ATTACHMENT 1

Comparison of the FRM-II HEU Design With an Alternative LEU Design

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After presentation of the foregoing paper by Dr. Nelson Hanan of Argonne National Laboratory (ANL) proposing an alternative LEU core with one fuel ring and a power level of 33 MW, a presentation[1] was made by Dr. Klaus Böning of the Technical University of Munich (TUM) comparing the FRM-II HEU design with an LEU design by TUM that had two fuel rings and a power level of 40 MW. Dr. Böning raised the following issues concerning the use of LEU fuel in FRM-II reactor designs: (1) qualification of HEU and LEU silicide fuels, (2) gamma heating in the heavy water reflector, (3) the radiological consequences of hypothetical accidents, and (4) cost and schedule. These issues are addressed in this Attachment.

In his presentation, Dr. Hanan mentioned that ANL was also investigating other LEU designs. This work led to a second alternative LEU design that has the same neutron flux performance (8×10^{14} n/cm^2/s peak neutron flux in the reflector) and the same fuel lifetime (50 full power days) as the HEU design, but uses LEU silicide fuel with a uranium density of only 4.5 g/cm^3. This design was achieved by using a fuel plate that has a fuel meat thickness of 0.76 mm, a cladding thickness of 0.38 mm, and a water channel gap of 2.2 mm. Table A1 compares the main characteristics of this second alternative LEU design with those of the FRM-II HEU design. The ANL core again has one fuel ring with the same dimensions as shown in Figure 1 of the foregoing paper. With this LEU design, a two stage process is no longer necessary because LEU silicide fuel with a uranium density of 4.5 g/cm^3 is fully qualified, licensable, and available now for use in a high flux reactor such as the FRM-II.

(1) Qualification of HEU and LEU Silicide Fuels

HEU Silicide Fuel: HEU silicide fuel (U_3Si_2-Al) with 93% enrichment and a uranium density of 3.0 g/cm^3 is totally untested and is not likely to be licensable without specific test data to qualify the fuel for use in the FRM-II.

The fuel meat in each plate of the FRM-II HEU design is composed of two radial regions with different uranium densities. A small part (about 1.25 cm in length) near the outer edge of each plate contains uranium with a density of 1.5 g/cm^3. The rest of the meat (about 5.1 cm in length) contains fuel with a uranium density of 3.0 g/cm^3. Thus, about 80% of the active core volume contains fuel with a uranium density of 3.0 g/cm^3.

In principle, HEU silicide fuel containing 93% enriched uranium with a density of 3.0 g/cm^3 might perform well in the FRM-II. To our knowledge, however, no irradiation tests - not even on one single fuel plate - have ever been performed on this fuel. 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. Minimal irradiation tests have been performed in the ORR reactor at the Oak Ridge National Laboratory by the RERTR Program on two miniplates containing U_3Si_2-Al fuel with 93% enrichment and a uranium density of 1.66 g/cm^3.

Table A1: Key Parameters in FRM-II HEU Design and the Second Alternative LEU Design

	FRM-II HEU Design	2nd Alternative LEU Design
Enrichment, %	93	20
Reactor Power (MW)	20	32
Cycle Length (Full Power Days) (a)	50	50
Average Number of Cores/Year (b)	5.0	5.0
Peak Thermal Flux, k_{eff}•φth,max (n/cm^2/s)	8.0 x 10^{14}	8.1 x 10^{14}
Reflector Volume (liters) with k_{eff}•φth>7x10^{14} n/ cm^2/s	82	146
Core Inner - Outer Radius (cm)	6.75 - 11.2	9.78 - 16.04
Core Height (cm)	70	80
Core Volume (liters)	17.6	40.6
Number of Fuel Plates	113	161
Core Loading (Kg U-235)	7.5	7.5
Fuel Type	U_3Si_2	U_3Si_2
Fuel Grading	Yes	No
Fuel Meat Uranium Density (g/cm^3)	3.0/1.5	4.5
Fuel Meat/Clad Thickness (mm)	0.60/0.38	0.76/0.38
Coolant Channel Thickness (mm)	2.2	2.2
Length of Involute Plate (cm)	6.83	9.15
K_{eff} at BOC	1.1937	1.2334
Core Average Burnup (% U-235 burned)	17.3	26.5
Average Fission Rate in Fuel Meat (fissions/cm^3/s) Peak Pointwise Fission Rate in Fuel Meat at BOC (c)	2.1 x 10^{14} 4.7 x 10^{14}	1.2 x 10^{14} 2.9 x 10^{14}
Average Fission Density in Fuel Meat (fissions/cm^3) Peak Fission Density in Fuel Meat at EOC (c)	1.0 x 10^{21} 1.5 x 10^{21}	0.5 x 10^{21} 0.9 x 10^{21}
Average Power Density in Core (W/ cm^3) Peak Power Density in Core - rod out at BOC	1139 2537	788 1919
Peak Temperature in Fuel Meat (˚C) BOC/EOC	150/180	130/160

(a) EOC excess reactivity = 7% Δk/k; (b) Based on 250 days operation per year; (c) In 3.0 g/cm^3 fuel of the HEU design.

LEU Silicide Fuel: 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. This fuel is available today and can be licensed for routine use today.

This fuel was licensed by the U.S. Nuclear Regulatory Commission in 1988 for use in U.S. non-power reactors. The NRC safety evaluation report[2] on the fuel was issued after irradiation testing of several hundred specimens, including miniplates, full-size plates, full-size elements, and a full reactor core in the 30 MW ORR reactor at the Oak Ridge National Laboratory. Additional testing that made important contributions to and confirmed these results were performed in Germany, France, the Netherlands, Sweden, Denmark, Switzerland, Japan, and Canada. Fourteen research reactors currently operate with LEU U_3Si_2-Al fuel. The high power reactors using silicide fuel with a uranium density of 4.8 g/cm^3 include the 50 MW JMTR reactor in Japan and the 70 MW OSIRIS reactor in France. This same fuel with a fuel meat thickness of 0.76 mm has been successfully tested in the 45 MW HFR reactor at Petten in the Netherlands. The 50 MW R2 reactor in Sweden routinely utilizes LEU silicide fuel with a fuel meat thickness of 0.76 mm and a uranium density of about 4.0 g/cm^3. Over 400 elements with LEU silicide fuel, including about 8,000 plates, have been fabricated and irradiated with an excellent safety record.

A number of fuel meat parameters are important to define fuel behavior. Table A2 compares estimated values of four of these key parameters in the FRM-II alternative LEU design, the 50 MW JMTR reactor, and the 70 MW OSIRIS reactor. The FRM-II LEU design would operate under conditions very close to those under which the JMTR and OSIRIS reactors currently operate. LEU U_3Si_2-Al fuel with a uranium density of 4.4 g/cm^3 has been irradiation tested[3] in the JMTR reactor to a fission density of 0.7 x 10^{21} fissions/cm^3 (33% U-235 burnup) at a temperature of 220 ˚C inside the fuel meat.

Table A2. Four Key Fuel Meat Parameters that Are Important in Defining Fuel Behavior

Key Fuel Meat Parameters	FRM-II LEU Design	JMTR LEU Fuel	OSIRIS LEU Fuel
Uranium Density (g/cm^3)	4.5	4.8	4.8
Peak Fission Density at EOC (fissions/cm^3)	0.9 x 10^{21}	0.7 x 10^{21}	1.4 x 10^{21}
Time-Averaged Fission Rate (fissions/cm^3/s)	2.0 x 10^{14}	1.6 x 10^{14}	1.3 x 10^{14}
Peak Temperature in Fuel Meat BOC/EOC (˚C)	130/160	125/155	105/135
Other Parameters			
Peak Pointwise Fission Rate (fissions/cm^3/s)	2.9 x 10^{14}	3.1 x 10^{14}	2.3 x 10^{14}
Residence Time in Core (Full Power Days)	50	48	122

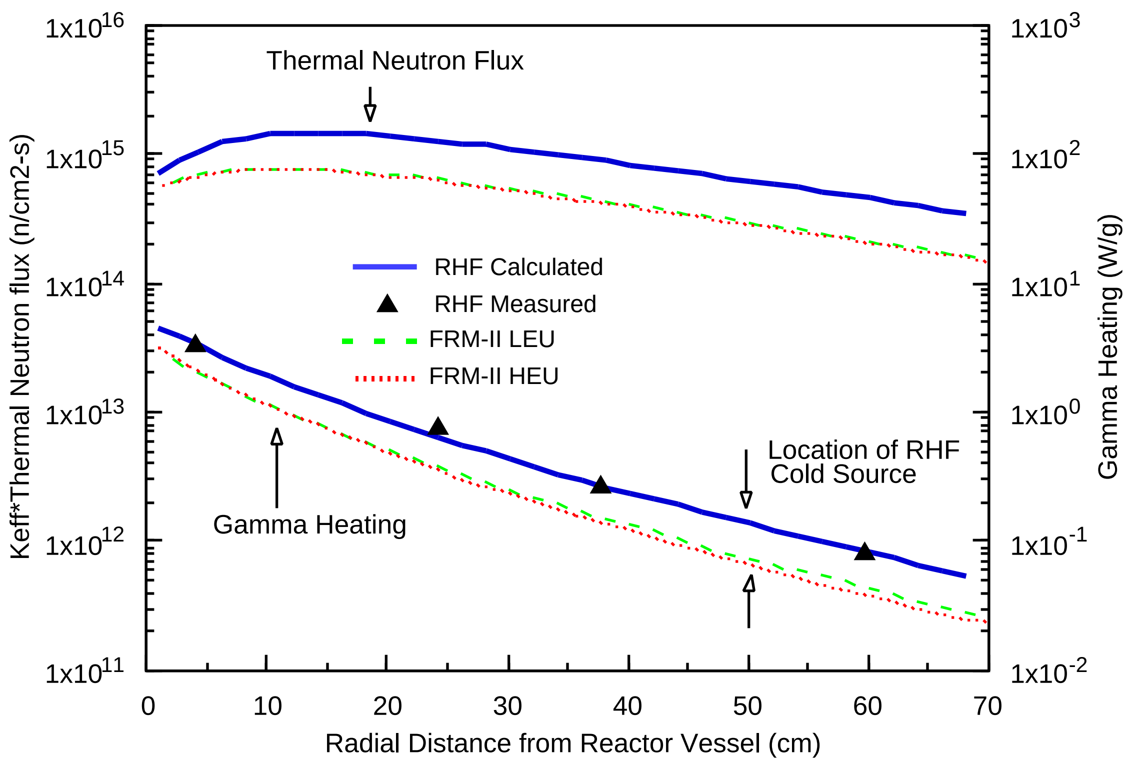
(2) Gamma Heating in the Heavy Water Reflector

Coupled neutron-gamma analyses using the Monte-Carlo code MCNP were performed to compare the energy deposited (gamma heating) in the heavy water reflector of both the FRM-II HEU design and the alternative LEU design. These analyses show that a cold source operating in the alternative LEU design would make a superb experimental facility even though the gamma heating would be slightly higher than in the HEU design.

The methodology for calculating gamma heating was first qualified by comparing calculated and measured data for the RHF (FOEHN)[4] reactor at Grenoble, France. These results are presented in Figure A1 and show excellent agreement. The uncertainty in the Monte Carlo analysis is less than 2% (1 σ). Figure A1 also shows the thermal neutron flux below 0.625 eV.

Results for the FRM-II HEU design and the alternative LEU design are also shown in Figure A1. If the cold source for the FRM-II were located at the same distance from the reactor vessel as the cold source for the RHF (about 50 cm from the vessel), the gamma heating per unit mass of reflector in the HEU and LEU designs would be about 0.064 W/g and 0.075 W/g, respectively. If the cold source were located closer to the core, the difference in gamma heating between the two designs would be even smaller. A cold source operating in the alternative 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 lower than in the RHF and the gamma heating in the LEU design would be a factor of 1.8 lower than in the RHF.

Figure A1. Gamma Heating and Thermal Neutron Fluxes in the FRM-II HEU Design, the Alternative FRM-II LEU Design, and the RHF Grenoble Reactor (calculated and measured).



(3) Radiological Consequences

This section addresses the radiological consequences of (1) increased plutonium production in LEU fuel and (2) the larger fission product inventory in the higher-powered alternative LEU design for the case of hypothetical accidents involving core melting. The results of this analysis show that the alternative LEU design meets in full the radiological consequences criteria[1] set by the German Ministry of Environment (Bundesministerium fur Umwelt - BMU).

The plutonium produced in the FRM-II core is calculated to be 10.4 grams in the HEU design and 158.5 grams in the second alternative LEU design. This increased plutonium production in the LEU design is not an issue by itself. Irradiated LEU fuel will always contain a larger plutonium inventory than irradiated HEU fuel. The pertinent question is the impact that this increased plutonium inventory will have on the radiological consequences of hypothetical accidents. In the analyses discussed below, the plutonium inventory of the FRM-II LEU design has no impact on the radiological consequences for hypothetical accidents involving melting of the core in water. In the analysis, the very conservative assumption was made that 0.015% of the plutonium inventory was released into the air of the reactor building. No credit was taken for plate-out of plutonium on reactor structures and no credit was taken for air filters.

It is expected that the inventory of fission products (other than plutonium) and their radiological consequences will be a factor of about 1.6 higher in the LEU design than in the HEU design because the power level of the LEU design is 1.6 times higher and both designs would operate for 50 days. As an example to confirm this expectation, doses were calculated for both the HEU and LEU designs using the same assumptions for atmospheric conditions, breathing rates, stack height, building leak rate, release factors for noble gases, halogens, and cesium (Ref. 5), and release factors for other radioactive isotopes (Ref. 6). The results of this analysis for a hypothetical accident in which the whole core would be molten under water are presented in Table A3. The conclusion is that the total doses, for any organ and at any time after the release, are nearly directly proportional to the reactor power level.

Table A3. Example Dose Calculations for the FRM-II HEU and LEU Designs for a Hypothetical Accident in Which the Entire Core Would Be Molten Under Water (500 m from the source).

	FRM-II HEU Design Dose (mSv) for Entire Core	Alternative LEU Design Dose (mSv) for Entire Core	Ratio of LEU Dose to HEU Dose
Bone	34.0	54.1	1.59
Lung	33.6	54.1	1.61
Thyroid	0.046	0.074	1.61
Whole body Internal	1.6	2.6	1.63
Whole Body External	6.5	10.1	1.55

Since the radiological consequences for hypothetical accidents involving the entire core are directly proportional to the reactor power level, the consequences of any postulated accident for the LEU design can be obtained directly from the results provided by TUM in Ref. 1, and reproduced here as Figure A2. In this Figure, the LEU integrated doses for Adults and Infants are presented together with those calculated by TUM for the HEU design. These results clearly show that for both the HEU design and the alternative LEU design, the integrated doses for both adults and infants are lower than the minimum value for which evacuation may be required, according to the norms of the BMU. This bound is shown as 100 mSv in Figure A2.

(4) Cost and Schedule

The design features and results obtained in this study are very different from those used by the TUM in their assessment[1] of the costs involved in using LEU fuel in the FRM-II. For example, the LEU core discussed here has one fuel ring (instead of two), a power level of 32 MW (instead of 40 MW), and requires only 48 more plates than the HEU core (instead of 226 more plates). One consequence of the difference in the additional number of fuel plates per core is that a direct extrapolation of the TUM's estimate of the cost increase to operate the FRM-II for 30 years with LEU fuel would be 64 Mio DM instead of 300 Mio DM[1]. In addition, the LEU fuel plates will be simpler to fabricate because they are not graded and would require only one compact per plate instead of two, as in the HEU design. Therefore, it is imperative that cost and schedule issues be thoroughly reviewed, taking into account the results presented in this Attachment.

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6. H-N Jow, et. Al., "XSOR Codes Users Manual", NUREG/CR-5360, Sandia National Laboratories, November 1993.

Figure A2. Radiological Consequences for a Wet Core Melt. Integrated Efective Dose (sum of whole body inhalation dose and whole body external dose) for the FRM-II HEU Design (solid curves labeled Erwachsener and Kleinkind) and the Alternative FRM-II LEU Design (dashed curves labeled LEU - Adults and LEU - Infants). This figure has been reproduced from Ref. 1.