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ANALYSES FOR THE CONVERSION OF THE PURDUE UNIVERSITY RESEARCH REACTOR FROM HEU TO LEU FUEL

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ABSTRACT

Analyses were performed in preparation for the conversion of the Purdue University Research Reactor, PUR-1, from HEU U-Al alloy to LEU Silicide fuel. The culmination of these analyses was the submission of a conversion analysis proposal to the USNRC in August 2006, in preparation for conversion to LEU in the summer of 2007. This study concludes that the replacement of the sixteen HEU assemblies, which contain 10 plates, with sixteen assemblies containing up to 14 plates, will allow for similar safety and performance as the HEU core. The analyses were performed by students and staff at the PUR-1 facility, with the support of the RERTR program at the Argonne National Laboratory.

PUR-1 is a pool-type reactor that was built for Purdue by the Lockheed Nuclear Corporation in 1962. It was designed for operation at 10 kW, but is licensed for 1 kW operation. The reactor serves the training, education and research needs of the School of Nuclear Engineering at Purdue University.

1 Introduction

The Purdue University Research Reactor (PUR-1) is a sixteen assembly, pool-type MTR with plate fuel, which was built in 1962 by the Lockheed Nuclear Corporation. It has a design power of 10 kW, and is licensed for operation at 1kW. PUR-1 is still using

its original highly enriched uranium (HEU) fuel load, and due to the low power of the reactor, the fuel has experienced limited burnup. The U-Al alloy HEU fuel is to be replaced with LEU fuel as part of the larger effort by NNSA and DOE to remove HEU from civilian reactors.

In order to best analyze the proposed LEU core, a detailed model of the HEU core was developed to determine operational and safety related parameters and compare them where possible to measured values and benchmarked data. Once a credible model for the HEU core was established, the model was modified to represent the LEU core, making the geometry and material definition changes as necessary. These calculations for the HEU and LEU cores utilized the MCNP5[i] Monte Carlo code, with the ENDF-VI.5 continuous energy cross-section library. Since PUR-1 has negligible depletion at an operating power of 1kW, all calculations were done considering a fresh core loading for both the HEU and LEU cores.

2 Reactor Description

PUR-1 has sixteen fueled assemblies: thirteen (13) standard assemblies with ten plates each, and 3 control assemblies with six plates each. The fuel plates are Uranium-Aluminum alloy, clad in 1100 Aluminum. The core itself is a 4x4 array of fueled assemblies, surrounded by a graphite reflector. On one side of the reflector, the graphite assemblies have sample tubes which comprise an irradiation facility which can be loaded and unloaded with samples while the reactor is shut down. The layout of PUR-1 is shown in Figure 1.

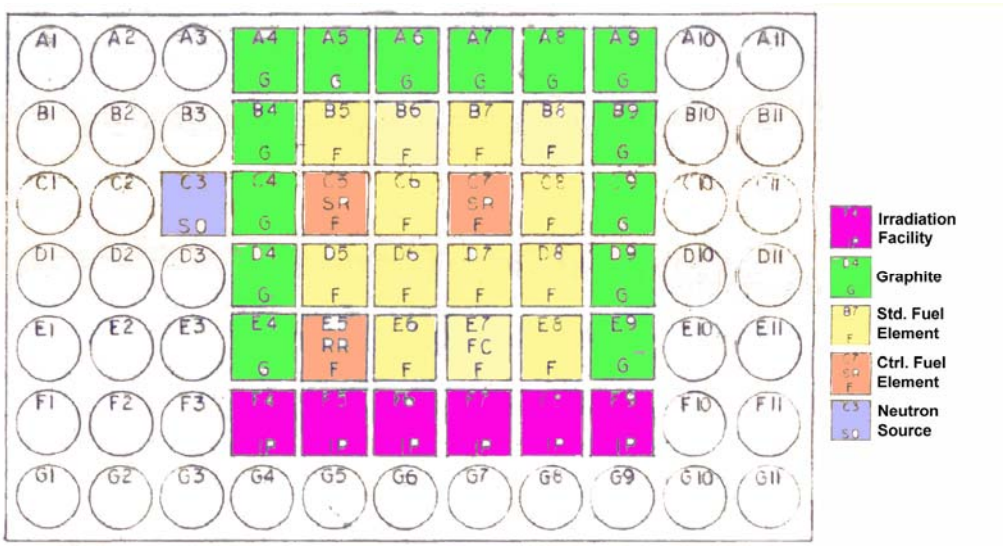

Figure 1: PUR-1 Core Layout

The present HEU core load has 124 of 148 possible fuel plates, with 24 dummy aluminum plates dispersed among the standard fuel assemblies. The three control assemblies each contain 6 fuel plates with no dummies. The ten U-Al and dummy plates of the standard assemblies are joined together by bolts at the corners, and placed in individual 6061 aluminum assembly cans. The 6 plates of the control

assemblies are joined in two groups of three, and placed in assembly cans that contain an empty middle region to allow free travel of the shim/safety and regulating control rods.

Two shim-safety rods (labeled SS-1 and SS-2) composed of borated, 304-stainless steel, and one regulating rod (labeled RR) made with an elongated 304-stainless steel tube comprise the control system for PUR-1. The reactor control system is the original Lockheed instrumentation, which is slowly being upgraded as funds allow.

3 The HEU MCNP5 Model

The MCNP5 model of the HEU core was developed utilizing all of the available information about the core, including original engineering drawings, fuel specifications, and other structural and material information. Where information was incomplete, actual measurements were obtained when possible. However, specific materials analyses were not available for all reactor components (e.g. the 6061 aluminum in the assembly cans). In such cases, the ASTM alloy information, or similar data, were used.

The reactor core model was constructed plate-by-plate, and assembly-by-assembly. This was a significant undertaking, but it provided excellent results and matched measured operation conditions very well. The MCNP5 model is shown in Figure 2.

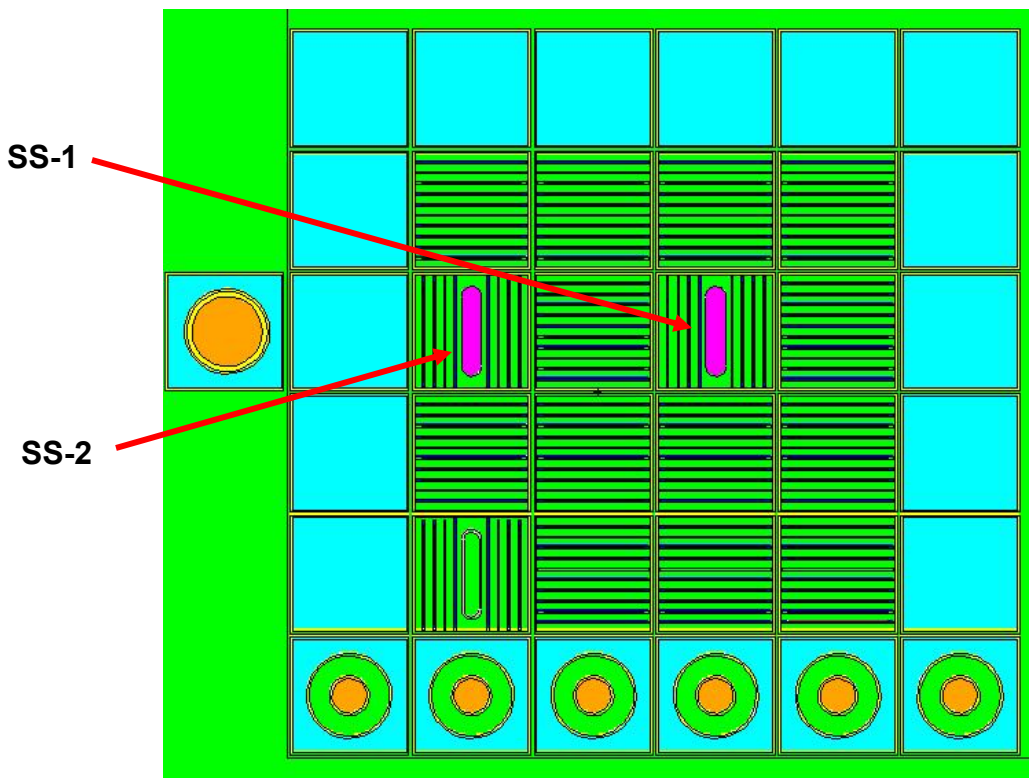

Figure 2: The HEU MCNP PUR-1 Core Model

Once the HEU model was developed, several cases were run to establish the credibility of the model. An initial criticality case with all control rods at their upper limit gave a k_{eff}

of 1.00753, compared with a measured value of 1.00431 taken by the reactor staff. Thus, the HEU core model has a reactivity bias is 0.32% Δk/k.

Several cases were then run to compare the model to 5 measured critical rod positions. The first two cases were with each of the shim safety rods controlling, respectively, and the other rods at their upper limits. Case 3 was a banked rods condition. Case 4 had RR at its lower limit, SS-1 at its upper limit, and SS-2 controlling. Case 5 had RR near mid-core, SS-1 at the upper limit, and SS-2 controlling. Table 1 details the results of these calculations.

Table 1: Comparison of calculated to measured critical rod positions for HEU core

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Case	RR Position (cm)	SS-2 Position (cm)	SS-1 Position (cm)	Eigenvalue	Bias %Δk/k
1	64.12	43.60	64.12	1.00305	0.30
2	64.12	64.12	49.68	1.00285	0.29
3	51.93	51.92	53.19	1.00327	0.33
4	1.89	54.40	64.12	1.00340	0.34
5	31.44	48.47	64.12	1.00327	0.33

The data from these cases reflect a consistent model bias, with an average bias of 0.32%Δk/k. More cases were then run for additional comparisons to measured reactor parameters. Control rod worths were calculated for each control rod and compared to measured values, which are re-measured each year as part of the annual inspection performed by reactor staff. This data, shown in Table 2, also shows good agreement between measured and calculated values.

Table 2: Comparison of measured and calculated control rod worths for HEU core

	Measured Value (Δk/k)	**Calculated Value (Δk/k)**	**Error %**
Shim Safety 1	0.0431	0.0436	1.16%
Shim Safety 2	0.0242	0.0235	-.2.89%
Regulating Rod	0.0026	0.0027	3.85%

Rod calibration curves for the two shim-safety rods were also calculated with the core model. Excellent agreement with measured curves for each of the shim-safety rods was obtained, as shown in Figures 3 and 4.

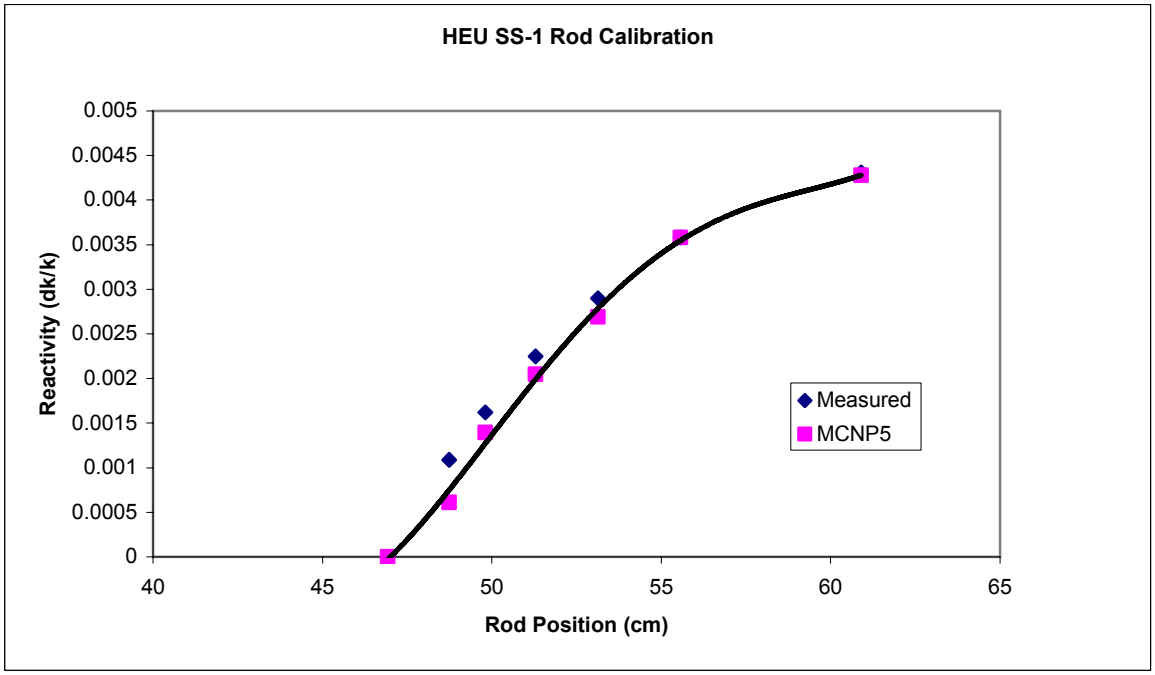

Figure 3: Comparison of Measured and MCNP5 Calibration Curve for SS-1

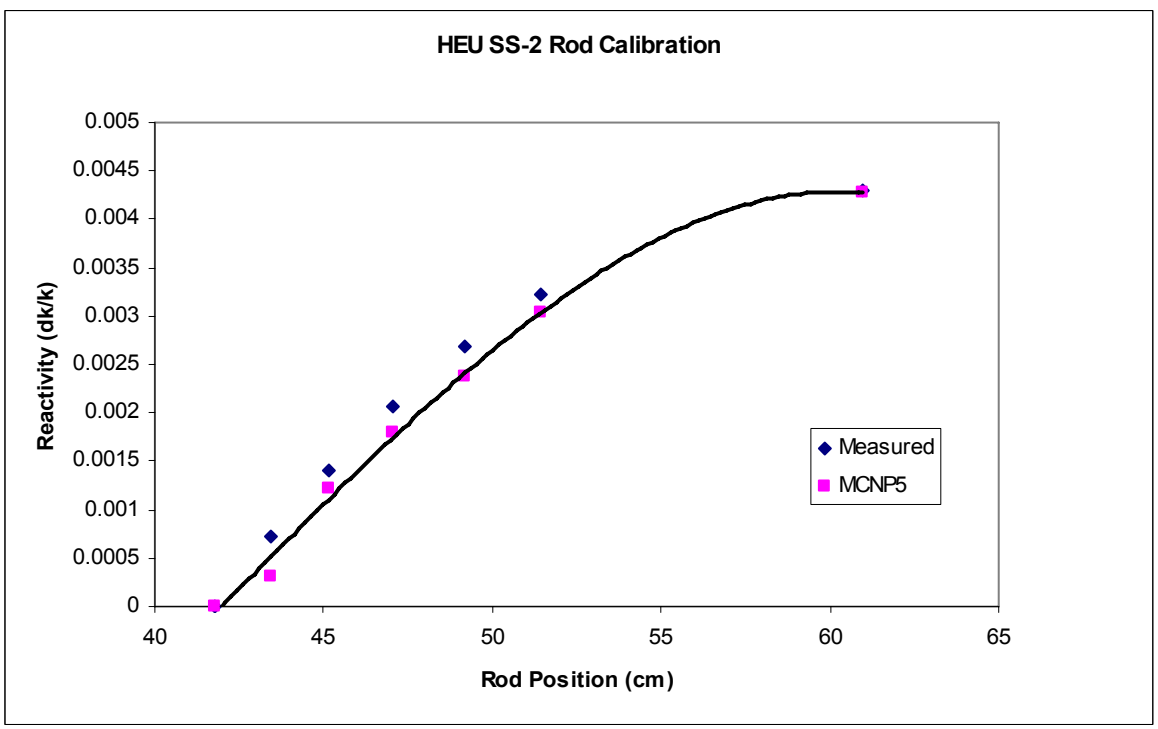

Figure 3: Comparison of Measured and MCNP5 Calibration Curve for SS-2

Based upon the good agreement of the HEU model with measured core parameters, an LEU model was then built that utilized a similar geometry to the HEU core. This model is described in the next section.

4 Development of the LEU Core Model

The HEU MCNP5 model was adjusted to meet the new fuel design and specifications of the LEU core. In the core design process, there was an objective of maintaining the 4x4 configuration of the present PUR-1 core and a sufficient number of LEU fuel plates to ensure a critical configuration. A parametric study in which the number of fuel plates per assembly was adjusted was performed. A design with 14 fuel plates in a standard LEU fuel assembly and 8 plates in the LEU control assemblies was determined to provide sufficient excess reactivity for the LEU core.
Parametric analyses were performed on the total number of fuel plates, as well as the position of dummy plates within the standard fuel assemblies. It was decided to not place dummy plates in the control assemblies in order to simplify the determination of actual critical configurations (i.e. dummy plate locations). . The final loading of fuel in the LEU model core was determined to be 190 plates, with the sixteen dummy plates spread evenly among the thirteen standard assemblies. The excess reactivity of this configuration was determined to be 0.468% Δk/k, which includes the reactivity bias of 0.32% Δk/k previously determined for the core model. This value is within the Technical Specification limit of 0.6% for PUR-1.

Control rod worths were calculated for the LEU core, and these are compared to the HEU core in Table 3. The rod worth curves for the two shim-safety rods are shown in Figures 5 and 6.

Table 3: Comparison of HEU and LEU Calculated Rod Worths

	HEU Calculated (Δk/k)	**LEU Calculated (Δk/k)**
Shim Safety 1	0.0436	0.0391
Shim Safety 2	0.0235	0.0200
Regulating Rod	0.0027	0.0029

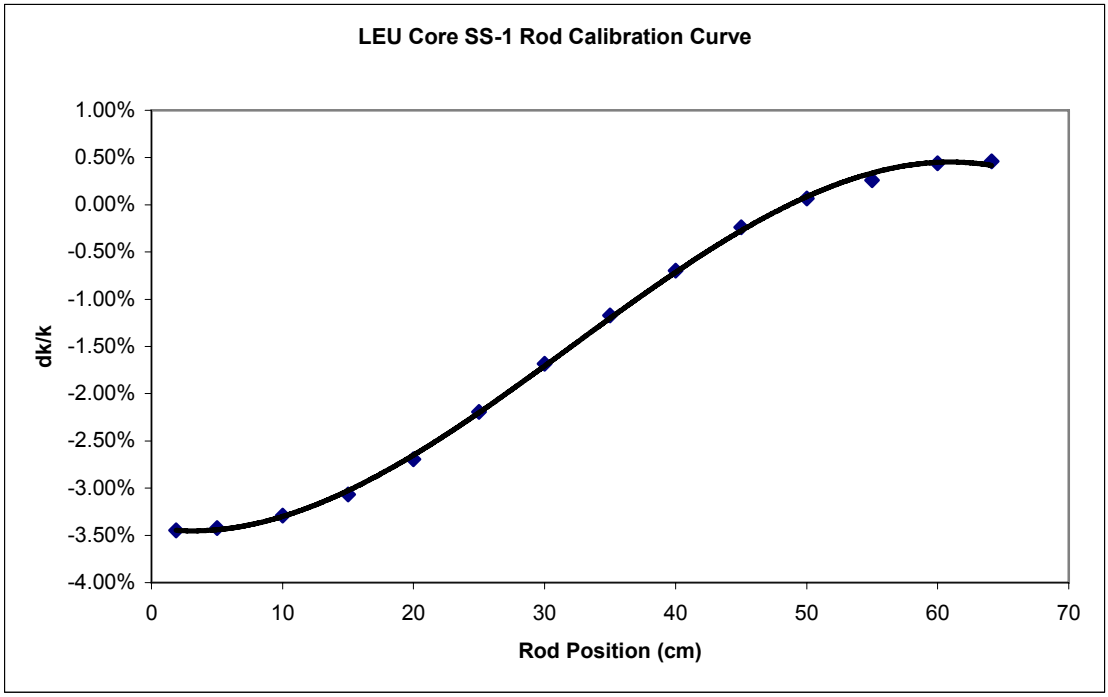

Figure 5: LEU Model Rod Worth Curve for SS-1.

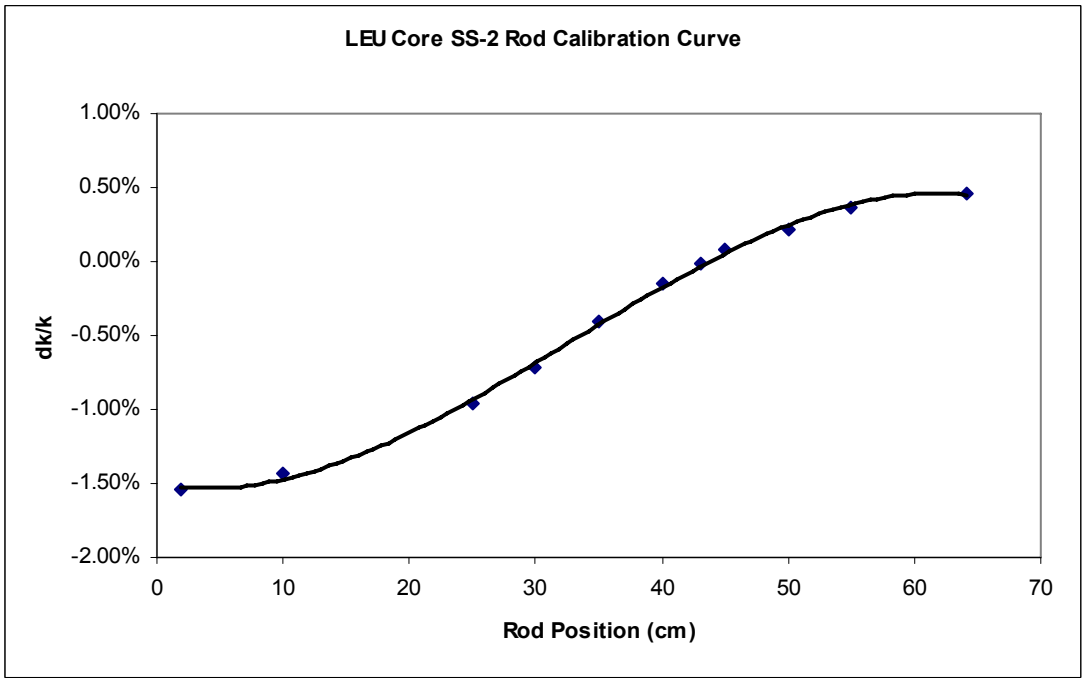

Figure 6: LEU Model Rod Worth Curve for SS-2.

The shutdown margin was calculated for the HEU and LEU cores, and compared to the measured value for PUR-1. These results are summarized in Table 4.

Table 4: Comparison of Shutdown Margins for the HEU and LEU Cores

	HEU Measured	HEU Calculated	LEU Calculated
SS-2 Worth ($\Delta k/k$)	- 2.42%	-2.35%	-2.89%
k_{excess} ($\Delta k/k$)	0.431%	0.431%	0%
Shutdown Margin ($\Delta k/k$)	-1.94%	-1.93%	-1.53%

Further calculations were performed with the MCNP5 model to determine the balance of the reactor physics parameters necessary to continue the safety analyses for the LEU core. These parameters are summarized in Table 5.

Table 5: Comparison of Other Core Physics Parameters for the HEU and LEU Cores

	HEU (calculated)	LEU (calculated)
$\alpha_{fuel}\left(\frac{\%\Delta k}{k \cdot {}^{o}C}\right)$	0	-9.91E-04
$\alpha_{moderator}\left(\frac{\%\Delta k}{k \cdot {}^{o}C}\right)$	-7.46E-03	-9.75E-03
$\alpha_{void}\left(\frac{\%\Delta k}{k \cdot \%void}\right)$	-9.88E-02	-1.68E-01
β_{eff}	0.795%	0.787%
ℓ (μs)	76.7	81.3

The MCNP5 model was also used to perform the heating calculations to determine the core and plate-power distributions, which were then used in the thermal-hydraulic and safety analyses necessary complete the conversion proposal to the USNRC. The safety analyses confirmed that the LEU core conforms to the reactor technical specifications.

5 Summary

The safety analyses for the conversion of PUR-1 from HEU to LEU fuel was submitted in August 2006. The keystone of the analyses was the MCNP5 model of the HEU and LEU cores developed by Purdue students and staff, under the guidance of RERTR staff at Argonne National Laboratory . The HEU model was constructed and then compared to PUR-1 operating conditions for final adjustments. Once the credibility of the HEU model was established, the LEU model was built.

The final results confirmed that replacement of the U-Al alloy HEU core with an LEU core containing U_3Si_2-Al fuel could maintain the operating performance of PUR-1 in all respects, most importantly safety. This will allow for continued operation of the reactor

for its mission of training, education, and research, and the removal of HEU material from the domain of civilian reactors.

6 Acknowledgements

This work was a collaborative effort between students and staff in the Nuclear Engineering Department at Purdue University, and Argonne National Laboratory. The Purdue participants would like to thank James E. Matos and John A. Stillman for their considerable guidance and assistance in this effort, particularly under time and other constraints.

7 References

[1] X-5 Monte Carlo Team, "MCNP-A General Monte Carlo N-Particle Transport Code, Version 5 Volume I, II and III," Los Alamos National Laboratory, Report LA-CP-03-0245 (2003)

[2] Safety Analysis Report for the Purdue University PUR-1 Reactor, June 30, 1986.

[3] Technical Specifications for the Purdue University Reactor, May 1988

[4] U.S. Nuclear Regulatory Commission, "Safety Evaluation Report Related to the Renewal of the Operating License for the Research Reactor at Purdue University", NUREG-1283, April 1988.

[5] Edward C. Merritt, "Report on Reactor Operations for the Period January 1, 2004 to December 31, 2004". Facility Docket Number 50-182, Purdue University Nuclear Engineering, March 2005