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FLUXES AT EXPERIMENT FACILITIES IN HEU AND LEU DESIGNS FOR THE FRM-II*

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ABSTRACT

An Alternative LEU Design for the FRM-II proposed by the RERTR Program at Argonne National Laboratory (ANL) has a compact core consisting of a single fuel element that uses LEU silicide fuel with a uranium density of 4.5 g/cm^3 and has a power level of 32 MW. Both the HEU design by the Technical University of Munich (TUM) and the alternative LEU design by ANL have the same fuel lifetime (50 days) and the same neutron flux performance (8 x 10^{14} n/cm^2-s in the reflector). LEU silicide fuel with 4.5 g/cm^3 has been thoroughly tested and is fully-qualified, licensable, and available now for use in a high flux reactor such as the FRM-II.

Several issues that were raised by TUM have been addressed in Refs. 1-3. The conclusions of these analyses are summarized below. This paper addresses four additional issues that have been raised in several forums, including Ref. 4: heat generation in the cold neutron source (CNS), the gamma and fast neutron fluxes which are components of the reactor noise in neutron scattering experiments in the experiment hall of the reactor, a fuel cycle length difference, and the reactivity worth of the beam tubes and other experiment facilities. The results show that: (a) for the same thermal neutron flux, the neutron and gamma heating in the CNS is smaller in the LEU design than in the HEU design, and cold neutron fluxes as good or better than those of the HEU design can be obtained with the LEU design; (b) the gamma and fast neutron components of the reactor noise in the experiment hall are about the same in both designs; (c) the fuel cycle length is 50 days for both designs; and (d) the absolute value of the reactivity worth of the beam tubes and other experiment facilities is smaller in the LEU design, allowing its fuel cycle length to be increased to 53 or 54 days.

Based on the excellent results for the Alternative LEU Design that were obtained in all analyses, the RERTR Program reiterates its conclusion that there are no major technical issues regarding use of LEU fuel instead of HEU fuel in the FRM-II and that it is definitely feasible to use LEU fuel in the FRM-II without compromising the safety or performance of the facility.

INTRODUCTION

Key parameters of the TUM HEU and the ANL Alternative LEU designs are summarized in Table 1. Several issues that were raised by TUM have been addressed in Refs. 1-3, and a summary of those analyses is provided below.

Four additional issues raised in Ref. 4 and other forums are addressed here: heat generation in the cold neutron source, the gamma and fast neutron fluxes which are components of the reactor noise in neutron scattering experiments in the experiment hall of the reactor, a fuel cycle length difference, and the reactivity worth of the neutron cold source, beam tubes, and other experiment facilities.

Table 1: Key Parameters of the FRM-II HEU Design and the Alternative LEU Design.

	FRM-II HEU Design	FRM-II Alternative LEU Design (a)
Enrichment, %	93.0	19.75
Reactor Power (MW)	20	32
Cycle Length (Full Power Days) (b)	50	50
Peak Thermal Flux, $k_{eff} \cdot \Phi_{th}$,max ($n/cm^2/s$)	8×10^{14}	8×10^{14}
Active Core Inner - Outer Radius (cm)	6.75 - 11.2	10.45 - 16.55
Active Core Height (cm)	70	80
Active Core Volume (liters)	17.6	41.4
Number of Fuel Plates	113	172
Core Loading (Kg U-235)	7.5	7.5
Fuel Type	U_3Si_2	U_3Si_2
Fuel Meat Uranium Density (g/cm^3)	3.0/1.5	4.5
Fuel Meat/Clad /Coolant Thickness (mm)	0.60/0.38/2.2	0.76/0.38/2.2
Design Coolant Velocity, m/s	18.0	18.0
Width of Involute Plate (cm)	6.83	8.735
Peak Temperature in Fuel Meat (°C) BOC/EOC	150/180	130/160

(a) With involute plate width of 8.735 cm, as in lower core of ORNL's Advanced Neutron Source design,
(b) EOC excess reactivity = 5% Δk/k for both the HEU and LEU designs

SUMMARY OF ANALYSES FROM REFERENCES 1, 2, AND 3

(1) Qualification of HEU and LEU Silicide Fuels

HEU silicide fuel (U_3Si_2-Al) with 93% enrichment and a uranium density of 3.0 g/cm^3 that is proposed by TUM for the HEU design is untested and is not likely to be licensable without specific test data to qualify the fuel for use in the FRM-II. Normal licensing practices in many countries require that tests be performed on the specific fuel that will be used in a reactor in order to provide the data on fuel behavior that is required for licensing.

LEU silicide fuel (U_3Si_2-Al) with uranium densities up to 4.8 g/cm^3 is fully-qualified for conditions close to those of the FRM-II LEU design. The fuel was qualified by means of extensive irradiation testing and post-irradiation examination of miniature fuel plates, full size elements, and a whole-core demonstration. This fuel is available today and can be licensed for routine use in the FRM-II.

(2) Fuel Element Hydraulic Stability

The lower core of the Advanced Neutron Source (ANS) reactor designed by Oak Ridge National Laboratory had involute plates that were 1.27 mm thick and had a width of 8.735 cm. The water channel thickness was 1.27 mm and the nominal water velocity was 20-22 m/s. Experiments and analyses performed at ORNL determined that the fuel plates in this design would be stable during operation. The alternative LEU design for the FRM-II has fuel plates having the same width (8.735 cm), but the plate thickness is 1.52 mm, the water channel thickness is 2.2 mm, and the nominal coolant velocity is 18 m/s. All three factors (a thicker plate, a thicker water channel, and a lower coolant velocity) will increase the hydraulic stability of these LEU fuel plates over that of the already stable ANS design. Analyses supporting this conclusion can be found in Refs. 1 and 2.

If the alternative LEU design is adopted, detailed analyses and tests similar to those performed for the ANS would need to be done and a prototype core would need to be flow tested. However, based on the very positive results that have already been obtained from experiments and analyses for the ANS design, we believe that the Alternative LEU Design for the FRM-II has a large safety margin with respect to hydraulic stability.

(3) Gamma Heating in the Heavy Water Reflector

Detailed analyses comparing the energy deposited (gamma heating) in the heavy water reflector of both the FRM-II HEU design and the alternative LEU design showed that a cold source operating in the heavy water reflector of the LEU design would make a superb experimental facility even though the gamma heating would be slightly higher than in the HEU design. At a distance of 50 cm from the reactor vessel, the gamma heating in the HEU design would be a factor of 2.1 times lower than in the RHF reactor at Grenoble, France, and the gamma heating in the LEU design would be a factor of 1.8 lower than in the RHF.

(4) Hypothetical Accident Involving the Moderator Material of the Reflector

Monte Carlo calculations were performed for the FRM-II HEU design and the alternative LEU design to evaluate the subcriticality margins for a hypothetical accident in which the heavy water reflector is replaced by light water. Results of this analysis show that the HEU design is subcritical by about 16% $\Delta k/k$ and that the alternative LEU designs is subcritical by about 8% $\Delta k/k$. These results conservatively assume that the central control rod has its beryllium follower in the core in its most reactive configuration. Thus, both cores satisfy this safety criteria.

(5) Loss of Primary Coolant Flow Transient

A loss of primary flow transient analysis described by TUM for the FRM-II HEU design was analyzed for both the HEU and alternative LEU designs using essentially the same assumptions as TUM. The results show that fuel integrity is maintained with a considerable safety margin in both cases. During the first seven days after initiation of the transient: (1) the temperature of the cladding in both cores is less than 120°C, far below the clad melting temperature of about 580°C and (2) the temperature of the light water pool is about 80°C in the alternative LEU design and about 60°C in the HEU design. As a result, the decay heat can be safely removed from the core by natural circulation for at least seven days, making a strong inherent safety case for both designs.

(6) Radiological Consequences

Analyses of the radiological consequences of increased plutonium production in LEU fuel and larger fission product inventory in the higher-powered alternative LEU design for the case of hypothetical accidents involving core melting show that the alternative LEU design meets in full the radiological consequences criteria set by the German Ministry of Environment (Bundesministerium für Umwelt - BMU). The plutonium that would be produced in the HEU and LEU cores were calculated to be 10.4 g and 158.5 g, respectively. Detailed analyses show that the increased plutonium inventory in the LEU core would have no impact on the radiological consequences of hypothetical accidents involving melting of the core in water, even with very conservative release assumptions. Analyses also show that the radiological consequences for a wet core melt with either the HEU design or the alternative LEU design are within the norms established by the BMU.

(7) Cost and Schedule

The design features and results obtained by ANL for the alternative LEU design were very different from those used by TUM in its assessment of the costs involved in using LEU fuel in the FRM-II. Thus, a careful review of both cost and schedule issues is thought to be important.

(8) LEU Conversion of HEU Design

Only by increasing the size of the HEU core is it possible to use LEU fuel in the FRM-II and have a comparable core lifetime and experiment performance. There is no possibility whatsoever that a suitable LEU fuel will be developed for use in the HEU geometry. To illustrate this point, calculations were done in which LEU uranium metal with a density of 19 g/cm^3, a totally unrealistic possibility, was substituted for the fuel meat of the HEU design. The result was that the core would operate for only about 25 days at a power level of 20 MW and would have a peak thermal flux of 7×10^{14} n/cm^2-s in the heavy water reflector. This performance level would not be acceptable.

ADDITIONAL ANALYSES

This paper addresses four additional issues that were raised in Ref. 4 and other forums: (1) heat generation in the cold neutron source (CNS), (2) gamma and fast neutron fluxes which are the components of the reactor noise in neutron scattering experiments in the experiment hall , (3) a fuel cycle length difference, and (4) reactivity worth of the beam tubes and other experiment facilities.

To address these issues, a detailed model of the cold neutron source, beam tubes and experiment facilities was created using information provided in Ref. 5; dimensions were scaled from Figure 4 in Ref. 5 (this figure is reproduced as Figure 1 in this paper). Since detailed information on the dimensions and shape of the beam tubes was not available, it was assumed that the beam tubes are conical in shape, and that the other experiment facilities are cylindrical. Information provided in Ref. 6 was used to model the cold neutron source. The MCNP[7] model used in the analyses performed for this paper is shown as Figure 2, which was produced by the computer code SABRINA[8] using the same input as that used in the MCNP calculations.

Heat Generation in the Cold Neutron Source

Figures 1 and 2 show a two- and a three-dimensional view of the model used for calculation of the neutron and gamma heat generated in the CNS. The CNS contains 24 liters of liquid deuterium and is contained in a spherical container of pure aluminum which is 0.2 cm thick; its diameter is 36 cm. A cylindrical wall of 0.6 cm zircaloy was used for the vacuum container. In Figure 2, the cylindrical vacuum container around the spherical cold source is not displayed for better visualization of the CNS.

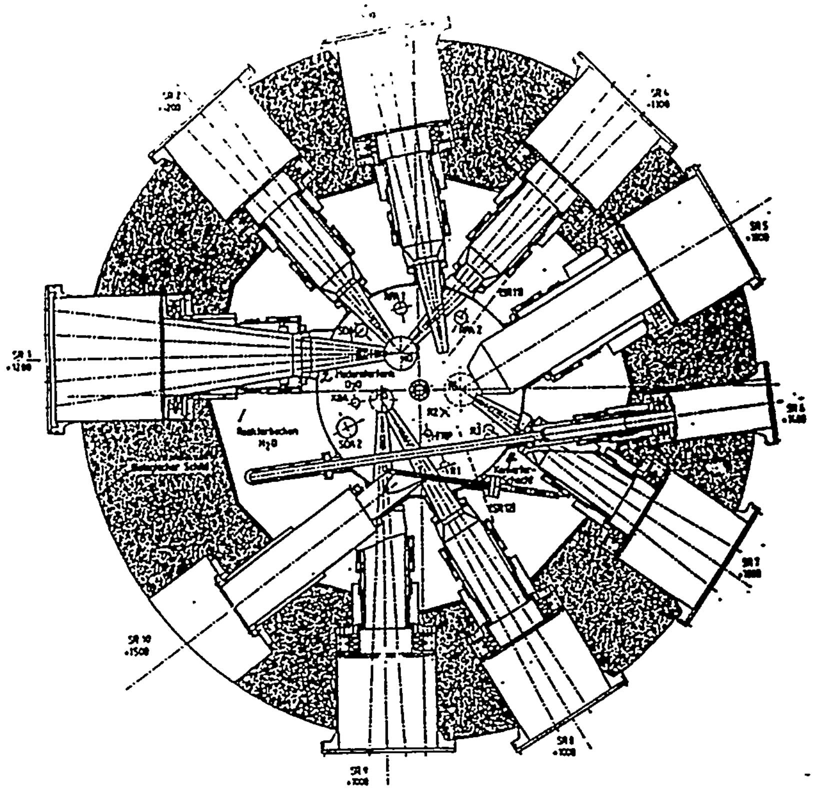

Figure 1: Horizontal Section Through TUM FRM-II
(Reproduced from Figure 4 of Ref. 5)

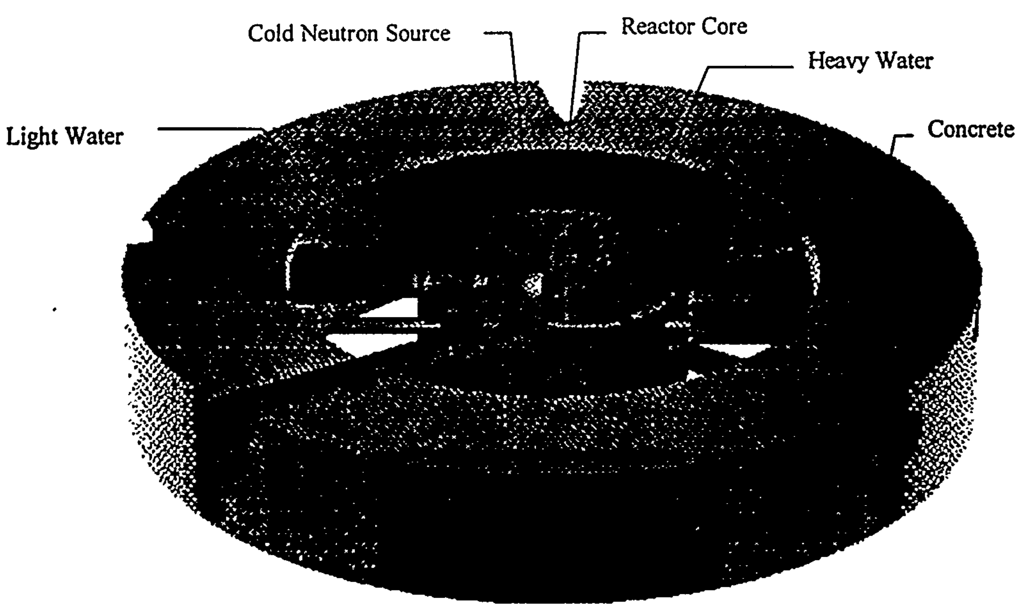

Figure 2. View of Model Used in MCNP Analyses

Based on information provided in Refs. 4 and 9, the center of the CNS in the HEU design is located 31.9 cm from the reactor vessel (45 cm from the center of the reactor). At this point, the unperturbed thermal neutron flux in the HEU design is about 5.2×10^{14} n/cm^2-s (see Figure 3). The CNS for the LEU design is located at 34.9 cm from reactor vessel, where the thermal neutron flux is also 5.2×10^{14} n/cm^2-s. The location of the beam tubes in the HEU design is based on their location in Figure 1. Their locations in the LEU design were chosen so that the thermal neutron fluxes are about the same as those in the HEU design.

The results of the calculations for CNS heating (Table 2) show that neutron and gamma heating in the LEU design is smaller than in the HEU design. This can be understood by referring to the CNS-HEU and CNS-LEU lines in Figure 3 which show that the gamma flux (and consequently the gamma heating) is smaller in the LEU design for the same thermal neutron flux. The neutron spectra at the CNS in Figure 4, show that the thermal neutron flux is larger and the fast neutron flux is smaller in the LEU design than in the HEU design. Thus, contrary to statements made in Ref. 4 and in other forums, cold neutron fluxes as good or better than those of the HEU design can be obtained with the LEU design.

Neutron spectra at the tip of each beam tube were also calculated and the results show that the thermal neutron fluxes are about the same or larger in the LEU design than in the HEU design. Figure 5 shows the neutron spectra at the tip of beam tubes SR5 and SR8 as examples.

Gamma and Fast Neutron Fluxes in the Experiment Hall

There are two sources of noise that would be generated in neutron scattering experiments to be performed in the experiment hall: reactor noise and natural background noise. This paper addresses the two components of the reactor noise - fast neutron and gamma fluxes streaming through the beam tubes and neutron and gamma leakage through the concrete biological shield. To investigate this noise, the beam tubes were modeled in both the HEU and LEU designs as conical surfaces with only air inside. The actual beam tube design was not found in the open literature, but this model is adequate to compare the gamma and fast neutron fluxes that would enter the experiment hall. The composition and thickness of the concrete biological shield were also not found in the open literature. In this paper, the composition of the concrete in the biological shield of the Brookhaven Medical Research Reactor (density of 4.1 g/cm^3) was used. A thickness of 150 cm of concrete was used for the HEU design based on Figure 1; in the LEU design the thickness of concrete was assumed to be 162 cm. Thus, the absolute values of the fast neutron and gamma fluxes leaking through the concrete should only be used for the purpose of comparing the HEU and LEU designs.

The results of this analysis are presented in Figures 6 and 7. Figure 6, which uses beam tubes SR1 and SR9 as examples, shows that there are only small differences between the gamma and the fast neutron fluxes inside the beam tubes of the HEU and LEU designs. Further optimization of the position of the beam tubes in the LEU design will decrease further the already small difference in beam tube fluxes between LEU and HEU designs.

Figure 7 shows that the neutron and gamma leakage through the biological shield of both designs are also nearly the same. Note also that streaming through the beam tubes results in noise that is more than one order of magnitude larger than noise generated by leakage through the biological shield.

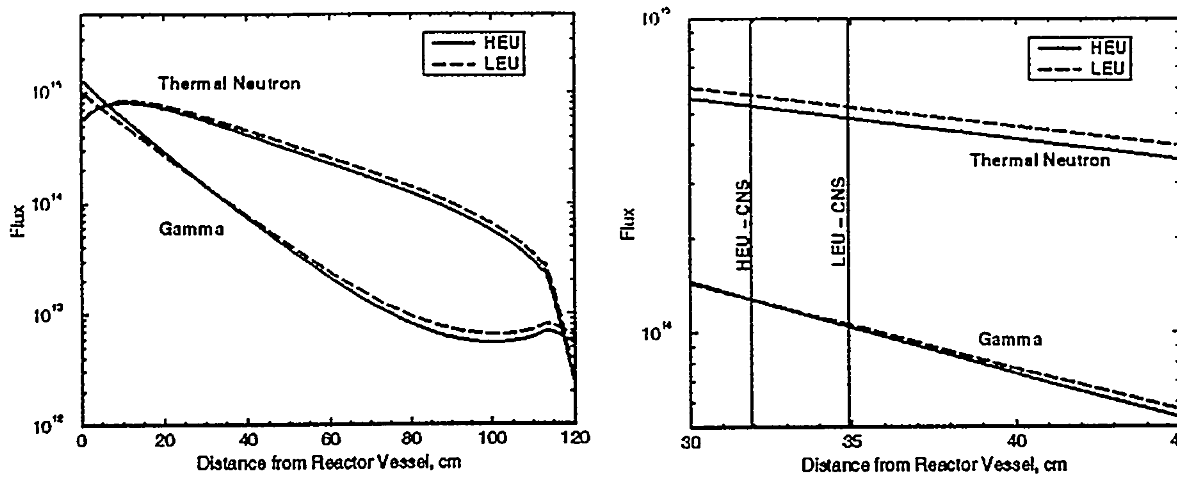

Figure 3. Unperturbed Reflector: HEU and LEU Thermal Neutron and Gamma Fluxes

Table 2. Cold Neutron Source Heating (Gamma and Neutron)

	HEU (Watts)	LEU (Watts)
Liquid Deuterium	2,030	1,560
Aluminum Structure	863	806
Total	2,893	2,366

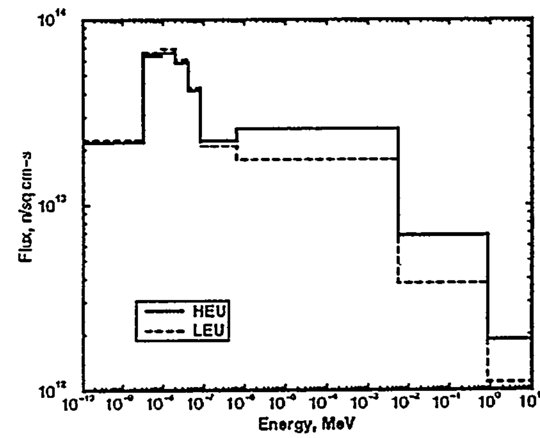

Figure 4: Spectra at the Cold Neutron Source

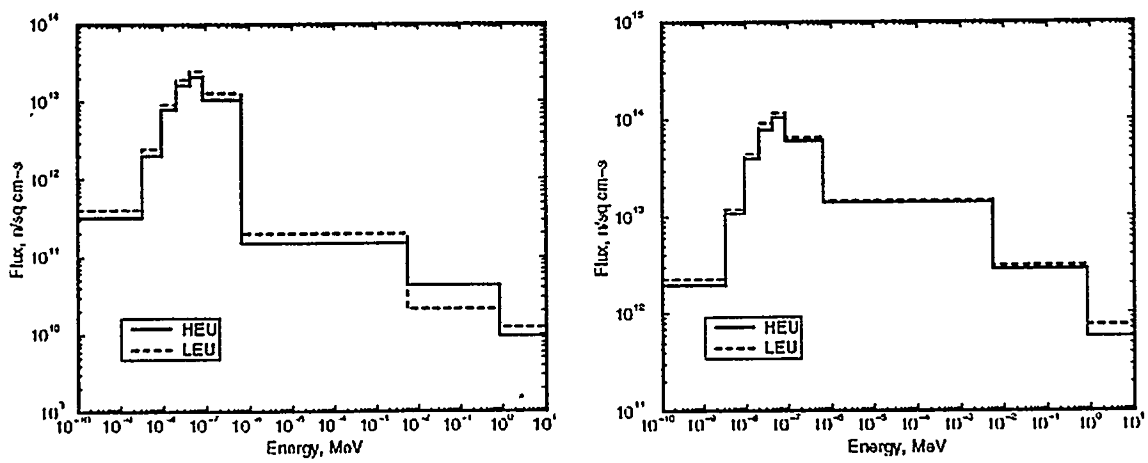

Figure 5. Spectra at the Tip of Beam Tubes SR 5 (left) and SR 8 (right)

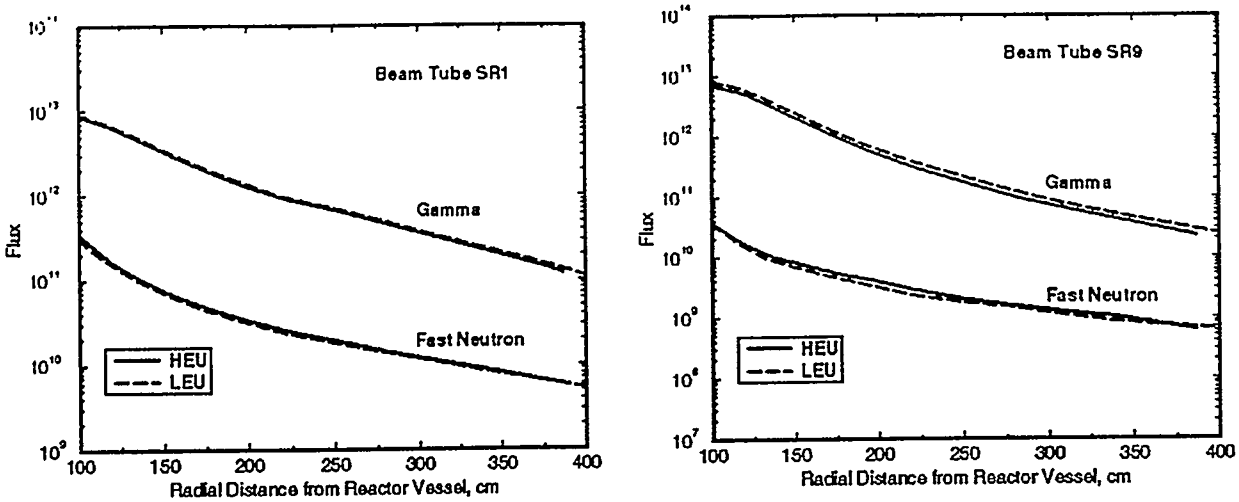

Figure 6. Fast Neutron and Gamma Fluxes Inside Beam Tubes

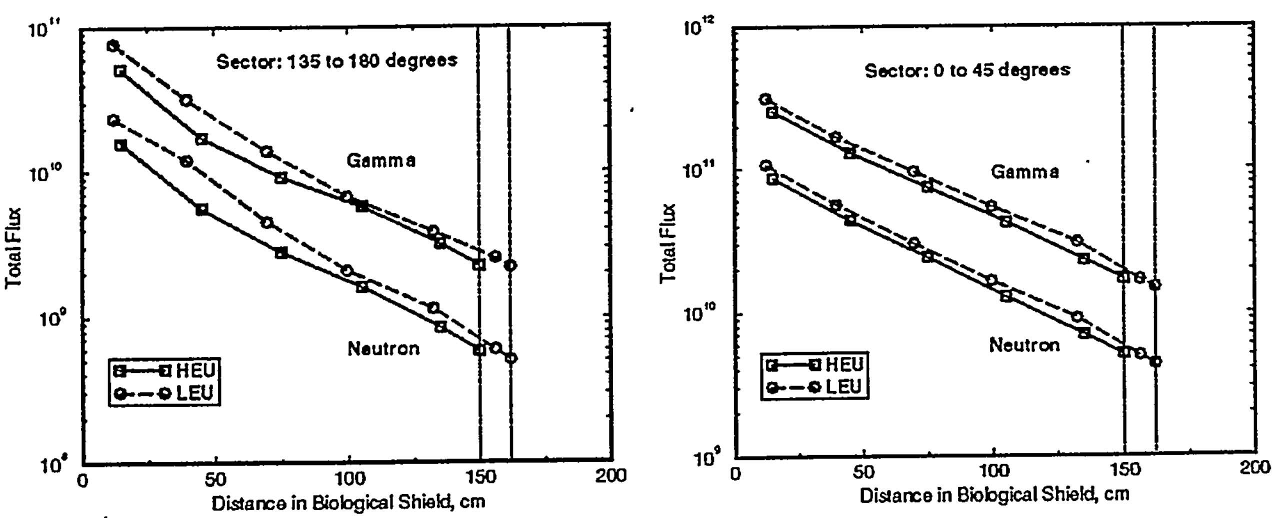

Figure 7. Total Neutron and Gamma Fluxes in Different Sectors of the Biological Shield (Biological Shield Thickness: 150 cm for HEU; 162 cm for LEU)

Fuel Cycle Length

Reference 4 states that the TUM calculations with the LEU design result in a " cycle length of the LEU core which is about 3 days shorter than the ANL result." This discrepancy, based on data provided by TUM[9], is due to the inadvertent use by TUM of a uranium enrichment of 19.28% instead of 19.75% in the LEU design. Figure 8 (reproduced from Ref. 10) shows the reactivity rundown, as calculated by ANL, for the HEU and LEU designs. The solid curve is the reactivity rundown for the HEU model received from TUM. The middle curve is the reactivity rundown for the TUM model of the ANL LEU design using the uranium enrichment of 19.28% provided in that model. The top curve is for the same model as the middle curve but with the correct uranium enrichment of 19.75%. If the end of cycle excess reactivity is taken to be the same 5% for both designs, the middle curve (19.28% enrichment) shows that the LEU core would operate for about 47 days and the top curve (19.75% enrichment) shows that the LEU lifetime would be the same 50 days as for the HEU core

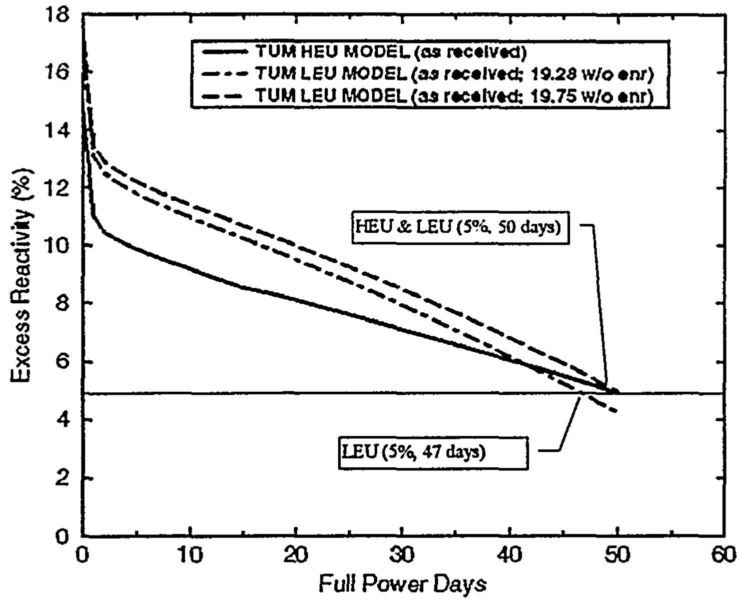

Figure 8. Reactivity Rundown for TUM Models of the FRM-II HEU Design and the ANL Alternative LEU Design

Reactivity Worth of Cold Source, Beam Tubes and Other Experiment Facilities

Reference 5, from which the CNS model used in this paper was obtained, states that the reactivity worth of the CNS for the HEU design is 1.5% Δk/k. Our calculations gave the same result of -1.47 +/- 0.1% Δk/k.

Results for the reactivity worth of the beam tubes and for the beam tubes and experiment facilities are provided in Table 3. It can be seen that the absolute value of the reactivity worth of the beam tubes/experiment facilities is between 0.6 % and 0.9% smaller in the LEU design. This difference in reactivity worth can be used to increase the fuel cycle length of the LEU from 50 days to 53 or 54 days.

Table 3. Reactivity Worth of Beam Tubes and Other Experiment Facilities (%Δk/k)

	HEU DESIGN	LEU DESIGN
A) Beam Tubes (including CNS and cylindrical container for the Hot Source)	3.4 +/- 0.1	2.8 +/- 0.1
B) Same as above plus other experiment facilities (see Figures 1 and 2)	4.5 +/- 0.1	3.6 +/- 0.1

CONCLUSIONS

This paper addresses four additional issues that were raised by TUM in several forums, including Ref. 4: heat generation in the cold neutron source (CNS), the gamma and fast neutron fluxes which are components of the reactor noise in neutron scattering experiments in the experiment hall, a fuel cycle length difference, and the reactivity worth of the beam tubes and other experiment facilities. The results show that : (a) for the same thermal neutron flux, the neutron and gamma heating in the CNS is smaller in the LEU design than in the HEU design, and cold neutron fluxes as good or better than those of the HEU design can be obtained with the LEU design; (b) the gamma and fast neutron components of the reactor noise in the experiment hall are about the same in both designs; (c) the fuel cycle length is 50 days for both designs; and (d) the absolute value of the reactivity worth of the beam tubes and other experiment facilities is smaller in the LEU design, allowing its fuel cycle length to be increased to 53 or 54 days.

Based on the excellent results that were obtained for the Alternate LEU Design in all analyses, the RERTR Program reiterates its conclusion that all of the major technical issues regarding use of LEU fuel instead of HEU fuel in the FRM-II have been successfully resolved and that it is definitely feasible to use fully-qualified and licensable LEU fuel in the FRM-II without compromising the safety or the performance of the facility.

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