same H/U5 as HEU	$T_{LEU}=12.15$; $T_{Al}=21.17$; $E_{Al}=0$ $V_m/V_f=30.41$ $H/U5=316.45$	0.96027 ± 0.00006
	LEU no Al Edge: ~same k_{eff} as HEU	$T_{LEU}=16$; $T_{Al}=23.25$; $E_{Al}=0$ $V_m/V_f=23.10$ $H/U5=240.32$	1.00585 ± 0.00006
	LEU with Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=100$ $V_m/V_f=10.73$; $H/U5=111.70$	1.07876 ± 0.00007
	LEU with Al Edge: ~same k_{eff} as HEU	$T_{LEU}=22$; $T_{Al}=20.25$; $E_{Al}=100$ $V_m/V_f=20.74$; $H/U5=215.78$	1.00640 ± 0.00006
KUCA B2/8''P48EU	HEU	$T=62.5$; $V_m/V_f=3.89$; $H/U5=206.96$	0.99769 ± 0.00006 (1.0010)
	LEU no Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=0$ $V_m/V_f=5.72$; $H/U5=59.17$	1.05199 ± 0.00007
	LEU no Al Edge: same H/U5 as HEU	$T_{LEU}=12.15$; $T_{Al}=21.17$; $E_{Al}=0$ $V_m/V_f=20.00$; $H/U5=206.96$	0.94585 ± 0.00006
	LEU no Al Edge: ~same k_{eff} as HEU	$T_{LEU}=19$; $T_{Al}=21.75$; $E_{Al}=0$ $V_m/V_f=12.79$; $H/U5=132.35$	0.99706 ± 0.00006
	LEU with Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=100$ $V_m/V_f=7.06$; $H/U5=73.05$	1.02899 ± 0.00007
	LEU with Al Edge: ~same k_{eff} as HEU	$T_{LEU}=28$; $T_{Al}=17.25$; $E_{Al}=100$ $V_m/V_f=10.71$; $H/U5=110.88$	0.99958 ± 0.00007
KUCA B1/8''P80EU	HEU	$T=62.5$; $V_m/V_f=1.94$; $H/U5=103.48$	0.99882 ± 0.00007 (1.0015)
	LEU no Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=0$ $V_m/V_f=2.86$; $H/U5=29.58$	0.99611 ± 0.00007
	LEU no Al Edge: same H/U5 as HEU	$T_{LEU}=12.15$; $T_{Al}=21.17$; $E_{Al}=0$ $V_m/V_f=10.00$; $H/U5=103.48$	0.93177 ± 0.00007
	LEU with Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=100$ $V_m/V_f=3.53$; $H/U5=36.52$	0.97932 ± 0.00007
KUCA B1/8''P60EU-EU	HEU	$T=62.5$; $V_m/V_f=0.97$; $H/U5=51.74$	1.00020 ± 0.00007 (1.0010)
	LEU no Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=0$ $V_m/V_f=1.43$; $H/U5=14.79$	0.99348 ± 0.00006
	LEU no Al Edge: same H/U5 as HEU	$T_{LEU}=12.15$; $T_{Al}=21.17$; $E_{Al}=0$ $V_m/V_f=5.00$ $H/U5=51.74$	0.92730 ± 0.00007
	LEU with Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=100$ $V_m/V_f=1.76$; $H/U5=18.26$	0.97635 ± 0.00006
KUCA B1/8''P48EU-EU-EU	HEU	$T=62.5$; $V_m/V_f=0.65$; $H/U5=34.49$	1.00114 ± 0.00007 (1.0015)
	LEU no Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=0$ $V_m/V_f=0.95$; $H/U5=9.86$	1.00863 ± 0.00005
	LEU no Al Edge: same H/U5 as HEU	$T_{LEU}=12.15$; $T_{Al}=21.17$; $E_{Al}=0$ $V_m/V_f=3.33$; $H/U5=34.49$	0.92533 ± 0.00006
	LEU with Al Edge: max loading	$T_{LEU}=42.5$; $T_{Al}=10$; $E_{Al}=100$ $V_m/V_f=1.18$; $H/U5=12.17$	0.98812 ± 0.00006

In Table 8, it can be also noted that the multiplication factor values of the LEU configurations relative to the values of the corresponding HEU cores decrease sharply with decreasing V_m/V_f or $H/U5$.

In particular, in the case of no aluminum edge, calculations have been performed for a specific thickness of the U-10Mo foils that preserves the same $H/U5$ as the corresponding HEU configuration. It can be seen that for KUCA A3/8''P36EU (high $H/U5$) the k_{eff} obtained in the LEU case is 4000 pcm less than the calculated value in the HEU case due to a combination of effects, including harder spectrum, shielding effects in the U-10Mo foil and absorption in the aluminum clad. Reducing the $H/U5$ ratio makes these effects become more and more relevant. For the configuration of lowest $H/U5$, i.e., KUCA B1/8''P48EU-EU-EU, the k_{eff} obtained in the LEU case is ~8000 pcm less than the calculated value in the HEU case. For this reason, as it can be seen in Table 8, for the LEU configurations with low $H/U5$ (i.e., KUCA B1/8''P80EU, B1/8''P60EU-EU and B1/8''P48EU-EU-EU), only the conditions of maximum loading without the aluminum edge would assure a reactivity value more or less comparable to that of the corresponding HEU cores.

However, for these configurations different solutions could be envisaged so that the desired k_{eff} in the LEU cases can be achieved with U-10Mo foil dimensions that are smaller than the maximum allowed. As an example, one may consider adding some fuel assemblies at the core boundary. Or, as in the case of KUCA B1/8''P60EU-EU and B1/8''P48EU-EU-EU, adjacent LEU plates could be merged into a single plate, eliminating the need for some of the Al cladding. As an example, Table 9 shows the k_{eff} results for KUCA B1/8''P80EU after the addition of two fuel assemblies and for KUCA B1/8''P60EU-EU and B1/8''P48EU-EU-EU after merging the adjacent 1/16-in. LEU plates according to the scheme illustrated in Figure 55.

Figure 55. Alternative LEU Fuel Loading for KUCA B1/8''P60EU-EU and B1/8''P48EU-EU-EU.

In the studies discussed so far on the conversion feasibility of the five selected KUCA configurations from HEU to LEU, all control and safety rods were assumed to be fully withdrawn ("excess reactivity" rod configuration). Calculations have been also performed for the "subcritical" control rod configuration (control rods fully inserted and safety rods completely withdrawn), in order to investigate any change of the control rod worth between the HEU and LEU cases.

Table 9. Calculated Multiplication Factor Values of U-10Mo LEU KUCA Configurations.

Configuration	Loading Type	k_{eff} Calculation
KUCA B1/8''P80EU	LEU no Al Edge, 2 assemblies added: max loading	1.01129 ± 0.00007
	LEU with 100 mils Al Edge, 2 assemblies added: max loading	0.99579 ± 0.00007
KUCA B1/8''P60EU-EU	LEU no Al Edge, merging 2 LEU plates in 1: max loading	1.01020 ± 0.00006
	LEU with 100 mils Al Edge, merging 2 LEU plates in 1: max loading	0.99159 ± 0.00006
KUCA B1/8''P48EU-EU-EU	LEU no Al Edge, merging 3 LEU plates in 2: max loading	1.02424 ± 0.00006
	LEU with 100 mils Al Edge merging 3 LEU plates in 2: max loading	1.00221 ± 0.00006

The fourth column of Table 10 shows the results that were obtained for the “excess reactivity” rod configuration for the HEU cores and the LEU cores where the thickness of the U-10Mo foils was optimized to give a k_{eff} comparable to that of the corresponding HEU cases.

For both HEU and LEU configurations, the fifth column of Table 10 shows the multiplication factor values obtained in the “subcritical” control rod configuration. Finally, the sixth column of Table 10, obtained from the difference of the multiplication factor values in the “excess reactivity” and “subcritical” rod configurations, gives for each KUCA core an indication of the reactivity change resulting from the insertion of the three control rods used in KUCA.

It can be seen that the control rod worth in the LEU cores is smaller than that obtained in the corresponding HEU cores. This result was expected due to the harder spectrum of the LEU configurations with respect to the HEU configurations. However, in Table 10 it can be also noted that this difference in the reactivity worths between the HEU and LEU cases increases remarkably when going to configurations with low moderator-to-fuel volume ratios. For instance, for the A3/8''P36EU configuration the difference in the reactivity worth between the HEU and LEU cores is ~100 and ~200 pcm without and with the use of the aluminum edge in the LEU case, respectively. On the contrary, for the P1/8''P48EU-EU-EU configuration the difference in the reactivity worth between the HEU and LEU cores is ~600 and ~500 pcm without and with the use of the aluminum edge in the LEU case, respectively.

Similarly, Table 11 compares the k_{eff} values of “excess reactivity” and “subcritical” control rod configurations obtained for the alternative loadings of the LEU configurations with low H/U5 (i.e., KUCA B1/8''P80EU, B1/8''P60EU-EU and B1/8''P48EU-EU-EU) that were presented in Table 9.

Table 10. Calculated Multiplication Factor Values of HEU and LEU KUCA Cores in Reactivity Excess and Subcritical Rod Configuration.

Configuration	Loading Type	Plate Dimensions (mils); V_m/V_f ; H/U5	Excess Reactivity Rod Configuration k_{eff} : Calculation	Subcritical Rod Configuration k_{eff} : Calculation	Δk_{eff}
KUCA A3/8''P36EU	HEU	T=62.5; $V_m/V_f=5.91$; H/U5=316.45	1.00402 ± 0.00006	0.98522 ± 0.00006	0.01880
	LEU no Al Edge: ~same k_{eff} as HEU	$T_{LEU} = 16$; $T_{Al} = 23.25$; $E_{Al} = 0$ $V_m/V_f=23.10$ H/U5 =240.32	1.00585 ± 0.00006	0.98821 ± 0.00006	0.01764
	LEU with Al Edge: ~same k_{eff} as HEU	$T_{LEU} = 22$; $T_{Al} = 20.25$; $E_{Al} = 100$ $V_m/V_f=20.74$; H/U5 =215.78	1.00640 ± 0.00006	0.98951 ± 0.00006	0.01689
KUCA B2/8''P48EU	HEU	T=62.5; $V_m/V_f=3.89$; H/U5=206.96	0.99769 ± 0.00006	0.98254 ± 0.00006	0.01515
	LEU no Al Edge: ~same k_{eff} as HEU	$T_{LEU} = 19$; $T_{Al} = 21.75$; $E_{Al} = 0$ $V_m/V_f=12.79$; H/U5 =132.35	0.99706 ± 0.00006	0.98256 ± 0.00006	0.01450
	LEU with Al Edge: ~same k_{eff} as HEU	$T_{LEU} = 28$; $T_{Al} = 17.25$; $E_{Al} = 100$ $V_m/V_f=10.71$; H/U5 =110.88	0.99958 ± 0.00007	0.98621 ± 0.00006	0.01337
KUCA B1/8''P80EU	HEU	T=62.5; $V_m/V_f=1.94$; H/U5=103.48	0.99882 ± 0.00007	0.97758 ± 0.00007	0.02124
	LEU no Al Edge: max loading	$T_{LEU} = 42.5$; $T_{Al} = 10$; $E_{Al} = 0$ $V_m/V_f=2.86$; H/U5 =29.58	0.99611 ± 0.00007	0.97833 ± 0.00007	0.01778
	LEU with Al Edge: max loading	$T_{LEU} = 42.5$; $T_{Al} = 10$; $E_{Al} = 100$ $V_m/V_f=3.53$; H/U5 =36.52	0.97932 ± 0.00007	0.96214 ± 0.00007	0.01718
KUCA B1/8''P60EU- EU	HEU	T=62.5; $V_m/V_f=0.97$; H/U5=51.74	1.00020 ± 0.00007	0.98268 ± 0.00007	0.01767
	LEU no Al Edge: max loading	$T_{LEU} = 42.5$; $T_{Al} = 10$; $E_{Al} = 0$ $V_m/V_f=1.43$; H/U5 =14.79	0.99348 ± 0.00006	0.98052 ± 0.00006	0.01296
	LEU with Al Edge: max loading	$T_{LEU} = 42.5$; $T_{Al} = 10$; $E_{Al} = 100$ $V_m/V_f=1.76$; H/U5 =18.26	0.97635 ± 0.00006	0.96323 ± 0.00006	0.01312
KUCA B1/8''P48EU- EU-EU	HEU	T=62.5; $V_m/V_f=0.65$; H/U5=34.49	1.00114 ± 0.00007	0.98543 ± 0.00007	0.01571
	LEU no Al Edge: max loading	$T_{LEU} = 42.5$; $T_{Al} = 10$; $E_{Al} = 0$ $V_m/V_f=0.95$; H/U5 =9.86	1.00863 ± 0.00005	0.99878 ± 0.00005	0.00985
	LEU with Al Edge: max loading	$T_{LEU} = 42.5$; $T_{Al} = 10$; $E_{Al} = 100$ $V_m/V_f=1.18$; H/U5 =12.17	0.98812 ± 0.00006	0.97768 ± 0.00006	0.01044

Table 11. Calculated Multiplication Factor Values of the Alternative Loadings of LEU KUCA Cores with Low H/U5 in Excess Reactivity and Subcritical Rod Configuration.

Configuration	Loading Type	Excess Reactivity Rod Configuration k_{eff} : Calculation	Subcritical Rod Configuration k_{eff} : Calculation	Δk_{eff}
KUCA B1/8''P80EU	LEU no Al Edge, 2 assemblies added: max loading	1.01129 $\pm$ 0.00007	0.99212 $\pm$ 0.00007	0.01917
	LEU with 100 mils Al Edge, 2 assemblies added: max loading	0.99579 $\pm$ 0.00007	0.97686 $\pm$ 0.00007	0.01893
KUCA B1/8''P60EU-EU	LEU no Al Edge, merging 2 LEU plates in 1: max loading	1.01020 $\pm$ 0.00006	0.99843 $\pm$ 0.00006	0.01177
	LEU with 100 mils Al Edge, merging 2 LEU plates in 1: max loading	0.99159 $\pm$ 0.00006	0.97924 $\pm$ 0.00006	0.01235
KUCA B1/8''P48EU-EU-EU	LEU no Al Edge, merging 3 LEU plates in 2: max loading	1.02424 $\pm$ 0.00006	1.01512 $\pm$ 0.00006	0.00912
	LEU with 100 mils Al Edge, merging 3 LEU plates in 2: max loading	1.00221 $\pm$ 0.00006	0.99233 $\pm$ 0.00006	0.00988

3.3.3 Flux Spectra Calculations

Flux spectra were obtained in a central assembly (see Table 12 for the exact location of the assemblies) of the proposed KUCA cores and were determined as average values in a specific region of the LEU foil (or HEU plate) closest to the core midplane. This region has a square section of 1 cm side and an axial extension that corresponds to the thickness of the LEU foil (or HEU plate). All flux spectra were obtained for the “subcritical” control rod configuration (controls rods in / safety rods out) using a 53 energy group structure.

Table 12. Location of Assemblies for Flux Spectra Determination in the KUCA Cores.

Configuration	Assembly Location ^(a)
KUCA A3/8’’P36EU	(K,15)
KUCA B2/8’’P48EU	(K,15)
KUCA B1/8’’P80EU	(J,15)
KUCA B1/8’’P60EU-EU	(J,15)
KUCA B1/8’’P48EU-EU-EU	(J,15)
^(a) Refer to Figure 53 for a graphical view of the assembly locations.	

Figure 56 shows the flux spectra of the five KUCA cores under study with HEU loadings, while Figure 57 shows the flux spectra of the corresponding LEU cores characterized by the same H/U5 atom ratio in the fuel unit cells. Then, for a better comparison the flux spectra obtained in the HEU and LEU cases with the same H/U5 are presented separately for each configuration in Figures 58 through 62.

It is observed that, as expected, the LEU configurations show a harder flux spectrum than that obtained in the corresponding HEU configurations. However, reducing the H/U5 atom ratio in the LEU fuel unit cell results in a less hard spectrum with respect to the HEU configurations.

Figure 56. Flux Spectra Comparison for the KUCA HEU Configurations.

Figure 57. Flux Spectra Comparison for the KUCA LEU Configurations with the Same H-to-U²³⁵ Atom Ratios in the Fuel Unit Cell of the Corresponding HEU Configurations.

Figure 58. Flux Spectra Comparison for the KUCA A3/8''P36EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 316.45$) in the Fuel Unit Cell.

Figure 59. Flux Spectra Comparison for the KUCA B2/8''P48EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 206.96$) in the Fuel Unit Cell.

Figure 60. Flux Spectra Comparison for the KUCA B1/8''P80EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 103.48$) in the Fuel Unit Cell.

Figure 61. Flux Spectra Comparison for the KUCA B1/8''P60EU-EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 51.74$) in the Fuel Unit Cell.

Figure 62. Flux Spectra Comparison for the KUCA B1/8''P48EU-EU-EU Configuration in the HEU and LEU Cases with the Same H-to-U235 Atom Ratios ($H/U5 = 34.49$) in the Fuel Unit Cell.

Calculations were also performed to analyze the impact on neutron flux spectra due to variations in the thickness of the U-10Mo foils of the LEU KUCA configurations. For this purpose, flux spectra were calculated for the A3/8''P36EU and B1/8''P80EU KUCA configurations using U-10Mo foils of three different thicknesses, specifically 10-, 16- and 22-mils thick for A3/8''P36EU and 30-, 36- and 42-mils thick for B1/8''P80EU.

Additionally, for the A3/8''P36EU and B1/8''P80EU KUCA configurations using U-10Mo foils of 22 mils and 42 mils thickness, the impact on flux spectra due to the use of the 100 mils aluminum edge all around the LEU foil was also investigated.

As shown in Figures 63 through 66, harder neutron spectra are obtained with thicker U-10Mo foils or by adding the 100 mils aluminum edge.

Finally, for the KUCA configuration B1/8''P60EU-EU flux spectra were compared between the case of maximum loading and the case where the two adjacent LEU plates in the fuel unit cell are merged into a single plate, according to the scheme illustrated in Figure 55. Iterative calculations were first performed in order to determine the thickness of the resulting LEU foil after merging the adjacent plates that would preserve more or less the same reactivity as the initial LEU configuration with the condition of maximum loading. All calculations were performed with the subcritical control rod configuration. As shown in Table 13, for the B1/8''P60EU-EU configuration more or less the same reactivity value that was obtained in the condition of maximum loading would be achieved if the two LEU foils are merged into a single foil with a thickness of 83 mils.

Figure 67 shows that the flux spectra calculated for the LEU B1/8''P60EU-EU configuration with conditions of maximum loading and in the LEU configuration obtained by merging the two LEU foils into a single foil with a thickness that preserves the same reactivity are practically the same. In fact, as shown in Table 13 the change in the LEU loading between the two LEU configurations leaves the moderator-to-fuel volume ratio and the H-to-U235 atom ratio in the cores practically unchanged.

Figure 63. Flux Spectra Comparison for the KUCA A3/8''P36EU Configuration in the HEU Case and the LEU Cases with Different Thicknesses of the U-10Mo Foil.

Figure 64. Flux Spectra Comparison for the KUCA B1/8''P80EU Configuration in the HEU Case and the LEU Cases with Different Thicknesses of the U-10Mo Foil.

Figure 65. Flux Spectra Comparison for the LEU KUCA A3/8''P36EU Configuration With and Without Aluminum Edge Around the U-10Mo Foils.

Figure 66. Flux Spectra Comparison for the LEU KUCA B1/8''P80EU Configuration With and Without Aluminum Edge Around the U-10Mo Foils.

Table 13. Calculated Multiplication Factor Values for KUCA B1/8''P60EU-EU in the Subcritical Rod Configuration.

Configuration	Loading Type	Plate Dimensions (mils); V_m/V_f ; $H/U5$	k_{eff} : Calculation
KUCA B1/8''P60EU-EU	HEU	$T=62.5$; $V_m/V_f=0.97$; $H/U5=51.74$	0.98268 ± 0.00007
	LEU no Al Edge: max loading	$T_{LEU} = 42.5$; $T_{Al} = 10$; $E_{Al} = 0$ $V_m/V_f = 1.43$; $H/U5 = 14.79$	0.98052 ± 0.00006
	LEU no Al Edge Merging 2 foils into 1: ~same k_{eff} of LEU, no Al Edge, max loading	$T_{LEU} = 83$; $T_{Al} = 21$; $E_{Al} = 0$ $V_m/V_f = 1.46$ $H/U5 = 15.15$	0.97951 ± 0.00006

Figure 67. Flux Spectra Comparison for the KUCA B1/8''P60EU-EU Configuration with HEU and LEU Loadings of Same k_{eff} .

4. CONCLUSIONS

The KUCA experiments were designed to establish measurement techniques for neutronic parameters in subcritical systems and to investigate the accuracy of the neutronic design of an ADSR. Due to the continuing interest in non-proliferation issues, new studies are being performed at KURRI to investigate the feasibility of converting the KUCA cores to the use of LEU fuel.

The KUCA cores consist of the solid-moderated and -reflected type-A and -B cores, and of the water-moderated and -reflected type-C core. The present document describes the results of the analysis carried out at Argonne on the KUCA type-A cores. In particular, calculated results of the KUCA benchmark assembly and of the feasibility studies on the conversion of the KUCA dry cores from HEU to LEU are discussed.

Calculations were performed with MCNP5 using ENDF/B-VII.0 nuclear data. The MCNP model was developed by explicitly describing all single plates, both for the polyethylene and the uranium.

Based on the benchmark specifications, reactivity calculations were performed with three different control rod configurations. The calculations show a consistent discrepancy between the calculated and experimental results of about 400 - 500 pcm for all KUCA configurations from Series I and of about 500 - 700 pcm for all KUCA configurations from Series II. It is however important to emphasize the fact that the foils located in the void region of the fuel assemblies “SV” of the KUCA configurations II-2, II-3 and II-4 have a reactivity effect of about 800 pcm. The use of different nuclear data libraries was shown to not have a significant impact on the discrepancies observed between the calculated and experimental results.

Indium rate distributions were calculated along the indium wire located at the core midplane with a (d,t) source in place. For the Series I and II configurations, the calculated indium rate distributions show reasonable agreement with the measurements in the shape of the distribution, particularly in the fuel zone. In the reflector/shield region the calculations show a depression in the distributions that in some cases is not seen in the measurements.

Calculations were performed to evaluate the conversion of the KUCA “type A” cores from HEU to LEU using both U-Al and U-10Mo LEU fuel. In the case of U-10Mo fuel, five “type-A” cores were considered with different moderator-to-fuel volume ratios (V_m/V_f) and different H-to-U235 atom ratios (H/U5) in the fuel unit cell as requested by the KUCA team. The option to add an aluminum clad and an aluminum edge to the U-10Mo foils was also considered.

With the same H/U5 in the fuel unit cell, the LEU configurations give a reactivity value lower than what is obtained for the corresponding HEU configurations, and this discrepancy increases with decreasing moderator to fuel volume ratio (V_m/V_f) and H/U5. As a consequence, for the LEU configurations with low H/U5 a reactivity value more or less comparable to that of the corresponding HEU cores can be only achieved in the conditions of maximum loading (i.e., the thickness of the aluminum clad is reduced to the minimum allowed of 10 mils) and without the aluminum edge. However, for these configurations different solutions, like adding fuel assemblies at the core boundary or merging adjacent LEU plates into a single plate, could be envisaged so that the desired k_{eff} in the LEU cases can be achieved with U-10Mo foil dimensions that are smaller than the maximum allowed.

The feasibility studies on the conversion of the KUCA cores from HEU to LEU was also carried out with an extensive analysis of flux spectra distributions in relevant position of the assemblies. Small shifts in the spectra, typical of other HEU-to-LEU conversion studies, are seen in the comparisons presented in this report. While further study of the KUCA cores is necessary to compare power levels, reactivity coefficients and other performance parameters, none of the results presented here indicate any reason that the conversion of the KUCA dry cores to LEU cannot be performed successfully.

5. REFERENCES

1. Cheolho Pyeon, “Experimental Benchmarks for Accelerator Driven Subcritical Reactor (ADSR) at Kyoto University Critical Assembly (KUCA),” Kyoto University Research Reactor Institute, Japan, November 2007.
2. Gerardo Aliberti, Hironobu Unesaki and Cheol-Ho Pyeon, “Analysis of KUCA type-A Cores,” RERTR 2012, Warsaw, Poland, October 14-17, 2012.
3. Gerardo Aliberti, James A. Morman, John G. Stevens, Hironobu Unesaki and Cheol-Ho Pyeon, “On the Conversion of KUCA Type-A Cores from HEU to LEU Using U10Mo Foils,” ANS Winter Meeting, Washington, D.C., November 10-14, 2013.

APPENDIX. MCNP INPUT FOR KUCA I-1 WITH SUBCRITICAL ROD CONFIGURATION

KUCA

```

100 9 5.40155E-05 -2 1 11 -10 60 -174 (21:-20:-31:30)      imp:n=1
101 0      -21 20 31 -30 60 -174 fill=100(-55.7 36.245 0.0) imp:n=1
102 0      -42 43 53 -52      lat=1 u=100 imp:n=1
      fill=-1:2 -2:3 0:0
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
103 9 5.40155E-05 -3 2 11 -10 60 -174 (23:-22:-31:30)      imp:n=1
104 0      -23 22 31 -30 60 -174 fill=101(-27.85 36.245 0.0) imp:n=1
105 0      -42 43 53 -52      lat=1 u=101 imp:n=1
      fill=-2:3 -2:3 0:0
      4 4 4 4 4 4
      4 5 5 5 5 4
      4 5 19 19 5 4
      4 5 19 19 5 5
      4 5 5 5 5 5
      4 5 5 5 5 5
106 9 5.40155E-05 -4 3 11 -10 60 -174 (25:-24:-31:30)      imp:n=1
107 0      -25 24 31 -30 60 -174 fill=102(0.0 36.245 0.0) imp:n=1
108 0      -42 43 53 -52      lat=1 u=102 imp:n=1
      fill=-1:1 -2:3 0:0
      4 4 4
      4 4 4
      4 4 4
      5 5 5
      5 5 5
      5 5 5
109 9 5.40155E-05 -5 4 11 -10 60 -174 (27:-26:-31:30)      imp:n=1
110 0      -27 26 31 -30 60 -174 fill=103(22.32 36.245 0.0) imp:n=1
111 0      -42 43 53 -52      lat=1 u=103 imp:n=1
      fill=-2:3 -2:3 0:0
      4 4 4 4 4 4
      4 5 5 5 5 4
      4 5 19 19 5 4
      5 5 19 19 5 4
      5 5 5 5 5 4
      5 5 5 5 5 4
112 9 5.40155E-05 -6 5 11 -10 60 -174 (29:-28:-31:30)      imp:n=1
113 0      -29 28 31 -30 60 -174 fill=104(50.17 36.245 0.0) imp:n=1
114 0      -42 43 53 -52      lat=1 u=104 imp:n=1
      fill=-1:2 -2:3 0:0
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
115 9 5.40155E-05 -2 1 12 -11 60 -174 (21:-20:-33:32)      imp:n=1
116 0      -21 20 33 -32 60 -174 fill=105(-55.7 8.395 0.0) imp:n=1
117 0      -42 43 53 -52      lat=1 u=105 imp:n=1
      fill=-1:2 -1:1 0:0
      4 5 5 5
      4 5 19 19
      4 5 19 19
118 9 5.40155E-05 -3 2 12 -11 60 -174 (23:-22:-33:32)      imp:n=1
119 0      -23 22 33 -32 60 -174 fill=106(-27.85 8.395 0.0) imp:n=1
120 0      -42 43 53 -52      lat=1 u=106 imp:n=1

```

```

        fill=-2:3 -1:1 0:0
        5 5 5 5 5
        5 5 5 5 5
        5 5 5 5 5
121 9 5.40155E-05 -4 3 12 -11 60 -174 (25:-24:-33:32)    imp:n=1
122 0      -25 24 33 -32 60 -174 fill=107(0.0 8.395 0.0) imp:n=1
123 0      -42 43 53 -52          lat=1 u=107 imp:n=1
        fill=-1:1 -1:1 0:0
        5 5 5
        5 5 5
        1 1 1
124 9 5.40155E-05 -5 4 12 -11 60 -174 (27:-26:-33:32)    imp:n=1
125 0      -27 28 33 -32 60 -174 fill=108(22.32 8.395 0.0) imp:n=1
126 0      -42 43 53 -52          lat=1 u=108 imp:n=1
        fill=-2:3 -1:1 0:0
        5 5 5 5 5
        5 5 5 5 5
        5 5 5 5 5
127 9 5.40155E-05 -6 5 12 -11 60 -174 (29:-28:-33:32)    imp:n=1
128 0      -29 28 33 -32 60 -174 fill=109(50.17 8.395 0.0) imp:n=1
129 0      -42 43 53 -52          lat=1 u=109 imp:n=1
        fill=-1:2 -1:1 0:0
        5 5 5 4
        19 19 5 4
        19 19 5 4
130 9 5.40155E-05 -2 1 13 -12 60 -174 (21:-20:-35:34)    imp:n=1
131 0      -21 20 35 -34 60 -174 fill=110(-55.7 -13.925 0.0) imp:n=1
132 0      -42 43 53 -52          lat=1 u=110 imp:n=1
        fill=-1:2 -2:3 0:0
        4 5 5 5
        4 5 5 5
        4 5 19 19
        4 5 19 19
        4 5 5 5
        4 4 4 4
133 9 5.40155E-05 -3 2 13 -12 60 -174 (23:-22:-35:34)    imp:n=1
134 0      -23 22 35 -34 60 -174 fill=111(-27.85 -13.925 0.0) imp:n=1
135 0      -42 43 53 -52          lat=1 u=111 imp:n=1
        fill=-2:3 -2:3 0:0
        5 5 5 5 21 1
        5 5 5 5 5 1
        5 5 5 5 6 1
        5 5 5 5 18 1
        5 5 5 5 5 21
        5 5 5 5 5 5
136 9 5.40155E-05 313 -4 3 13 -12 60 -174 (25:-24:-35:34)    imp:n=1
137 0      313 -25 24 35 -34 60 -174 fill=112(-0.0 -13.925 0.0) imp:n=1
138 0      -42 43 53 -52          lat=1 u=112 imp:n=1
        fill=-1:1 -2:3 0:0
        1 1 1
        1 20 1
        1 1 1
        1 1 1
        5 1 5
        5 4 5
139 9 5.40155E-05 313 -5 4 13 -12 60 -174 (27:-26:-35:34)    imp:n=1
140 0      313 -27 26 35 -34 60 -174 fill=113(22.32 -13.925 0.0) imp:n=1
141 0      -42 43 53 -52          lat=1 u=113 imp:n=1
        fill=-2:3 -2:3 0:0
        1 6 5 5 5 5
        1 5 5 5 5 5
        1 21 5 5 5 5
        1 18 5 5 5 5
        6 5 5 5 5 5
        5 5 5 5 5 5

```

```

142 9 5.40155E-05 -6 5 13 -12 60 -174 (29:-28:-35:34)      imp:n=1
143 0      -29 28 35 -34 60 -174 fill=114(50.17 -13.925 0.0) imp:n=1
144 0      -42 43 53 -52      lat=1 u=114 imp:n=1
      fill=-1:2 -2:3 0:0
      5 5 5 4
      5 5 4 4
      5 5 4 4
      5 5 4 4
      4 4 4 4
      4 4 4 4
145 9 5.40155E-05 -2 1 14 -13 60 -174 (21:-20:-37:36)      imp:n=1
146 0      -21 20 37 -36 60 -174 fill=115(-55.7 -47.305 0.0) imp:n=1
147 0      -42 43 53 -52      lat=1 u=115 imp:n=1
      fill=-1:2 -2:3 0:0
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
148 9 5.40155E-05 -3 2 14 -13 60 -174 (23:-22:-37:36)      imp:n=1
149 0      -23 22 37 -36 60 -174 fill=116(-27.85 -47.305 0.0) imp:n=1
150 0      -42 43 53 -52      lat=1 u=116 imp:n=1
      fill=-2:3 -2:3 0:0
      5 5 5 5 5 5
      5 5 5 5 5 5
      4 4 4 4 4 5
      4 4 4 4 4 5
      4 4 4 4 4 4
      4 4 4 4 4 4
151 9 5.40155E-05 313 -4 3 14 -13 60 -174 (25:-24:-37:36)      imp:n=1
152 0      313 -25 24 37 -36 60 -174 fill=117(0.0 -47.305 0.0) imp:n=1
153 0      -42 43 53 -52      lat=1 u=117 imp:n=1
      fill=-1:1 -2:3 0:0
      5 5 5
      5 5 5
      5 5 5
      5 5 5
      4 4 4
      4 4 4
154 9 5.40155E-05 313 -5 4 14 -13 60 -174 (27:-26:-37:36)      imp:n=1
155 0      313 -27 26 37 -36 60 -174 fill=118(22.32 -47.305 0.0) imp:n=1
156 0      -42 43 53 -52      lat=1 u=118 imp:n=1
      fill=-2:3 -2:3 0:0
      5 5 5 5 5 5
      5 5 5 5 5 5
      5 4 4 4 4 4
      5 4 4 4 4 4
      4 4 4 4 4 4
      4 4 4 4 4 4
157 9 5.40155E-05 -6 5 14 -13 60 -174 (29:-28:-37:36)      imp:n=1
158 0      -29 28 37 -36 60 -174 fill=119(50.17 -47.305 0.0) imp:n=1
159 0      -42 43 53 -52      lat=1 u=119 imp:n=1
      fill=-1:2 -2:3 0:0
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
      4 4 4 4
160 7 6.00385E-02 -313 312 14 -12      imp:n=1
161 9 5.40155E-05 -312 311 14 -12      imp:n=1
162 11 3.83231E-02 -311 14 -12      imp:n=1
163 0      (6:-1:-14:10:-60:174)      imp:n=0
c

```

c DEFINITION OF UNIVERSES: ASSEMBLY F

```
200 7 6.00385E-02 41 -40 51 -50 -61 u=1 imp:n=1
201 2 1.20984E-01 41 -40 51 -50 61 -62 u=1 imp:n=1
202 5 1.20013E-01 41 -40 51 -50 62 -63 u=1 imp:n=1
203 1 5.72591E-02 41 -40 51 -50 63 -64 u=1 imp:n=1
204 4 1.20325E-01 41 -40 51 -50 64 -65 u=1 imp:n=1
205 3 1.21307E-01 41 -40 51 -50 65 -66 u=1 imp:n=1
206 1 5.72591E-02 41 -40 51 -50 66 -67 u=1 imp:n=1
207 4 1.20325E-01 41 -40 51 -50 67 -68 u=1 imp:n=1
208 3 1.21307E-01 41 -40 51 -50 68 -69 u=1 imp:n=1
209 1 5.72591E-02 41 -40 51 -50 69 -70 u=1 imp:n=1
210 4 1.20325E-01 41 -40 51 -50 70 -71 u=1 imp:n=1
211 3 1.21307E-01 41 -40 51 -50 71 -72 u=1 imp:n=1
212 1 5.72591E-02 41 -40 51 -50 72 -73 u=1 imp:n=1
213 4 1.20325E-01 41 -40 51 -50 73 -74 u=1 imp:n=1
214 3 1.21307E-01 41 -40 51 -50 74 -75 u=1 imp:n=1
215 1 5.72591E-02 41 -40 51 -50 75 -76 u=1 imp:n=1
216 4 1.20325E-01 41 -40 51 -50 76 -77 u=1 imp:n=1
217 3 1.21307E-01 41 -40 51 -50 77 -78 u=1 imp:n=1
218 1 5.72591E-02 41 -40 51 -50 78 -79 u=1 imp:n=1
219 4 1.20325E-01 41 -40 51 -50 79 -80 u=1 imp:n=1
220 3 1.21307E-01 41 -40 51 -50 80 -81 u=1 imp:n=1
221 1 5.72591E-02 41 -40 51 -50 81 -82 u=1 imp:n=1
222 4 1.20325E-01 41 -40 51 -50 82 -83 u=1 imp:n=1
223 3 1.21307E-01 41 -40 51 -50 83 -84 u=1 imp:n=1
224 1 5.72591E-02 41 -40 51 -50 84 -85 u=1 imp:n=1
225 4 1.20325E-01 41 -40 51 -50 85 -86 u=1 imp:n=1
226 3 1.21307E-01 41 -40 51 -50 86 -87 u=1 imp:n=1
227 1 5.72591E-02 41 -40 51 -50 87 -88 u=1 imp:n=1
228 4 1.20325E-01 41 -40 51 -50 88 -89 u=1 imp:n=1
229 3 1.21307E-01 41 -40 51 -50 89 -90 u=1 imp:n=1
230 1 5.72591E-02 41 -40 51 -50 90 -91 u=1 imp:n=1
231 4 1.20325E-01 41 -40 51 -50 91 -92 u=1 imp:n=1
232 3 1.21307E-01 41 -40 51 -50 92 -93 u=1 imp:n=1
233 1 5.72591E-02 41 -40 51 -50 93 -94 u=1 imp:n=1
234 4 1.20325E-01 41 -40 51 -50 94 -95 u=1 imp:n=1
235 3 1.21307E-01 41 -40 51 -50 95 -96 u=1 imp:n=1
236 1 5.72591E-02 41 -40 51 -50 96 -97 u=1 imp:n=1
237 4 1.20325E-01 41 -40 51 -50 97 -98 u=1 imp:n=1
238 3 1.21307E-01 41 -40 51 -50 98 -99 u=1 imp:n=1
239 1 5.72591E-02 41 -40 51 -50 99 -100 u=1 imp:n=1
240 4 1.20325E-01 41 -40 51 -50 100 -101 u=1 imp:n=1
241 3 1.21307E-01 41 -40 51 -50 101 -102 u=1 imp:n=1
242 1 5.72591E-02 41 -40 51 -50 102 -103 u=1 imp:n=1
243 4 1.20325E-01 41 -40 51 -50 103 -104 u=1 imp:n=1
244 3 1.21307E-01 41 -40 51 -50 104 -105 u=1 imp:n=1
245 1 5.72591E-02 41 -40 51 -50 105 -106 u=1 imp:n=1
246 4 1.20325E-01 41 -40 51 -50 106 -107 u=1 imp:n=1
247 3 1.21307E-01 41 -40 51 -50 107 -108 u=1 imp:n=1
248 1 5.72591E-02 41 -40 51 -50 108 -109 u=1 imp:n=1
249 4 1.20325E-01 41 -40 51 -50 109 -110 u=1 imp:n=1
250 3 1.21307E-01 41 -40 51 -50 110 -111 u=1 imp:n=1
251 1 5.72591E-02 41 -40 51 -50 111 -112 u=1 imp:n=1
252 4 1.20325E-01 41 -40 51 -50 112 -113 u=1 imp:n=1
253 3 1.21307E-01 41 -40 51 -50 113 -114 u=1 imp:n=1
254 1 5.72591E-02 41 -40 51 -50 114 -115 u=1 imp:n=1
255 4 1.20325E-01 41 -40 51 -50 115 -116 u=1 imp:n=1
256 3 1.21307E-01 41 -40 51 -50 116 -117 u=1 imp:n=1
257 1 5.72591E-02 41 -40 51 -50 117 -118 u=1 imp:n=1
258 4 1.20325E-01 41 -40 51 -50 118 -119 u=1 imp:n=1
259 3 1.21307E-01 41 -40 51 -50 119 -120 u=1 imp:n=1
260 1 5.72591E-02 41 -40 51 -50 120 -121 u=1 imp:n=1
261 4 1.20325E-01 41 -40 51 -50 121 -122 u=1 imp:n=1
262 3 1.21307E-01 41 -40 51 -50 122 -123 u=1 imp:n=1
263 1 5.72591E-02 41 -40 51 -50 123 -124 u=1 imp:n=1
```

```

264 4 1.20325E-01 41 -40 51 -50 124 -125 u=1 imp:n=1
265 3 1.21307E-01 41 -40 51 -50 125 -126 u=1 imp:n=1
266 1 5.72591E-02 41 -40 51 -50 126 -127 u=1 imp:n=1
267 4 1.20325E-01 41 -40 51 -50 127 -128 u=1 imp:n=1
268 3 1.21307E-01 41 -40 51 -50 128 -129 u=1 imp:n=1
269 1 5.72591E-02 41 -40 51 -50 129 -130 u=1 imp:n=1
270 4 1.20325E-01 41 -40 51 -50 130 -131 u=1 imp:n=1
271 3 1.21307E-01 41 -40 51 -50 131 -132 u=1 imp:n=1
272 1 5.72591E-02 41 -40 51 -50 132 -133 u=1 imp:n=1
273 4 1.20325E-01 41 -40 51 -50 133 -134 u=1 imp:n=1
274 3 1.21307E-01 41 -40 51 -50 134 -135 u=1 imp:n=1
275 1 5.72591E-02 41 -40 51 -50 135 -136 u=1 imp:n=1
276 4 1.20325E-01 41 -40 51 -50 136 -137 u=1 imp:n=1
277 3 1.21307E-01 41 -40 51 -50 137 -138 u=1 imp:n=1
278 1 5.72591E-02 41 -40 51 -50 138 -139 u=1 imp:n=1
279 4 1.20325E-01 41 -40 51 -50 139 -140 u=1 imp:n=1
280 3 1.21307E-01 41 -40 51 -50 140 -141 u=1 imp:n=1
281 1 5.72591E-02 41 -40 51 -50 141 -142 u=1 imp:n=1
282 4 1.20325E-01 41 -40 51 -50 142 -143 u=1 imp:n=1
283 3 1.21307E-01 41 -40 51 -50 143 -144 u=1 imp:n=1
284 1 5.72591E-02 41 -40 51 -50 144 -145 u=1 imp:n=1
285 4 1.20325E-01 41 -40 51 -50 145 -146 u=1 imp:n=1
286 3 1.21307E-01 41 -40 51 -50 146 -147 u=1 imp:n=1
287 1 5.72591E-02 41 -40 51 -50 147 -148 u=1 imp:n=1
288 4 1.20325E-01 41 -40 51 -50 148 -149 u=1 imp:n=1
289 3 1.21307E-01 41 -40 51 -50 149 -150 u=1 imp:n=1
290 1 5.72591E-02 41 -40 51 -50 150 -151 u=1 imp:n=1
291 4 1.20325E-01 41 -40 51 -50 151 -152 u=1 imp:n=1
292 3 1.21307E-01 41 -40 51 -50 152 -153 u=1 imp:n=1
293 1 5.72591E-02 41 -40 51 -50 153 -154 u=1 imp:n=1
294 4 1.20325E-01 41 -40 51 -50 154 -155 u=1 imp:n=1
295 3 1.21307E-01 41 -40 51 -50 155 -156 u=1 imp:n=1
296 1 5.72591E-02 41 -40 51 -50 156 -157 u=1 imp:n=1
297 4 1.20325E-01 41 -40 51 -50 157 -158 u=1 imp:n=1
298 3 1.21307E-01 41 -40 51 -50 158 -159 u=1 imp:n=1
299 1 5.72591E-02 41 -40 51 -50 159 -160 u=1 imp:n=1
300 4 1.20325E-01 41 -40 51 -50 160 -161 u=1 imp:n=1
301 3 1.21307E-01 41 -40 51 -50 161 -162 u=1 imp:n=1
302 1 5.72591E-02 41 -40 51 -50 162 -163 u=1 imp:n=1
303 4 1.20325E-01 41 -40 51 -50 163 -164 u=1 imp:n=1
304 3 1.21307E-01 41 -40 51 -50 164 -165 u=1 imp:n=1
305 1 5.72591E-02 41 -40 51 -50 165 -166 u=1 imp:n=1
306 4 1.20325E-01 41 -40 51 -50 166 -167 u=1 imp:n=1
307 3 1.21307E-01 41 -40 51 -50 167 -168 u=1 imp:n=1
308 1 5.72591E-02 41 -40 51 -50 168 -169 u=1 imp:n=1
309 4 1.20325E-01 41 -40 51 -50 169 -170 u=1 imp:n=1
310 3 1.21307E-01 41 -40 51 -50 170 -171 u=1 imp:n=1
311 5 1.20013E-01 41 -40 51 -50 171 -172 u=1 imp:n=1
312 2 1.20984E-01 41 -40 51 -50 172 -173 u=1 imp:n=1
313 4 1.20325E-01 41 -40 51 -50 173 u=1 imp:n=1
314 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=1 imp:n=1
315 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=1 imp:n=1
316 9 5.40155E-05 (-47:46:-57:56) u=1 imp:n=1
c DEFINITION OF UNIVERSES: ASSEMBLY SV
350 7 6.00385E-02 41 -40 51 -50 -61 u=2 imp:n=1
351 2 1.20984E-01 41 -40 51 -50 61 -200 u=2 imp:n=1
352 5 1.20013E-01 41 -40 51 -50 200 -201 u=2 imp:n=1
353 1 5.72591E-02 41 -40 51 -50 201 -202 u=2 imp:n=1
354 4 1.20325E-01 41 -40 51 -50 202 -203 u=2 imp:n=1
355 3 1.21307E-01 41 -40 51 -50 203 -204 u=2 imp:n=1
356 1 5.72591E-02 41 -40 51 -50 204 -205 u=2 imp:n=1
357 4 1.20325E-01 41 -40 51 -50 205 -206 u=2 imp:n=1
358 3 1.21307E-01 41 -40 51 -50 206 -207 u=2 imp:n=1
359 1 5.72591E-02 41 -40 51 -50 207 -208 u=2 imp:n=1
360 4 1.20325E-01 41 -40 51 -50 208 -209 u=2 imp:n=1

```

```
361 3 1.21307E-01 41 -40 51 -50 209 -210 u=2 imp:n=1
362 1 5.72591E-02 41 -40 51 -50 210 -211 u=2 imp:n=1
363 4 1.20325E-01 41 -40 51 -50 211 -212 u=2 imp:n=1
364 3 1.21307E-01 41 -40 51 -50 212 -213 u=2 imp:n=1
365 1 5.72591E-02 41 -40 51 -50 213 -214 u=2 imp:n=1
366 4 1.20325E-01 41 -40 51 -50 214 -215 u=2 imp:n=1
367 3 1.21307E-01 41 -40 51 -50 215 -216 u=2 imp:n=1
368 1 5.72591E-02 41 -40 51 -50 216 -217 u=2 imp:n=1
369 4 1.20325E-01 41 -40 51 -50 217 -218 u=2 imp:n=1
370 3 1.21307E-01 41 -40 51 -50 218 -219 u=2 imp:n=1
371 1 5.72591E-02 41 -40 51 -50 219 -220 u=2 imp:n=1
372 4 1.20325E-01 41 -40 51 -50 220 -221 u=2 imp:n=1
373 3 1.21307E-01 41 -40 51 -50 221 -222 u=2 imp:n=1
374 1 5.72591E-02 41 -40 51 -50 222 -223 u=2 imp:n=1
375 4 1.20325E-01 41 -40 51 -50 223 -224 u=2 imp:n=1
376 3 1.21307E-01 41 -40 51 -50 224 -225 u=2 imp:n=1
377 1 5.72591E-02 41 -40 51 -50 225 -226 u=2 imp:n=1
378 4 1.20325E-01 41 -40 51 -50 226 -227 u=2 imp:n=1
379 3 1.21307E-01 41 -40 51 -50 227 -228 u=2 imp:n=1
380 1 5.72591E-02 41 -40 51 -50 228 -229 u=2 imp:n=1
381 4 1.20325E-01 41 -40 51 -50 229 -230 u=2 imp:n=1
382 3 1.21307E-01 41 -40 51 -50 230 -231 u=2 imp:n=1
383 1 5.72591E-02 41 -40 51 -50 231 -232 u=2 imp:n=1
384 4 1.20325E-01 41 -40 51 -50 232 -233 u=2 imp:n=1
385 3 1.21307E-01 41 -40 51 -50 233 -234 u=2 imp:n=1
386 1 5.72591E-02 41 -40 51 -50 234 -235 u=2 imp:n=1
387 4 1.20325E-01 41 -40 51 -50 235 -236 u=2 imp:n=1
388 3 1.21307E-01 41 -40 51 -50 236 -237 u=2 imp:n=1
389 1 5.72591E-02 41 -40 51 -50 237 -238 u=2 imp:n=1
390 4 1.20325E-01 41 -40 51 -50 238 -239 u=2 imp:n=1
391 3 1.21307E-01 41 -40 51 -50 239 -240 u=2 imp:n=1
392 1 5.72591E-02 41 -40 51 -50 240 -241 u=2 imp:n=1
393 4 1.20325E-01 41 -40 51 -50 241 -242 u=2 imp:n=1
394 3 1.21307E-01 41 -40 51 -50 242 -243 u=2 imp:n=1
395 1 5.72591E-02 41 -40 51 -50 243 -244 u=2 imp:n=1
396 4 1.20325E-01 41 -40 51 -50 244 -245 u=2 imp:n=1
397 3 1.21307E-01 41 -40 51 -50 245 -246 u=2 imp:n=1
398 1 5.72591E-02 41 -40 51 -50 246 -247 u=2 imp:n=1
399 4 1.20325E-01 41 -40 51 -50 247 -248 u=2 imp:n=1
400 3 1.21307E-01 41 -40 51 -50 248 -249 u=2 imp:n=1
401 9 5.40155E-05 (-302:301:-306:305)
      313 41 -40 51 -50 249 -250 u=2 imp:n=1
402 1 5.72591E-02 41 -40 51 -50 250 -251 u=2 imp:n=1
403 4 1.20325E-01 41 -40 51 -50 251 -252 u=2 imp:n=1
404 3 1.21307E-01 41 -40 51 -50 252 -253 u=2 imp:n=1
405 1 5.72591E-02 41 -40 51 -50 253 -254 u=2 imp:n=1
406 4 1.20325E-01 41 -40 51 -50 254 -255 u=2 imp:n=1
407 3 1.21307E-01 41 -40 51 -50 255 -256 u=2 imp:n=1
408 1 5.72591E-02 41 -40 51 -50 256 -257 u=2 imp:n=1
409 4 1.20325E-01 41 -40 51 -50 257 -258 u=2 imp:n=1
410 3 1.21307E-01 41 -40 51 -50 258 -259 u=2 imp:n=1
411 1 5.72591E-02 41 -40 51 -50 259 -260 u=2 imp:n=1
412 4 1.20325E-01 41 -40 51 -50 260 -261 u=2 imp:n=1
413 3 1.21307E-01 41 -40 51 -50 261 -262 u=2 imp:n=1
414 1 5.72591E-02 41 -40 51 -50 262 -263 u=2 imp:n=1
415 4 1.20325E-01 41 -40 51 -50 263 -264 u=2 imp:n=1
416 3 1.21307E-01 41 -40 51 -50 264 -265 u=2 imp:n=1
417 1 5.72591E-02 41 -40 51 -50 265 -266 u=2 imp:n=1
418 4 1.20325E-01 41 -40 51 -50 266 -267 u=2 imp:n=1
419 3 1.21307E-01 41 -40 51 -50 267 -268 u=2 imp:n=1
420 1 5.72591E-02 41 -40 51 -50 268 -269 u=2 imp:n=1
421 4 1.20325E-01 41 -40 51 -50 269 -270 u=2 imp:n=1
422 3 1.21307E-01 41 -40 51 -50 270 -271 u=2 imp:n=1
423 1 5.72591E-02 41 -40 51 -50 271 -272 u=2 imp:n=1
424 4 1.20325E-01 41 -40 51 -50 272 -273 u=2 imp:n=1
```

```

425 3 1.21307E-01 41 -40 51 -50 273 -274 u=2 imp:n=1
426 1 5.72591E-02 41 -40 51 -50 274 -275 u=2 imp:n=1
427 4 1.20325E-01 41 -40 51 -50 275 -276 u=2 imp:n=1
428 3 1.21307E-01 41 -40 51 -50 276 -277 u=2 imp:n=1
429 1 5.72591E-02 41 -40 51 -50 277 -278 u=2 imp:n=1
430 4 1.20325E-01 41 -40 51 -50 278 -279 u=2 imp:n=1
431 3 1.21307E-01 41 -40 51 -50 279 -280 u=2 imp:n=1
432 1 5.72591E-02 41 -40 51 -50 280 -281 u=2 imp:n=1
433 4 1.20325E-01 41 -40 51 -50 281 -282 u=2 imp:n=1
434 3 1.21307E-01 41 -40 51 -50 282 -283 u=2 imp:n=1
435 1 5.72591E-02 41 -40 51 -50 283 -284 u=2 imp:n=1
436 4 1.20325E-01 41 -40 51 -50 284 -285 u=2 imp:n=1
437 3 1.21307E-01 41 -40 51 -50 285 -286 u=2 imp:n=1
438 1 5.72591E-02 41 -40 51 -50 286 -287 u=2 imp:n=1
439 4 1.20325E-01 41 -40 51 -50 287 -288 u=2 imp:n=1
440 3 1.21307E-01 41 -40 51 -50 288 -289 u=2 imp:n=1
441 1 5.72591E-02 41 -40 51 -50 289 -290 u=2 imp:n=1
442 4 1.20325E-01 41 -40 51 -50 290 -291 u=2 imp:n=1
443 3 1.21307E-01 41 -40 51 -50 291 -292 u=2 imp:n=1
444 1 5.72591E-02 41 -40 51 -50 292 -293 u=2 imp:n=1
445 4 1.20325E-01 41 -40 51 -50 293 -294 u=2 imp:n=1
446 3 1.21307E-01 41 -40 51 -50 294 -295 u=2 imp:n=1
447 1 5.72591E-02 41 -40 51 -50 295 -296 u=2 imp:n=1
448 4 1.20325E-01 41 -40 51 -50 296 -297 u=2 imp:n=1
449 3 1.21307E-01 41 -40 51 -50 297 -298 u=2 imp:n=1
450 5 1.20013E-01 41 -40 51 -50 298 -299 u=2 imp:n=1
451 2 1.20984E-01 41 -40 51 -50 299 -300 u=2 imp:n=1
452 4 1.20325E-01 41 -40 51 -50 300 u=2 imp:n=1
453 9 5.40155E-05 (-41:40:-51:50) 313 45 -44 55 -54 u=2 imp:n=1
454 7 6.00385E-02 (-45:44:-55:54) 313 47 -46 57 -56 u=2 imp:n=1
455 9 5.40155E-05 (-47:46:-57:56) 313 u=2 imp:n=1
456 7 6.00385E-02 -313 312 u=2 imp:n=1
457 9 5.40155E-05 -312 311 u=2 imp:n=1
458 11 3.83231E-02 -311 u=2 imp:n=1
459 7 6.00385E-02 302 -301 306 -305 249 -250
(-304:303:-306:305:-309:310) u=2 imp:n=1
460 9 5.40155E-05 313 304 -303 306 -305 309 -310 u=2 imp:n=1
c DEFINITION OF UNIVERSES: ASSEMBLY 26
490 7 6.00385E-02 41 -40 51 -50 -61 u=3 imp:n=1
491 2 1.20984E-01 41 -40 51 -50 61 -62 u=3 imp:n=1
492 7 6.00385E-02 41 -40 51 -50 62 -340 u=3 imp:n=1
493 4 1.20325E-01 41 -40 51 -50 340 -341 u=3 imp:n=1
494 3 1.21307E-01 41 -40 51 -50 341 -342 u=3 imp:n=1
495 7 6.00385E-02 41 -40 51 -50 342 -343 u=3 imp:n=1
496 4 1.20325E-01 41 -40 51 -50 343 -344 u=3 imp:n=1
497 3 1.21307E-01 41 -40 51 -50 344 -345 u=3 imp:n=1
498 7 6.00385E-02 41 -40 51 -50 345 -346 u=3 imp:n=1
499 4 1.20325E-01 41 -40 51 -50 346 -347 u=3 imp:n=1
500 3 1.21307E-01 41 -40 51 -50 347 -348 u=3 imp:n=1
501 7 6.00385E-02 41 -40 51 -50 348 -349 u=3 imp:n=1
502 4 1.20325E-01 41 -40 51 -50 349 -350 u=3 imp:n=1
503 3 1.21307E-01 41 -40 51 -50 350 -351 u=3 imp:n=1
504 7 6.00385E-02 41 -40 51 -50 351 -352 u=3 imp:n=1
505 4 1.20325E-01 41 -40 51 -50 352 -353 u=3 imp:n=1
506 3 1.21307E-01 41 -40 51 -50 353 -354 u=3 imp:n=1
507 5 1.20013E-01 41 -40 51 -50 354 -355 u=3 imp:n=1
508 1 5.72591E-02 41 -40 51 -50 355 -356 u=3 imp:n=1
509 4 1.20325E-01 41 -40 51 -50 356 -357 u=3 imp:n=1
510 3 1.21307E-01 41 -40 51 -50 357 -358 u=3 imp:n=1
511 1 5.72591E-02 41 -40 51 -50 358 -359 u=3 imp:n=1
512 4 1.20325E-01 41 -40 51 -50 359 -360 u=3 imp:n=1
513 3 1.21307E-01 41 -40 51 -50 360 -361 u=3 imp:n=1
514 1 5.72591E-02 41 -40 51 -50 361 -362 u=3 imp:n=1
515 4 1.20325E-01 41 -40 51 -50 362 -363 u=3 imp:n=1
516 3 1.21307E-01 41 -40 51 -50 363 -364 u=3 imp:n=1

```


517	1	5.72591E-02	41	-40	51	-50	364	-365	u=3	imp:n=1
518	4	1.20325E-01	41	-40	51	-50	365	-366	u=3	imp:n=1
519	3	1.21307E-01	41	-40	51	-50	366	-367	u=3	imp:n=1
520	1	5.72591E-02	41	-40	51	-50	367	-368	u=3	imp:n=1
521	4	1.20325E-01	41	-40	51	-50	368	-369	u=3	imp:n=1
522	3	1.21307E-01	41	-40	51	-50	369	-370	u=3	imp:n=1
523	1	5.72591E-02	41	-40	51	-50	370	-371	u=3	imp:n=1
524	4	1.20325E-01	41	-40	51	-50	371	-372	u=3	imp:n=1
525	3	1.21307E-01	41	-40	51	-50	372	-373	u=3	imp:n=1
526	1	5.72591E-02	41	-40	51	-50	373	-374	u=3	imp:n=1
527	4	1.20325E-01	41	-40	51	-50	374	-375	u=3	imp:n=1
528	3	1.21307E-01	41	-40	51	-50	375	-376	u=3	imp:n=1
529	1	5.72591E-02	41	-40	51	-50	376	-377	u=3	imp:n=1
530	4	1.20325E-01	41	-40	51	-50	377	-378	u=3	imp:n=1
531	3	1.21307E-01	41	-40	51	-50	378	-379	u=3	imp:n=1
532	1	5.72591E-02	41	-40	51	-50	379	-380	u=3	imp:n=1
533	4	1.20325E-01	41	-40	51	-50	380	-381	u=3	imp:n=1
534	3	1.21307E-01	41	-40	51	-50	381	-382	u=3	imp:n=1
535	1	5.72591E-02	41	-40	51	-50	382	-383	u=3	imp:n=1
536	4	1.20325E-01	41	-40	51	-50	383	-384	u=3	imp:n=1
537	3	1.21307E-01	41	-40	51	-50	384	-385	u=3	imp:n=1
538	1	5.72591E-02	41	-40	51	-50	385	-386	u=3	imp:n=1
539	4	1.20325E-01	41	-40	51	-50	386	-387	u=3	imp:n=1
540	3	1.21307E-01	41	-40	51	-50	387	-388	u=3	imp:n=1
541	1	5.72591E-02	41	-40	51	-50	388	-389	u=3	imp:n=1
542	4	1.20325E-01	41	-40	51	-50	389	-390	u=3	imp:n=1
543	3	1.21307E-01	41	-40	51	-50	390	-391	u=3	imp:n=1
544	1	5.72591E-02	41	-40	51	-50	391	-392	u=3	imp:n=1
545	4	1.20325E-01	41	-40	51	-50	392	-393	u=3	imp:n=1
546	3	1.21307E-01	41	-40	51	-50	393	-394	u=3	imp:n=1
547	1	5.72591E-02	41	-40	51	-50	394	-395	u=3	imp:n=1
548	4	1.20325E-01	41	-40	51	-50	395	-396	u=3	imp:n=1
549	3	1.21307E-01	41	-40	51	-50	396	-397	u=3	imp:n=1
550	1	5.72591E-02	41	-40	51	-50	397	-398	u=3	imp:n=1
551	4	1.20325E-01	41	-40	51	-50	398	-399	u=3	imp:n=1
552	3	1.21307E-01	41	-40	51	-50	399	-400	u=3	imp:n=1
553	1	5.72591E-02	41	-40	51	-50	400	-401	u=3	imp:n=1
554	4	1.20325E-01	41	-40	51	-50	401	-402	u=3	imp:n=1
555	3	1.21307E-01	41	-40	51	-50	402	-403	u=3	imp:n=1
556	1	5.72591E-02	41	-40	51	-50	403	-404	u=3	imp:n=1
557	4	1.20325E-01	41	-40	51	-50	404	-405	u=3	imp:n=1
558	3	1.21307E-01	41	-40	51	-50	405	-406	u=3	imp:n=1
559	1	5.72591E-02	41	-40	51	-50	406	-407	u=3	imp:n=1
560	4	1.20325E-01	41	-40	51	-50	407	-408	u=3	imp:n=1
561	3	1.21307E-01	41	-40	51	-50	408	-409	u=3	imp:n=1
562	1	5.72591E-02	41	-40	51	-50	409	-410	u=3	imp:n=1
563	4	1.20325E-01	41	-40	51	-50	410	-411	u=3	imp:n=1
564	3	1.21307E-01	41	-40	51	-50	411	-412	u=3	imp:n=1
565	1	5.72591E-02	41	-40	51	-50	412	-413	u=3	imp:n=1
566	4	1.20325E-01	41	-40	51	-50	413	-414	u=3	imp:n=1
567	3	1.21307E-01	41	-40	51	-50	414	-415	u=3	imp:n=1
568	1	5.72591E-02	41	-40	51	-50	415	-416	u=3	imp:n=1
569	4	1.20325E-01	41	-40	51	-50	416	-417	u=3	imp:n=1
570	3	1.21307E-01	41	-40	51	-50	417	-418	u=3	imp:n=1
571	1	5.72591E-02	41	-40	51	-50	418	-419	u=3	imp:n=1
572	4	1.20325E-01	41	-40	51	-50	419	-420	u=3	imp:n=1
573	3	1.21307E-01	41	-40	51	-50	420	-421	u=3	imp:n=1
574	1	5.72591E-02	41	-40	51	-50	421	-422	u=3	imp:n=1
575	4	1.20325E-01	41	-40	51	-50	422	-423	u=3	imp:n=1
576	3	1.21307E-01	41	-40	51	-50	423	-424	u=3	imp:n=1
577	1	5.72591E-02	41	-40	51	-50	424	-425	u=3	imp:n=1
578	4	1.20325E-01	41	-40	51	-50	425	-426	u=3	imp:n=1
579	3	1.21307E-01	41	-40	51	-50	426	-427	u=3	imp:n=1
580	1	5.72591E-02	41	-40	51	-50	427	-428	u=3	imp:n=1
581	4	1.20325E-01	41	-40	51	-50	428	-429	u=3	imp:n=1

```

582 3 1.21307E-01 41 -40 51 -50 429 -430 u=3 imp:n=1
583 1 5.72591E-02 41 -40 51 -50 430 -431 u=3 imp:n=1
584 4 1.20325E-01 41 -40 51 -50 431 -432 u=3 imp:n=1
585 3 1.21307E-01 41 -40 51 -50 432 -433 u=3 imp:n=1
586 5 1.20013E-01 41 -40 51 -50 433 -434 u=3 imp:n=1
587 7 6.00385E-02 41 -40 51 -50 434 -435 u=3 imp:n=1
588 4 1.20325E-01 41 -40 51 -50 435 -436 u=3 imp:n=1
589 3 1.21307E-01 41 -40 51 -50 436 -437 u=3 imp:n=1
590 7 6.00385E-02 41 -40 51 -50 437 -438 u=3 imp:n=1
591 4 1.20325E-01 41 -40 51 -50 438 -439 u=3 imp:n=1
592 3 1.21307E-01 41 -40 51 -50 439 -440 u=3 imp:n=1
593 7 6.00385E-02 41 -40 51 -50 440 -441 u=3 imp:n=1
594 4 1.20325E-01 41 -40 51 -50 441 -442 u=3 imp:n=1
595 3 1.21307E-01 41 -40 51 -50 442 -443 u=3 imp:n=1
596 7 6.00385E-02 41 -40 51 -50 443 -444 u=3 imp:n=1
597 4 1.20325E-01 41 -40 51 -50 444 -445 u=3 imp:n=1
598 3 1.21307E-01 41 -40 51 -50 445 -446 u=3 imp:n=1
599 7 6.00385E-02 41 -40 51 -50 446 -447 u=3 imp:n=1
600 4 1.20325E-01 41 -40 51 -50 447 -448 u=3 imp:n=1
601 3 1.21307E-01 41 -40 51 -50 448 -172 u=3 imp:n=1
602 2 1.20984E-01 41 -40 51 -50 172 -173 u=3 imp:n=1
603 4 1.20325E-01 41 -40 51 -50 173 u=3 imp:n=1
604 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=3 imp:n=1
605 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=3 imp:n=1
606 9 5.40155E-05 (-47:46:-57:56) u=3 imp:n=1
c DEFINITION OF UNIVERSES: ALUMINUM SHEATH
630 9 5.40155E-05 45 -44 55 -54 u=4 imp:n=1
631 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=4 imp:n=1
632 9 5.40155E-05 (-47:46:-57:56) u=4 imp:n=1
c DEFINITION OF UNIVERSES: POLYETHYLENE REFLECTOR
640 5 1.20013E-01 41 -40 51 -50 u=5 imp:n=1
641 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=5 imp:n=1
642 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=5 imp:n=1
643 9 5.40155E-05 (-47:46:-57:56) u=5 imp:n=1
c DEFINITION OF UNIVERSES: CONTROL/SAFETY ROD C1,C2,C3,S4-S6 FULLY WITHDRAWN
660 6 5.17979E-02 -470 477 u=6 imp:n=1
661 7 6.00385E-02 470 -471 477 u=6 imp:n=1
662 9 5.40155E-05 471 -472 477 u=6 imp:n=1
663 7 6.00385E-02 472 -473 477 u=6 imp:n=1
664 7 6.00385E-02 -473 476 -477 u=6 imp:n=1
665 9 5.40155E-05 473 476 u=6 imp:n=1
666 9 5.40155E-05 -476 u=6 imp:n=1
c DEFINITION OF UNIVERSES: CONTROL ROD C3
680 6 5.17979E-02 -470 475 u=7 imp:n=1
681 7 6.00385E-02 470 -471 475 u=7 imp:n=1
682 9 5.40155E-05 471 -472 475 u=7 imp:n=1
683 7 6.00385E-02 472 -473 475 u=7 imp:n=1
684 7 6.00385E-02 -473 474 -475 u=7 imp:n=1
685 9 5.40155E-05 473 474 u=7 imp:n=1
686 9 5.40155E-05 -474 u=7 imp:n=1
c DEFINITION OF UNIVERSES: NEUTRON SHIELD AND BEAM DUCT b
700 7 6.00385E-02 41 -40 51 -50 -490 u=8 imp:n=1
701 5 1.20013E-01 41 -40 51 -50 490 -491 u=8 imp:n=1
702 8 1.18233E-01 41 -40 51 -50 491 -492 u=8 imp:n=1
703 8 1.18233E-01 41 -40 51 -50 492 -493 u=8 imp:n=1
704 8 1.18233E-01 41 -40 51 -50 493 -494 u=8 imp:n=1
705 5 1.20013E-01 41 -40 51 -50 494 u=8 imp:n=1
706 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=8 imp:n=1
707 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=8 imp:n=1
708 9 5.40155E-05 (-47:46:-57:56) u=8 imp:n=1
c DEFINITION OF UNIVERSES: NEUTRON SHIELD AND BEAM DUCT bs
720 7 6.00385E-02 41 -40 51 -50 -490 u=9 imp:n=1
721 5 1.20013E-01 41 -40 51 -50 490 -510 u=9 imp:n=1
722 8 1.18233E-01 41 -40 51 -50 510 -511 u=9 imp:n=1
723 9 5.40155E-05 (-302:301:-306:305) 41 -40 51 -50 511 -249 u=9 imp:n=1

```

```

724 9 5.40155E-05 (-302:301:-306:305)
      41 -40 51 -50 249 -250 u=9 imp:n=1
725 9 5.40155E-05 (-302:301:-306:305) 41 -40 51 -50 250 -512 u=9 imp:n=1
726 8 1.18233E-01 41 -40 51 -50 512 -513 u=9 imp:n=1
727 5 1.20013E-01 41 -40 51 -50 513 u=9 imp:n=1
728 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=9 imp:n=1
729 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=9 imp:n=1
730 9 5.40155E-05 (-47:46:-57:56) u=9 imp:n=1
732 7 6.00385E-02 302 -301 306 -305 511 -249
      (-304:303:-306:305:-514:515) u=9 imp:n=1
733 9 5.40155E-05 304 -303 306 -305 514 -515 u=9 imp:n=1
734 7 6.00385E-02 302 -301 306 -305 249 -250
      (-304:303:-306:305:-309:310) u=9 imp:n=1
735 9 5.40155E-05 304 -303 306 -305 309 -310 u=9 imp:n=1
736 7 6.00385E-02 302 -301 306 -305 250 -512
      (-304:303:-306:305:-516:517) u=9 imp:n=1
737 9 5.40155E-05 304 -303 306 -305 516 -517 u=9 imp:n=1
c DEFINITION OF UNIVERSES: NEUTRON SHIELD AND BEAM DUCT f
740 7 6.00385E-02 41 -40 51 -50 -490 u=10 imp:n=1
741 5 1.20013E-01 41 -40 51 -50 490 -530 u=10 imp:n=1
742 8 1.18233E-01 41 -40 51 -50 530 -531 u=10 imp:n=1
743 10 8.44131E-02 41 -40 51 -50 531 -532 u=10 imp:n=1
744 10 8.44131E-02 41 -40 51 -50 532 -511 u=10 imp:n=1
745 10 8.44131E-02 41 -40 51 -50 511 -249 u=10 imp:n=1
746 10 8.44131E-02 41 -40 51 -50 249 -250 u=10 imp:n=1
747 10 8.44131E-02 41 -40 51 -50 250 -512 u=10 imp:n=1
748 10 8.44131E-02 41 -40 51 -50 512 -533 u=10 imp:n=1
749 10 8.44131E-02 41 -40 51 -50 533 -534 u=10 imp:n=1
750 8 1.18233E-01 41 -40 51 -50 534 -535 u=10 imp:n=1
751 5 1.20013E-01 41 -40 51 -50 535 u=10 imp:n=1
752 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=10 imp:n=1
753 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=10 imp:n=1
754 9 5.40155E-05 (-47:46:-57:56) u=10 imp:n=1
c DEFINITION OF UNIVERSES: NEUTRON SHIELD AND BEAM DUCT fs
765 7 6.00385E-02 41 -40 51 -50 -490 u=11 imp:n=1
766 5 1.20013E-01 41 -40 51 -50 490 -530 u=11 imp:n=1
767 8 1.18233E-01 41 -40 51 -50 530 -531 u=11 imp:n=1
768 10 8.44131E-02 41 -40 51 -50 531 -532 u=11 imp:n=1
769 10 8.44131E-02 41 -40 51 -50 532 -511 u=11 imp:n=1
770 9 5.40155E-05 (-302:301:-306:305) 41 -40 51 -50 511 -249 u=11 imp:n=1
771 9 5.40155E-05 (-302:301:-306:305)
      41 -40 51 -50 249 -250 u=11 imp:n=1
772 9 5.40155E-05 (-302:301:-306:305) 41 -40 51 -50 250 -512 u=11 imp:n=1
773 10 8.44131E-02 41 -40 51 -50 512 -533 u=11 imp:n=1
774 10 8.44131E-02 41 -40 51 -50 533 -534 u=11 imp:n=1
775 8 1.18233E-01 41 -40 51 -50 534 -535 u=11 imp:n=1
776 5 1.20013E-01 41 -40 51 -50 535 u=11 imp:n=1
777 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=11 imp:n=1
778 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=11 imp:n=1
779 9 5.40155E-05 (-47:46:-57:56) u=11 imp:n=1
781 7 6.00385E-02 302 -301 306 -305 511 -249
      (-304:303:-306:305:-514:515) u=11 imp:n=1
782 9 5.40155E-05 304 -303 306 -305 514 -515 u=11 imp:n=1
783 7 6.00385E-02 302 -301 306 -305 249 -250
      (-304:303:-306:305:-309:310) u=11 imp:n=1
784 9 5.40155E-05 304 -303 306 -305 309 -310 u=11 imp:n=1
785 7 6.00385E-02 302 -301 306 -305 250 -512
      (-304:303:-306:305:-516:517) u=11 imp:n=1
786 9 5.40155E-05 304 -303 306 -305 516 -517 u=11 imp:n=1
c DEFINITION OF UNIVERSES: NEUTRON SHIELD AND BEAM DUCT s
790 7 6.00385E-02 41 -40 51 -50 -490 u=12 imp:n=1
791 5 1.20013E-01 41 -40 51 -50 490 -511 u=12 imp:n=1
792 9 5.40155E-05 (-302:301:-306:305) 41 -40 51 -50 511 -249 u=12 imp:n=1
793 9 5.40155E-05 (-302:301:-306:305)
      41 -40 51 -50 249 -250 u=12 imp:n=1

```

```

794 9 5.40155E-05 (-302:301:-306:305) 41 -40 51 -50 250 -512 u=12 imp:n=1
795 5 1.20013E-01 41 -40 51 -50 512 u=12 imp:n=1
796 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=12 imp:n=1
797 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=12 imp:n=1
798 9 5.40155E-05 (-47:46:-57:56) u=12 imp:n=1
800 7 6.00385E-02 302 -301 306 -305 511 -249
(-304:303:-306:305:-514:515) u=12 imp:n=1
801 9 5.40155E-05 304 -303 306 -305 514 -515 u=12 imp:n=1
802 7 6.00385E-02 302 -301 306 -305 249 -250
(-304:303:-306:305:-309:310) u=12 imp:n=1
803 9 5.40155E-05 304 -303 306 -305 309 -310 u=12 imp:n=1
804 7 6.00385E-02 302 -301 306 -305 250 -512
(-304:303:-306:305:-516:517) u=12 imp:n=1
805 9 5.40155E-05 304 -303 306 -305 516 -517 u=12 imp:n=1
c DEFINITION OF UNIVERSES: NEUTRON SHIELD AND BEAM DUCT s'
810 7 6.00385E-02 41 -40 51 -50 -490 u=13 imp:n=1
811 5 1.20013E-01 41 -40 51 -50 490 -249 u=13 imp:n=1
812 9 5.40155E-05 (-302:301:-306:305)
41 -40 51 -50 249 -250 u=13 imp:n=1
813 5 1.20013E-01 41 -40 51 -50 250 u=13 imp:n=1
814 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=13 imp:n=1
815 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=13 imp:n=1
816 9 5.40155E-05 (-47:46:-57:56) u=13 imp:n=1
818 7 6.00385E-02 302 -301 306 -305 249 -250
(-304:303:-306:305:-309:310) u=13 imp:n=1
819 9 5.40155E-05 304 -303 306 -305 309 -310 u=13 imp:n=1
c DEFINITION OF UNIVERSES: ALUMINUM
960 7 6.00385E-02 41 -40 51 -50 u=18 imp:n=1
961 9 5.40155E-05 (-41:40:-51:50) 45 -44 55 -54 u=18 imp:n=1
962 7 6.00385E-02 (-45:44:-55:54) 47 -46 57 -56 u=18 imp:n=1
963 9 5.40155E-05 (-47:46:-57:56) u=18 imp:n=1
c DEFINITION OF UNIVERSES: VOID
968 9 5.40155E-05 41 -40 51 -50 u=19 imp:n=1
969 9 5.40155E-05 (-41:40:-51:50) u=19 imp:n=1
c DEFINITION OF UNIVERSES: VOID POLYETHYLENE
974 9 5.40155E-05 -550 u=20 imp:n=1
975 5 1.20013E-01 550 u=20 imp:n=1
c DEFINITION OF UNIVERSES: CONTROL/SAFETY ROD C1,C2,C3,S4-S6 FULL INSERTED
990 6 5.17979E-02 -470 479 u=21 imp:n=1
991 7 6.00385E-02 470 -471 479 u=21 imp:n=1
992 9 5.40155E-05 471 -472 479 u=21 imp:n=1
993 7 6.00385E-02 472 -473 479 u=21 imp:n=1
994 7 6.00385E-02 -473 478 -479 u=21 imp:n=1
995 9 5.40155E-05 473 478 u=21 imp:n=1
996 9 5.40155E-05 -478 u=21 imp:n=1

```

c Surface cards

```

1 px -64.095
2 px -41.775
3 px -8.395
4 px 8.395
5 px 41.775
6 px 64.095
10 py 50.17
11 py 16.79
12 py 0.0
13 py -33.38
14 py -66.76
20 px -63.995
21 px -41.875
22 px -41.675
23 px -8.495
24 px -8.295
25 px 8.295
26 px 8.495

```

```

27 px 41.675
28 px 41.875
29 px 63.995
30 py 50.07
31 py 16.89
32 py 16.69
33 py 0.1
34 py -0.1
35 py -33.28
36 py -33.48
37 py -66.66
40 px 2.54
41 px -2.54
42 px 2.765
43 px -2.765
44 px 2.565
45 px -2.565
46 px 2.715
47 px -2.715
50 py 2.54
51 py -2.54
52 py 2.765
53 py -2.765
54 py 2.565
55 py -2.565
56 py 2.715
57 py -2.715
c ccccccccccccccccccccccccccc Assembly F cccccccccccccccccccccccccccc
60 pz -76.2
61 pz -73.66
c 62 pz -72.39 !Not needed
62 pz -71.12
63 pz -22.4521
64 pz -22.2934
65 pz -21.9848
66 pz -21.3548
67 pz -21.1961
68 pz -20.8875
69 pz -20.2575
70 pz -20.0988
71 pz -19.7902
72 pz -19.1602
73 pz -19.0015
74 pz -18.6929
75 pz -18.0629
76 pz -17.9042
77 pz -17.5956
78 pz -16.9656
79 pz -16.8069
80 pz -16.4983
81 pz -15.8683
82 pz -15.7096
83 pz -15.4010
84 pz -14.7710
85 pz -14.6123
86 pz -14.3037
87 pz -13.6737
88 pz -13.5150
89 pz -13.2064
90 pz -12.5764
91 pz -12.4177
92 pz -12.1091
93 pz -11.4791
94 pz -11.3204
95 pz -11.0118

```

96	pz	-10.3818
97	pz	-10.2231
98	pz	-9.9145
99	pz	-9.2845
100	pz	-9.1258
101	pz	-8.8172
102	pz	-8.1872
103	pz	-8.0285
104	pz	-7.7199
105	pz	-7.0899
106	pz	-6.9312
107	pz	-6.6226
108	pz	-5.9926
109	pz	-5.8339
110	pz	-5.5253
111	pz	-4.8953
112	pz	-4.7366
113	pz	-4.4280
114	pz	-3.7980
115	pz	-3.6393
116	pz	-3.3307
117	pz	-2.7007
118	pz	-2.5420
119	pz	-2.2334
120	pz	-1.6034
121	pz	-1.4447
122	pz	-1.1361
123	pz	-0.5061
124	pz	-0.3474
125	pz	-0.0388
126	pz	0.5912
127	pz	0.7499
128	pz	1.0585
129	pz	1.6885
130	pz	1.8472
131	pz	2.1558
132	pz	2.7858
133	pz	2.9445
134	pz	3.2531
135	pz	3.8831
136	pz	4.0418
137	pz	4.3504
138	pz	4.9804
139	pz	5.1391
140	pz	5.4477
141	pz	6.0777
142	pz	6.2364
143	pz	6.5450
144	pz	7.1750
145	pz	7.3337
146	pz	7.6423
147	pz	8.2723
148	pz	8.4310
149	pz	8.7396
150	pz	9.3696
151	pz	9.5283
152	pz	9.8369
153	pz	10.4669
154	pz	10.6256
155	pz	10.9342
156	pz	11.5642
157	pz	11.7229
158	pz	12.0315
159	pz	12.6615
160	pz	12.8202

```
c 171 pz 17.0507 !this was the exact point, but I use the bench specification
c 171 pz 17.0521
c 172 pz 68.2625
c 173 pz 74.6125
c 174 pz 76.2
c cccccccccccccccccccccccccccccc Assembly SV cccccccccccccccccccccccccccccc
c 200 pz -73.66 !see surface 61
c 200 pz -72.39 !not needed
c 200 pz -71.12 !this was the exact point, but I use the bench specification
200 pz -71.1199
201 pz -22.7574
202 pz -22.5987
203 pz -22.2901
204 pz -21.6601
205 pz -21.5014
206 pz -21.1928
207 pz -20.5628
208 pz -20.4041
209 pz -20.0955
210 pz -19.4655
211 pz -19.3068
212 pz -18.9982
213 pz -18.3682
214 pz -18.2095
215 pz -17.9009
216 pz -17.2709
217 pz -17.1122
218 pz -16.8036
219 pz -16.1736
220 pz -16.0149
221 pz -15.7063
222 pz -15.0763
223 pz -14.9176
224 pz -14.6090
225 pz -13.9790
226 pz -13.8203
227 pz -13.5117
228 pz -12.8817
229 pz -12.7230
230 pz -12.4144
231 pz -11.7844
232 pz -11.6257
233 pz -11.3171
234 pz -10.6871
235 pz -10.5284
236 pz -10.2198
237 pz -9.5898
238 pz -9.4311
239 pz -9.1225
240 pz -8.4925
241 pz -8.3338
242 pz -8.0252
243 pz -7.3952
244 pz -7.2365
245 pz -6.9279
```

246 pz -6.2979
247 pz -6.1392
248 pz -5.8306
c 249 pz -5.2006 !this was the exact point, but I use the bench specification
249 pz -5.2
250 pz -0.2
251 pz -0.0413
252 pz 0.2673
253 pz 0.8973
254 pz 1.0560
255 pz 1.3646
256 pz 1.9946
257 pz 2.1533
258 pz 2.4619
259 pz 3.0919
260 pz 3.2506
261 pz 3.5592
262 pz 4.1892
263 pz 4.3479
264 pz 4.6565
265 pz 5.2865
266 pz 5.4452
267 pz 5.7538
268 pz 6.3838
269 pz 6.5425
270 pz 6.8511
271 pz 7.4811
272 pz 7.6398
273 pz 7.9484
274 pz 8.5784
275 pz 8.7371
276 pz 9.0457
277 pz 9.6757
278 pz 9.8344
279 pz 10.1430
280 pz 10.7730
281 pz 10.9317
282 pz 11.2403
283 pz 11.8703
284 pz 12.0290
285 pz 12.3376
286 pz 12.9676
287 pz 13.1263
288 pz 13.4349
289 pz 14.0649
290 pz 14.2236
291 pz 14.5322
292 pz 15.1622
293 pz 15.3209
294 pz 15.6295
295 pz 16.2595
296 pz 16.4182
297 pz 16.7268
c 298 pz 17.3568 !this was the exact point, but I use the bench specification
298 pz 17.3574
299 pz 68.8975
300 pz 75.2475
301 px 2.5
302 px -2.5
303 px 2.3
304 px -2.3
305 py 2.5
306 py -2.5
c 307 py 2.3
c 308 py -2.3


```
c pz -5.  
310 pz -0.4  
311 c/y 8.395 -2.7 0.075  
312 c/y 8.395 -2.7 0.1  
313 c/y 8.395 -2.7 0.11  
c cccccccccccccccccccccc Assembly 26 cccccccccccccccccccccccccc  
c 340 pz -73.66 !see surface 61  
c 340 pz -72.39 !not needed  
c 340 pz -71.12 !see surface 62  
340 pz -70.9613  
341 pz -70.6438  
342 pz -70.0088  
343 pz -69.8501  
344 pz -69.5326  
345 pz -68.8976  
346 pz -68.7389  
347 pz -68.4214  
348 pz -67.7864  
349 pz -67.6277  
350 pz -67.3102  
351 pz -66.6752  
352 pz -66.5165  
353 pz -66.1990  
c 354 pz -65.5640 !this was the exact point, but I use the bench specification  
354 pz -65.6333  
355 pz -16.9654  
356 pz -16.8067  
357 pz -16.4981  
358 pz -15.8681  
359 pz -15.7094  
360 pz -15.4008  
361 pz -14.7708  
362 pz -14.6121  
363 pz -14.3035  
364 pz -13.6735  
365 pz -13.5148  
366 pz -13.2062  
367 pz -12.5762  
368 pz -12.4175  
369 pz -12.1089  
370 pz -11.4789  
371 pz -11.3202  
372 pz -11.0116  
373 pz -10.3816  
374 pz -10.2229  
375 pz -9.9143  
376 pz -9.2843  
377 pz -9.1256  
378 pz -8.8170  
379 pz -8.1870  
380 pz -8.0283  
381 pz -7.7197  
382 pz -7.0897  
383 pz -6.9310  
384 pz -6.6224  
385 pz -5.9924  
386 pz -5.8337  
387 pz -5.5251  
388 pz -4.8951  
389 pz -4.7364  
390 pz -4.4278  
391 pz -3.7978  
392 pz -3.6391  
393 pz -3.3305  
394 pz -2.7005
```

```

395 pz -2.5418
396 pz -2.2332
397 pz -1.6032
398 pz -1.4445
399 pz -1.1359
400 pz -0.5059
401 pz -0.3472
402 pz -0.0386
403 pz 0.5914
404 pz 0.7501
405 pz 1.0587
406 pz 1.6887
407 pz 1.8474
408 pz 2.1560
409 pz 2.7860
410 pz 2.9447
411 pz 3.2533
412 pz 3.8833
413 pz 4.0420
414 pz 4.3506
415 pz 4.9806
416 pz 5.1393
417 pz 5.4479
418 pz 6.0779
419 pz 6.2366
420 pz 6.5452
421 pz 7.1752
422 pz 7.3339
423 pz 7.6425
424 pz 8.2725
425 pz 8.4312
426 pz 8.7398
427 pz 9.3698
428 pz 9.5285
429 pz 9.8371
430 pz 10.4671
431 pz 10.6258
432 pz 10.9344
c 433 pz 11.5644 !this was the exact point, but I use the bench specification
433 pz 11.5654
434 pz 62.7758
435 pz 62.9346
436 pz 63.2520
437 pz 63.8870
438 pz 64.0458
439 pz 64.3632
440 pz 64.9982
441 pz 65.1570
442 pz 65.4744
443 pz 66.1094
444 pz 66.2682
445 pz 66.5856
446 pz 67.2206
447 pz 67.3794
448 pz 67.6968
c 449 pz 68.3318 !this was the exact point, but I use the bench specification
c 449 pz 68.2625 !see surface 172
c 449 pz 74.6125 !see surface 173
c ccccccccccccccc Control rods and Safety Rods ccccccccccccccc
470 cz 1.69
471 cz 2.
472 cz 2.25
473 cz 2.5
474 pz -12.866 $Aluminum (position C3 52.434 cm)
475 pz -12.366 $B2O3

```

```

476 pz 54.7 $Aluminum (position upper limit 120 cm for C1,C2,C3,S4-S6)
477 pz 55.2 $B2O3
478 pz -65.3 $Aluminum (full inserted 11.4 cm for C1,C2,C3,S4-S6)
479 pz -64.8 $B2O3
c ccccccccccccc Neutron shield and beam duct b ccccccccccccc
490 pz -74.2
491 pz -40.8
492 pz -15.4
493 pz 10
494 pz 35.4
c ccccccccccccc Neutron shield and beam duct bs ccccccccccccc
510 pz -35.6
511 pz -10.2
c 512 pz -5.2 !see surface 249
c 512 pz -0.2 !see surface 250
512 pz 4.8
513 pz 30.2
514 pz -10.
515 pz -5.4
c 516 pz -5. !see surface 309
c 516 pz -0.4 !see surface 310
516 pz 0.
517 pz 4.6
c ccccccccccccc Neutron shield and beam duct f ccccccccccccc
530 pz -45.6
531 pz -20.2
532 pz -15.2
c 533 pz -10.2 !see surface 511
c 533 pz -5.2 !see surface 249
c 533 pz -0.2 !see surface 250
c 533 pz 4.8 !see surface 512
533 pz 9.8
534 pz 14.8
535 pz 40.2
c ccccccccccccc Neutron shield and beam duct s ccccccccccccc
c 550 pz -10.2 !see surface 511
c 550 pz -5.2 !see surface 249
c 550 pz -0.2 !see surface 250
c 550 pz 4.8 !see surface 512
c ccccccccccccc Neutron shield and beam duct s' ccccccccccccc
c 550 pz -5.2 !see surface 249
c 550 pz -0.2 !see surface 250
c ccccccccccccc 1/2 Phi" Void Polyethylene ccccccccccccc
550 cz 0.635

```

```

mode n
c 1/16" t highly enriched Uranium fuel plate (U-Al alloy)
m1 92235.70c 1.50694E-03
92238.70c 1.08560E-04
13027.70c 5.56436E-02
C SUM 5.72591E-02
C 1/2" t polyethylene reflector plate
m2 1001.70c 8.06560E-02
6000.70c 4.03280E-02
mt2 poly.10t
C SUM 1.20984E-01
C 1/4" t polyethylene reflector plate
m3 1001.70c 8.08711E-02
6000.70c 4.04356E-02
mt3 poly.10t
C SUM 1.21307E-01
C 1/8" t polyethylene reflector plate
m4 1001.70c 8.02167E-02
6000.70c 4.01084E-02
mt4 poly.10t

```

```

C      SUM      1.20325E-01
C      polyethylene square rod
m5      1001.70c 8.00083E-02
        6000.70c 4.00042E-02
mt5      poly.10t
C      SUM      1.20013E-01
C      control and safety rods
m6      5010.70c 3.87448E-03
        5011.70c 1.68447E-02
        8016.70c 3.10787E-02
C      SUM      5.17979E-02
C      aluminum sheath for the core and 1/16" t Al plate
m7      13027.70c 6.00385E-02
C      SUM      6.00385E-02
C      B10 (10 wt%)
m8      1001.70c 7.02275E-02
        6000.70c 3.60038E-02
        5010.70c 8.97693E-04
        5011.70c 3.90281E-03
        8016.70c 7.20074E-03
C      SUM      1.18233E-01
C      Air
m9      7014.70c 4.37433E-05
        8016.70c 1.02722E-05
C      SUM      5.40155E-05
C      Iron
m10     26054.70c 4.93395E-03
        26056.70c 7.74524E-02
        26057.70c 1.78871E-03
        26058.70c 2.38045E-04
C      SUM      8.44131E-02
C      Indium Wire: density 7.31 g/cm3
m11     49113.70c 1.64406E-03
        49115.70c 3.66790E-02
C      SUM      3.83231E-02
kcode  1000000 1.0 20 200
sdef    pos= 0. -11.16 -2.7
        axs= 0 0 1
        x =d1
        y =d2
        z =d3
        erg d4
si1     h -14.02 14.02
sp1     d 0 1
si2     h -11.06 11.06
sp2     d 0 1
si3     h -19.75 19.75
sp3     d 0 1
sp4     -3
PRDMP   0 1 0 10
totnu
print

```

Nuclear Engineering Division

Argonne National Laboratory
9700 South Cass Avenue, Bldg. 208
Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC