Science and Global Security, 9:61–79, 2002
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0892-9882/02 $12.00 + .00
DOI: 10.1080/08929880290008403

The Conversion of Research Reactors to Low-Enriched Fuel and the Case of the FRM-II

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The use of highly enriched uranium (HEU) as fuel in research reactors runs contrary to the concept of proliferation-resistant nuclear technologies. Consequently, for more than two decades, international activities have been undertaken to terminate the use of HEU in research reactors by supporting the conversion of these facilities to low-enriched uranium (LEU). Achievements, setbacks and perspectives of these efforts are discussed in this article.

The German research reactor FRM-II, which will presumably begin operation in 2002, would be the world's first HEU-fueled reactor in more than 10 years. Among proponents and critics of HEU use in this reactor there is disagreement on the scientific impact of FRM-II conversion, which could be based on designs proposed by Argonne National Laboratory (ANL). In order to support the decision-making process, independent computer simulations have been performed that provide detailed information on the scientific usability of the converted reactor. The most important results of these calculations are presented and discussed.

Received 31 May 2001; accepted 14 November 2001.

An earlier version of this article was presented at the 12th International Summer Symposium on Science and World Affairs, August 23–31, 2000, Moscow (Russia). Results of the calculations on the FRM-II were reported at the 23rd International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR), October 1–6, 2000, Las Vegas (USA).

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The use of highly enriched uranium (HEU), one of the major nuclear weapons-usable materials, to fuel civilian research reactors is one of the most vulnerable aspects of the civilian nuclear fuel cycle.[1] It inevitably goes along with handling, transportation, and long-term storage of the material and, therefore, perpetuates the risk of theft by nonstate actors and the risk of diversion by states for weapons purposes. Consequently, for more than two decades, international efforts have aimed at terminating the use of HEU by converting research reactors to low-enriched uranium (LEU) fuel, which cannot be used as fissile material in a nuclear weapon. Today, although the number of HEU-fueled reactors in the world is decreasing, the remaining facilities still require approximately one metric tonne of fresh HEU per year.[2] In the midterm future, however, if no new facilities were built and existing ones are converted as planned, the use of HEU in the civilian sector could eventually be phased out completely, which would significantly increase the proliferation resistance of the nuclear fuel cycle.

HEU VERSUS LEU

The basic function of research reactors is to provide a maximum number of neutrons available for scientific, industrial, or medical applications. To this end, in research reactors where neutrons result from the fission process, the density of fissile nuclei in the fuel has to be maximized. This can be accomplished by two different strategies:

- Use of highly enriched uranium (HEU), that is, uranium with a fraction of the fissile isotope uranium-235 greater than 20%, but usually greater than 90%; or
- Use of a high uranium density in the fuel matrix which allows the use of low-enriched uranium (LEU, fraction of U-235 $< 20\%$) to provide an equivalent fission density.

Partly due to technical constraints, the HEU option was predominantly pursued in the 1950s and 1960s while accepting, and eventually underestimating, associated proliferation risks. Only in the late 1970s was the development of new research reactor fuels initiated when the *International Nuclear Fuel Cycle Evaluation* (INFCE) conference recommended the conversion of research reactors to low-enriched fuel as an important measure to increase the proliferation resistance of the nuclear fuel cycle. In particular, the *Reduced Enrichment for Research and Test Reactors* (RERTR) program, which was originally established by the U.S.A. but now receives broad international support, provided the principal impetus to these activities by coordinating international activities, encouraging reactor operators to abandon HEU, and preparing feasibility studies for the conversion of existing reactors.[3]

In the early 1980s, typical uranium densities in research reactor fuel were of the order of 1 g(U)/cc (grams uranium per cubic centimeter). The long-term estimated fuel fabrication potential, that is, the upper limit of conceivable uranium densities in such fuels, was believed to have been reached at approximately 3 g(U)/cc.[4] Only later, once new suitable uranium compounds and fuel matrices had been discovered, were higher uranium densities achieved. Today, the densities are as high as 4.8 g(U)/cc. Fuels that will permit uranium densities of 7–9 g(U)/cc are currently under development and will reach maturity around 2006–2008.[5]

SURVEY OF CONVERSION ACTIVITIES AND THE CASE OF THE NEW GERMAN RESEARCH REACTOR FRM-II

Figure 1 shows the construction start of research reactors with a thermal power ≥ 1 MW that use or have used HEU fuel.[6] The figure includes only those facilities

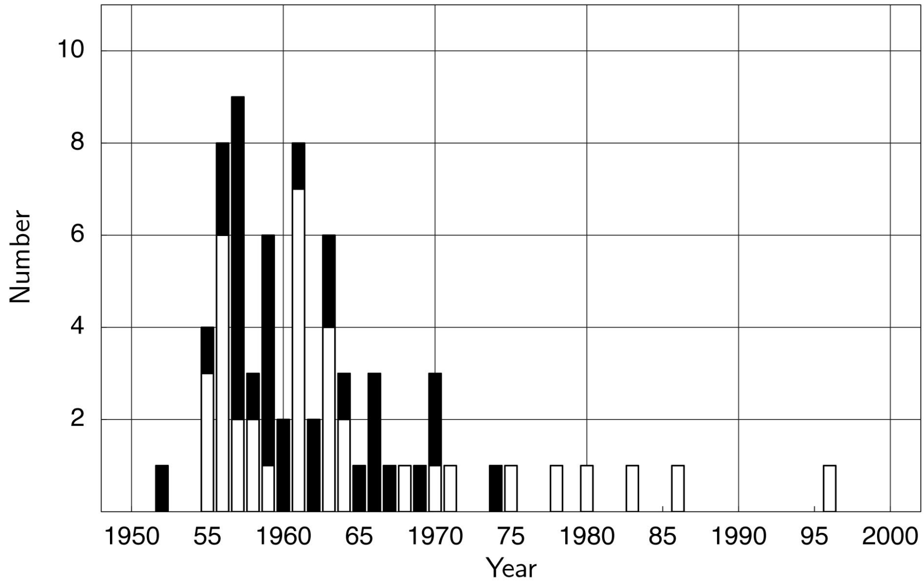

Figure 1: Construction start of research reactors operational in 2000 with a thermal power ≥ 1 MW that used or still use HEU. Marked in black are those reactors where conversion has been fully or partially completed or where conversion or final shutdown is definitely scheduled. See Note 6 for references.

that are still in operation or under construction and highlights those reactors where conversion has been fully or partially completed or where conversion or final shutdown is definitely scheduled.[7]

A dramatic reduction of newly planned reactors based on HEU fuel has occurred since the late 1970s. The actual conversion of older reactors built prior to 1980 is an immediate success of RERTR and associated support programs. In addition to that, for most of those reactors that are still fueled with HEU, the conditions and requirements for conversion have been specified in detailed feasibility studies.[8] In a few instances, suitable LEU fuel is unavailable and only the currently developed, next generation of research reactor fuel (uranium-molybdenum fuel) will allow the conversion of the facilities concerned. In some important cases, agreements exist between fuel providers and reactor operators that guarantee that conversion will take place as soon as the specific fuel is available. This holds true, in particular, for the most important research reactor in the EU and worldwide, the high flux reactor at the Institut Laue Langevin (ILL) in Grenoble (France).

Table 1 lists general information for all research reactors with a thermal power $\geq$1 MW since 1980.[9] Currently, three reactors (located in China, Libya, and Russia) out of a total of 26 reactors are fueled with HEU.[10]

The German research reactor FRM-II[11] is the only research reactor today where start-up is planned with HEU fuel.[12] All other reactors currently planned or under construction will use LEU fuel from the very beginning. This includes projects in Australia, Canada, China, France, Morocco, Thailand, and Taiwan. In particular, the Chinese and the French projects (CARR, 60 MW, and JHR, 100 MW, respectively) stand out since they reflect the political reorientation of former traditional HEU users.[13] Hence, even the nuclear-weapon states support the emerging nonproliferation norm not to build HEU-fueled reactors and to abandon, at least gradually, the use of HEU in the civilian sector. These developments underline the dramatic departure which FRM-II would represent within the international nonproliferation regime. It therefore attracted early attention of the RERTR program.

Alternative LEU designs were first proposed by Argonne National Laboratory (ANL) in 1995, before construction of FRM-II had started.[14] Subsequently, ANL developed additional core designs based on LEU fuel that maintained the cycle length and the maximum thermal neutron flux of the original design while the power would have been increased to 32 MW.[15] Finally, as discussed in the next section, when a new German federal government was elected in 1998 and renewed interest in conversion of FRM-II emerged, ANL provided the essential input for possible conversion strategies taking into account the advanced construction level at that time. However, among proponents and critics

Table 1: Research reactors in operation with construction start not earlier than 1980 (top) and research reactors under construction or planned (bottom) with thermal power ≥ 1 MW (Enrichment is given in weight percent, HEU-fueled reactors are starred).

Country	**Code**	**Name**	**Construction start**	**Power**	**Enrichment of fuel**
		IN OPERATION			
Algeria	DZ-0001	NUR	1987	1 MW	20%
	DZ-0002	ES-SALAM	1988	15 MW	3%
Bangladesh	BD-0001	TRIGA II	1981	3 MW	20%
China	CN-0007	PPR	1986	1 MW	20%
	CN-0010	NHR-5	1986	5 MW	3%
	CN-0012	MJTR	1986	5 MW	90%*
Egypt	EG-0002	ETRR-2	1992	22 MW	20%
Indonesia	ID-0003	GA SIB.	1983	30 MW	20%
Japan	JP-0008	JRR-3M	1985	20 MW	20%
South Korea	KR-0004	HANARO	1987	30 MW	20%
Libya	LY-0001	IRT-1	1980	10 MW	80%*
Malaysia	MY-0001	TRIGA II	1981	1 MW	20%
Peru	PE-0002	RP-10	1980	10 MW	20%
Russia	RU-0020	RBT-10/2	1983	10 MW	63%*
USA	US-0238	TRIGA II	1987	1 MW	20%
	US-0240	TRIGA II	1986	1 MW	20%
		UNDER CONSTRUCTION OR PLANNED			
Australia		ANSTO RR	2002	20 MW	20%
Canada		Maple 1	1990	10 MW	20%
		Maple 2	1998	10 MW	20%
		CNF	2003	40 MW	20%
China		CARR	2003	60 MW	20%
Germany	DE-0051	FRM-II	1996	20 MW	93%*
France		JHR	2003	100 MW	20%
Morocco	MA-0001	MA-R1	1999	2 MW	20%
Thailand	TH-0002	MPR-10	2000	10 MW	20%
Taiwan		TRR-II	2001	20 MW	20%

of the current design, there is disagreement on the scientific impact of FRM-II conversion. In order to support the decision-making process, independent computer simulations have been performed that provide detailed information on the scientific usability of the converted reactor. The most important results of these calculations are presented and discussed in the following part of this article.

From a more general perspective, the analysis also exemplifies the potential of advanced high-density LEU fuels in a direct comparison between an HEU design and an alternative LEU design for a given reactor while maintaining the main characteristics of the facility.

THE CONVERSION VARIANTS FOR THE FRM-II

The research reactor FRM-II has been under construction from 1996 to 2002. Located in Garching near Munich (Germany), it will be operated by Technical University of Munich (TUM) and will be primarily dedicated to neutron research. The reactor is designed for a thermal power of 20 MW and would have a peak unperturbed thermal neutron flux of 8×10^{14} n/cm^2 s. The FRM-II uses one single fuel element containing a total uranium inventory of 8.1 kg, enriched to 93% in 113 involute-shaped fuel plates (Figure 2, left). The estimated cycle length will be slightly higher than 50 days. The core is light water cooled and located in the center of a heavy water filled moderator tank where, in particular, a cold neutron source and the beam tubes are placed (illustrated in Figure 3).[16]

The fact that HEU will be used as fuel for the reactor was strongly criticized from the very beginning at a national and international level.[17] Nevertheless, due to the support of the Bavarian and the former German Federal Government, construction of the reactor commenced in 1996 without seriously contemplating the use of LEU. In January 1999, a few months after the change of the Federal

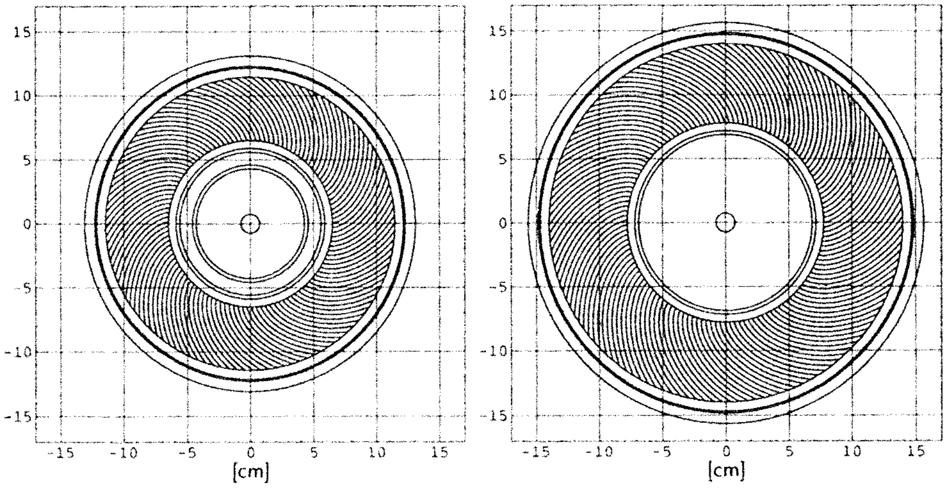

Figure 2: Geometry of the two alternative fuel elements for the FRM-II: HEU design (left) and LEU design as proposed by ANL (right). *xy*-plane at $z = 0$. The active height is 70 cm for both designs.

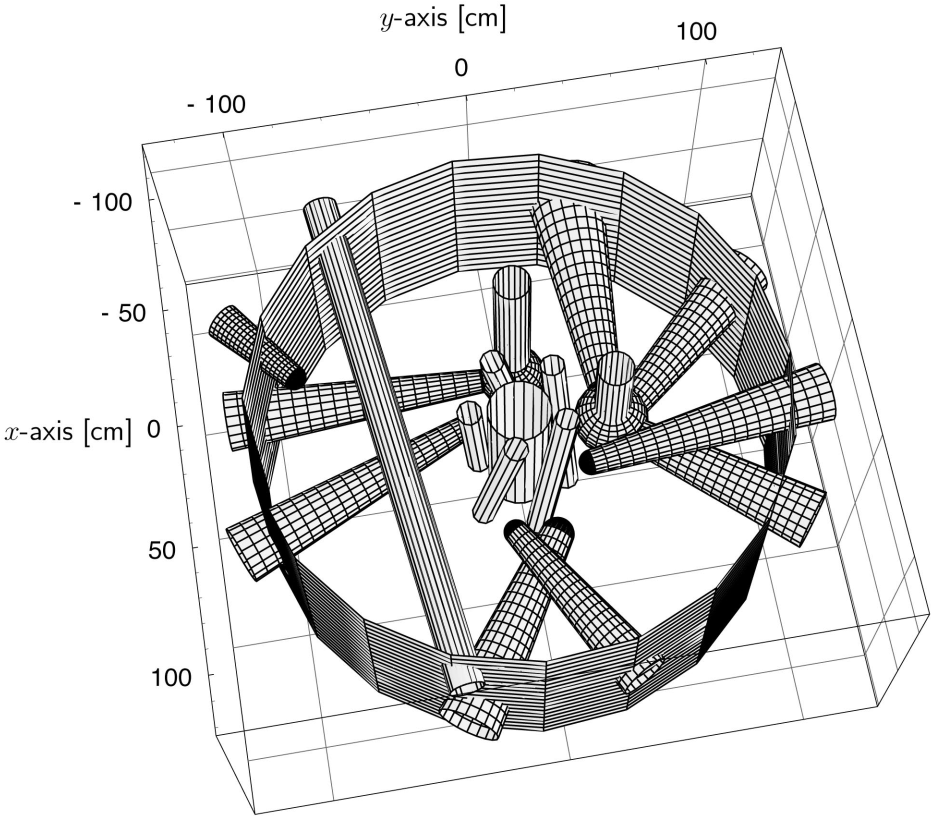

Figure 3: Illustration of the main components in the moderator tank: beam tubes 1 to 10, cold and hot neutron source and safety rods 1 to 5. The axes being defined as indicated, beam tube 1 runs parallel to the *x*-axis and is directed on the cold neutron source centered around $(x, y, z) = (-5, 40, 0)$ cm.

Government, an expert commission was established by the Federal Ministry of Education and Research (BMBF). Its task was to clarify whether conversion of the reactor would be possible after construction had begun, what the (negative) scientific impact of conversion would be, and what consequences the use of HEU would have with respect to aspects of nuclear nonproliferation. Three conversion variants were defined during the discussion, mainly based on LEU designs developed by ANL.[18]

Variant 1. Increasing the thermal power of the reactor from 20 MW to 32 MW. Based on a larger fuel element and on LEU fuel available today, this measure

Table 2: Data for alternative fuel elements.

	TUM design	**ANL design**
Dimensions of fuel element		
Minimum inner radius of fuel element	59.00 mm	71.80 mm
Outer radius of inner core-tube	65.00 mm	77.80 mm
Inner radius of outer core-tube	114.50 mm	140.00 mm
Maximum outer radius of fuel element	121.50 mm	147.00 mm
Dimensions of fuel plate		
Thickness of fuel meat	0.60 mm	0.76 mm
Thickness of cladding	0.38 mm	0.38 mm
Thickness of cooling channel	2.20 mm	2.20 mm
Arc-length of inner fuel zone	51.50 mm	—
Arc-length of outer fuel zone	10.90 mm	—
Arc-length of active zone of plate	62.40 mm	80.31 mm
Arc-length of plate (inner to outer tube)	69.40 mm	87.33 mm
Total height of fuel plate	720.00 mm	720.00 mm
Height of active zone	700.00 mm	700.00 mm
Number of plates	113	131
Uranium inventory		
Enrichment	92.65 wt%	26.00 wt%
Total mass of uranium in core	8108 g	26865 g
Total mass of uranium-235 in core	7512 g	6985 g
Mass of uranium per plate	71.75 g	205.08 g

would provide the same thermal neutron flux and cycle length as the standard HEU design. This option was discarded by the commission at an early stage because it would essentially result in rebuilding the facility and entail unacceptable costs and delay.[19]

Variant 2. Conversion of the reactor prior to completion. While maintaining the 20 MW power level and the cycle length, this would imply the use of a fuel element with an increased radius and, hence, reconfiguration and partial modification of the components in the moderator tank (Figure 2, right, and Table 2). Two different options are considered (variants 2a and 2b, cf. Table 3

Table 3: Data for FRM-II conversion strategies.

		Variant 2a	**Variant 2b**	**Variant 3a**	**Variant 3b**
Start	Fuel type	U_3Si_2	U_3Si		
(≥2002)	Enrichment	24–26 wt%	19.75 wt%	No action!	No action!
	Uranium density	4.8 g/cm^3	6.2 g/cm^3		
Goal	Fuel type	UMo	UMo	UMo	UMo
(≥2006)	Enrichment	19.75 wt%	19.75 wt%	19.75 wt%	40–70 wt%
	Uranium density	7–9 g/cm^3	7–9 g/cm^3	7–9 g/cm^3	max. 8.0 g/cm^3

for details). As soon as the currently developed uranium-molybdenum fuel is available, the uranium-silicide fuel would be replaced without further modifications of the reactor.

Variant 3. Conversion of the reactor after completion when new fuel types with ultrahigh uranium densities are available, presumably between 2006 and 2008. Again, two different strategies are discussed: conversion to LEU fuel using an enlarged fuel element which would entail modification of the activated reactor (variant 3a), or conversion to fuel enriched to 40–60%, which would not require any reactor modifications (variant 3b, cf. Table 3).

The commission's report discussed the pros and cons of these conversion strategies and concluded that conversion before start-up is technically feasible and the most reasonable solution with respect to nonproliferation policy.[20] However, the report does not give clear preference to any of the options, partly because the information concerning the conversion variants was either incomplete or controversially assessed due to differing data provided by TUM and ANL. This controversy motivated the calculations discussed below.

In October 2001, an agreement was reached between the German Federal Government and the Bavarian State Government which, in essence, envisions conversion variant 3b to be implemented.[21]Accordingly, the reactor would start operation with HEU as initially planned and be converted by December 2010 to a fuel enriched to maximally 50%.

METHOD OF CALCULATION

Based on a three-dimensional model of the reactor core,[22] the Monte Carlo neutron transport code MCNP (Version 4B)[23] has been used to determine all neutron-physical quantities that are relevant for an assessment of the impact of conversion on the scientific usability of the reactor. This includes, in particular, the neutron spectrum, the heating of the cold source due to neutron and gamma radiation, the impact of the experimental components in the moderator tank, as well as the spectrum-averaged neutron cross-sections, which in turn are a prerequisite to determine the cycle length by means of burnup calculations.

The MCNP simulations have been prepared by routines written in *Mathematica* (Version 4.0.1).[24] Depending on the parameters chosen, in particular those defining the design of the core (geometry and number of fuel plates, radii, etc.), *Mathematica* automatically generates the entire MCNP input file. This procedure is extremely helpful when different fuel element designs are analyzed. For example, the representation chosen for the involute-shaped fuel

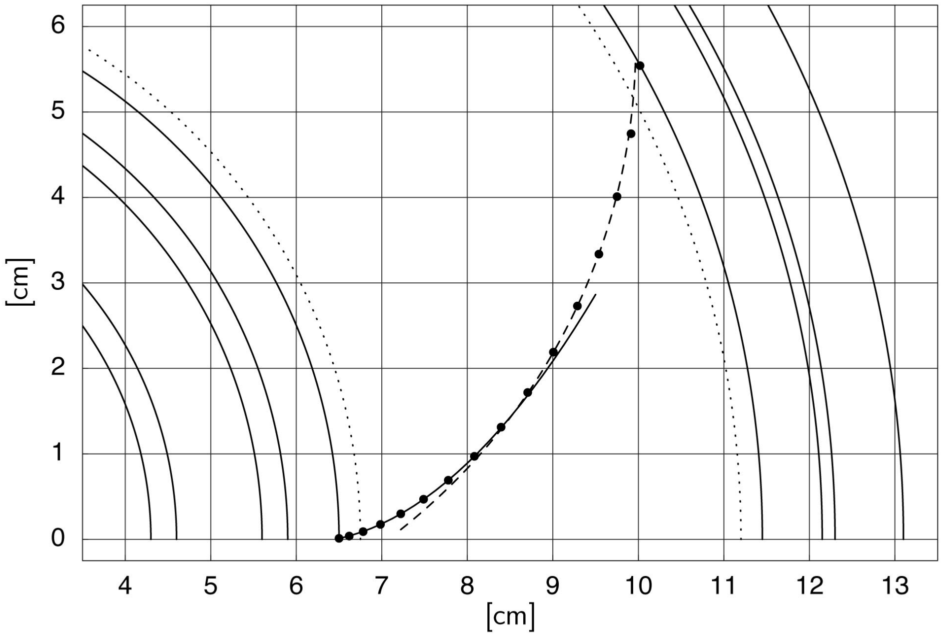

Figure 4: Representation of involute-shaped fuel plate in the simulations by appropriate approximation functions: parabola (—) and circle (- -) in *xy*-plane. Bullets indicate the exact coordinates of the involute. The dotted lines limit the active zones of the fuel plates.

plates that cannot be directly modeled in MCNP, is shown in Figure 4. The optimum parameters of the approximation functions are automatically determined by the program and translated into MCNP syntax. *Mathematica* finally provides convenient means for the numerical and graphical evaluation of the MCNP output.

In the unperturbed case, the fuel element enclosed by the central channel tube is located in the center of the moderator tank without additional experimental and reactor components in place. The tank has a height of 300 cm, a diameter of 220 cm, and contains heavy water with a density of 1.1 g/cc.[25] In the general case, where the cylindrical symmetry is no longer conserved, the cold neutron source and the horizontal beam tubes have been included in the model. Since complete and up-to-date design information on the cold neutron source has not been available, the simulations use a simplified model in which the liquid deuterium-hydrogen mixture (95 wt% D_2 and 5 wt% H_2, density: 0.2 g/cc) is contained in a spherical zirconium shell of 31 cm diameter.[26] Further details of the device have not been modeled.[27]

RESULTS OF THE CALCULATIONS

The most important results obtained for the different conversion variants are listed in Table 4. While the results for the different LEU options are very similar to each other, variant 2a is presumably the most attractive conversion option because the other strategies (2b, 3a, and 3b) each suffer from a serious disadvantage. Variant 2b is based on U_3Si fuel which is characterized by an inferior irradiation behavior. Although this fuel is supposed to behave well under FRM-II conditions, additional licensing procedures to qualify the fuel would probably become necessary. Thereby, the attractiveness of conversion option 2b is significantly reduced compared to option 2a, which uses standard U_3Si_2

Table 4: Basic results of the calculations for the FRM-II conversion variants 2 and 3 (Quantities for the unperturbed case: maximum thermal neutron flux $\phi_{th,max}$ and thermal neutron flux at position of cold neutron source $\phi_{th,cns}$. Relative heating of the cold neutron source for the perturbed case with main experimental components in the moderator tank modeled. Values given in percent are relative to the standard HEU design (100%).)

	HEU	**Variant 2a (Start)**	**Variant 2b (Start)**	**Variant 2 (Goal)**
Fuel type	U_3Si_2	U_3Si_2	U_3Si	UMo(6wt%)
Enrichment (wt%)	ca. 93	26.00	19.75	19.75
Uranium density (g/cm^3)	3.0/1.5	4.8	6.2	7.1
Unperturbed case				
$\phi_{th,max}$ (10^{14} n/(cm^{2}s))	8.06	6.40 (79.3%)	6.44 (79.9%)	6.27 (77.8%)
$\phi_{th,cns}$ (10^{14} n/(cm^{2}s))	5.69	4.93 (86.6%)	4.95 (87.0%)	4.81 (84.6%)
Perturbed case				
Relative heating of CNS	100.0%	100.8%	100.8%	98.7%

	HEU (Start)	**Variant 3a (Goal)**	**Variant 3b (Goal)**
Fuel type	U_3Si_2	UMo(6wt%)	UMo(6wt%)
Enrichment (wt%)	ca. 93	19.75	50.00
Uranium density (g/cm^3)	3.0/1.5	7.1	8.0/4.0
Unperturbed case			
$\phi_{th,max}$ (10^{14} n/(cm^{2}s))	8.06	6.27 (77.8%)	7.63 (94.6%)
$\phi_{th,cns}$ (10^{14} n/(cm^{2}s))	5.69	4.81 (84.6%)	5.45 (95.9%)
Perturbed case			
Relative heating of CNS	100.0%	98.7%	95.1%

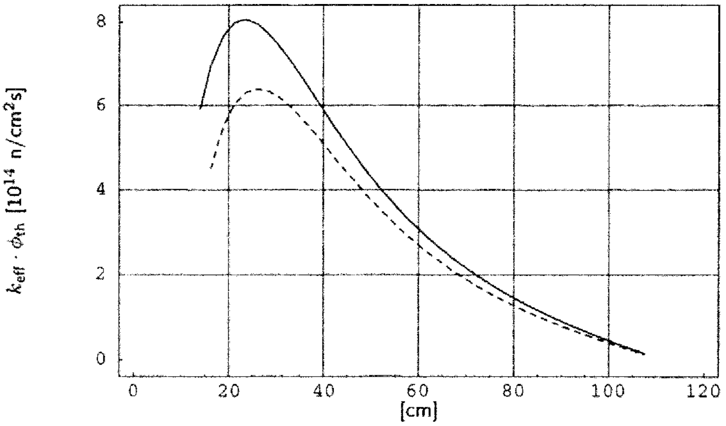

Figure 5: Radial distribution of thermal neutron flux for the HEU design (—) and for the conversion variant 2a (- -). The maximum value of the conversion variant reaches 79%, the thermal neutron flux at $r = 40$ cm reaches 87% of the HEU reference value. Distance is measured from the core centerline.

fuel. Variant 3a requires modification of the activated reactor, and thus can be considered an extremely unrealistic option, whereas variant 3b relies on fuel clearly beyond the LEU limit and would basically have no advantage from the perspective of nonproliferation (see discussion below). Therefore, only variant 2a is discussed in more detail.[28]

The radial distribution of the thermal neutron flux for the unperturbed situation, that is, without additional experimental components in the moderator tank, is shown in Figure 5. The maximum value of conversion variant 2a reaches 79% of the HEU reference value. This value, however, appears close to the core where no neutrons are extracted for experiments and is, therefore, of little value when assessing the scientific usability of the reactor. A more relevant number is the neutron flux at the position of the cold neutron source at $r \approx 40$ cm. The reduction in the thermal neutron flux is less pronounced at this distance of the core: the flux reaches 87% of the HEU reference value.

As outlined above, in more complex simulations, the most important experimental components have also been modeled (cf. Figure 3). In particular, the cold neutron source and the beam tubes are considered in order to determine the gamma and neutron heating of the cold source as well as the neutron spectrum in the beam tubes at greater distances from the core.

It has been stated by the TUM project leaders that a larger fuel element (as proposed by ANL) would lead to increased heating of the cold source, which would in turn lead to unsurmountable cooling problems. This effect was not

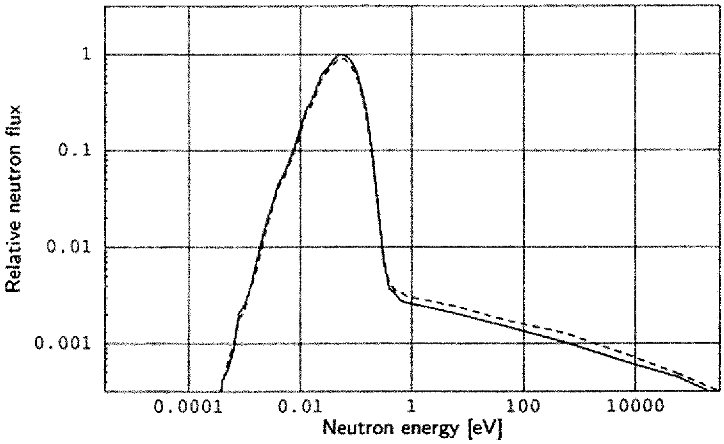

Figure 6: Neutron spectrum in beam tube 1 at $x = -70$ cm, axis as defined in Figure 3. Standard HEU design (—) and Variant 2a (- -). Relative maximum value of LEU design: 90.7% of HEU value. Each spectrum is based on evaluation of 40 million neutron histories.

confirmed by the simulations which, instead, support the results published by ANL.[29] In case of the variants 2a and 2b, the heat deposited in the cold neutron source increases by less than 1%, in all other cases heat deposition decreases.[30]

The neutron spectrum in beam tube 1, which alone will be responsible for more than 40% of the scientific usability of the facility,[31] is shown in Figure 6. The maximum value of the cold neutron flux is reduced by slightly less than 10% compared to the original HEU design. The fast neutron flux, which is considered an undesired background signal, increases (between 1 eV and 10 MeV) by 17% on average.

ASSESSMENT OF THE CONVERSION VARIANTS

A number of considerations must be taken into account when assessing the overall impact of the conversion variants proposed for the FRM-II (relative to the original HEU design). Besides the scientific usability of the converted reactor and nonproliferation issues associated with the different conversion options, reliability of fuel supply, disposition of the spent fuel, delays, and economic considerations equally deserve attention.

Scientific Usability

The reduced neutron flux in all LEU conversion variants will require extended measuring times. Based on the calculations performed and comparing the values (for variant 2a) at the position of the cold neutron source where the neutron flux is reduced by 13.4%, an extended measuring time of approximately 15% results.[32] Reduction of the neutron flux tends to become less pronounced at greater distances from the core. In beam tube 1 it amounts to a mere 10%. The quality of the neutron spectrum, namely the signal to noise ratio, is not significantly affected by the use of a LEU core.

Nonproliferation

In a situation where other important high flux reactors are prepared for conversion to LEU, Germany sets a counterproductive example for the international research reactor community and puts at stake the remarkable progress that RERTR achieved over the last decade.[33] Ultimately, the case of the FRM-II may impede the complete phase-out of HEU use in the civilian sector for the next decades.

With respect to the properties of the spent fuel, it has to be noted that the burnup of the fuel is very low. The fraction of uranium-235 in the HEU fuel is reduced from an initial enrichment of 93% to an average value of approximately 88.5%, that is, by only 4.5%. Since the total uranium inventory per fuel element also remains rather high (slightly more than 7 kg), the spent fuel equally represents a serious proliferation hazard.

While uranium enriched to 20% is indeed extremely unattractive for weapons-use, the critical mass of uranium drops rapidly for higher enrichment levels (Figure 7). In the case of a beryllium-reflected metallic sphere, the absolute value of one critical mass increases from 15 kg for an enrichment of 93% by less than a factor of three if the enrichment is reduced to 50%. This has to be compared with the critical mass of approximately 220 kg for uranium enriched to 20%. As a consequence, an alternative fuel enriched to 50%, as proposed for the currently envisioned conversion variant 3b, cannot be categorized as proliferation proof. Conversion of the reactor along this option will not lead to a significant improvement in proliferation resistance.

Fuel Supply and Disposition

The HEU annually required for operation of the FRM-II amounts to more than 40 kg (five fuel elements with an uranium inventory of 8.1 kg each). According to the *Schumer Amendment* from 1992, the U.S.A. does not supply fuel for the FRM-II. For this reason, the reactor operator is planning to cover long-term fuel supply with HEU provided by Russia. For the entire lifetime of the facility, the project would rely upon the availability of a material that is internationally proscribed. It has to be emphasized that variant 3b would not solve the supply

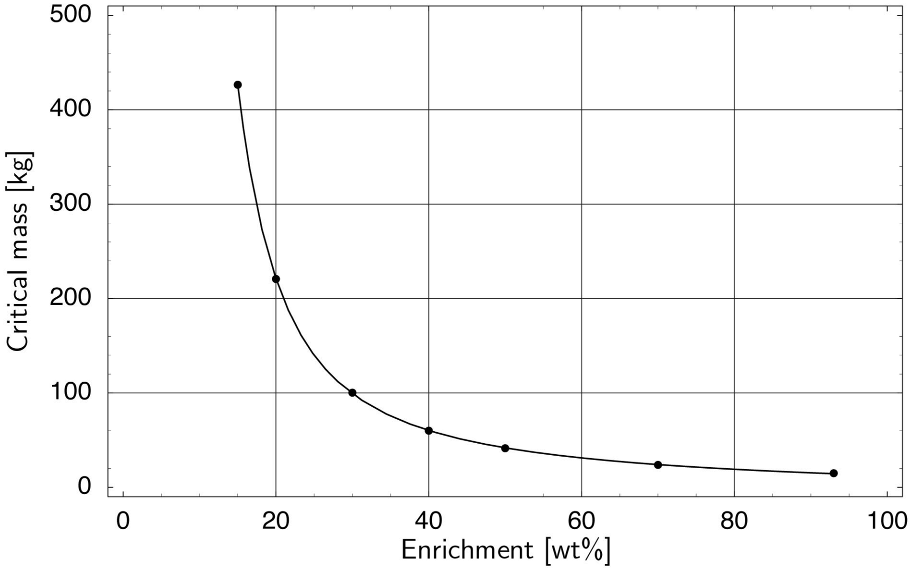

Figure 7: Critical mass of a beryllium-reflected uranium sphere as a function of the uranium-235 enrichment. MCNP 4B simulations at 300 K with ENDF/B-VI cross section libraries. Reflector thickness is 10 cm. Assumed value of uranium density: 19 g/cm^3. Enrichment is given in weight percent (wt%).

dilemma faced by the operator since the fuel enriched to 50% is equally classified as HEU. The second conversion option exceeding the 20% limit (variant 2a, 24–26% enrichment), however, could be acceptable from the perspective of nonproliferation, in particular, because it is seen as a temporary solution.

Unexpected problems may also emerge at the back-end of the fuel cycle. Since cooperation with the U.S. *Spent Fuel Acceptance Program* is excluded, and reprocessing services for uranium-silicide fuels are not available, Germany eventually may have to develop and implement a disposition strategy for the spent HEU fuel from FRM-II which could turn out to be an expensive venture. For instance, the U.S.A. is currently developing the *Melt & Dilute* technology to deal with its legacy of spent research reactor fuel in a two billion dollar program.[34]

Delays and Costs

Except for variant 3b where almost no significant downtime would be expected, conversion of the reactor is probably associated with a delay or temporary shut-down of 2–3 years. The crucial issue is when this downtime would be most acceptable. An analysis of the availability of European neutron research facilities suggests that a delay today would have a smaller impact than a several year downtime for conversion in 10 years or so when other facilities dedicated to neutron research will be shut down and the planned *European Spallation Source* (ESS) will not yet be available. Again, this speaks strongly in favor of conversion prior to start-up of FRM-II (variants 2a and 2b).

Additional costs that would result from modifications or downtimes of the reactor, will arise in any of the conversion scenarios. Even if accurate analyses are not available, these costs should be acceptable compared to the total budget of the project. Within this context, it would have been favorable to decide on the conversion strategy shortly after the commission had published its report in June 1999, when the moderator tank had not yet been installed.

However, the HEU option may also lead to significant follow-up costs. For example, the likely domestic final disposition of HEU and the impossibility of cooperation with the U.S. programs will incur additional financial burdens at the back-end of the fuel cycle.

CONCLUSION

The calculations discussed in this article are focused on the FRM-II conversion scenarios identified by an expert commission in 1999 and confirm, in essence, the data previously published by ANL. In the additional simulations presented in this article, where the main components of the moderator tank and, in particular, the beam tubes have been included in the model, further data for the different conversion strategies have been acquired.

Balancing the pros and cons discussed above, variant 2a turns out to be the most attractive option. It would entail immediate conversion of the reactor prior to start-up and is only temporarily based on a fuel slightly above the LEU limit (24–26% enrichment). The simulations predict that the measuring times would have to be extended by at most 15% compared to the current HEU design.

Conversion of the reactor at a later time would either imply modification of the activated reactor or the use of a fuel enriched to 40–60% while maintaining the current geometry. This latter option corresponds to the strategy currently envisioned in an agreement between the German Federal and the Bavarian State Government which requires the conversion to a fuel enriched to 50% by December 2010. Conversion of a research reactor to such a fuel does not constitute a satisfactory option from the perspective of nonproliferation, especially if understood as a permanent solution.

The direct comparison between HEU and LEU designs, even under the extremely restrictive conditions imposed by the advanced construction level of the FRM-II when conversion was first considered, demonstrates the potential of advanced high-density LEU fuels which can almost reproduce the performance of their HEU counterparts. Hence, even from the technical perspective, the arguments for the use of HEU are becoming obsolete.

The FRM-II based on the current HEU design sets a negative precedent that could easily be avoided. It represents a clear withdrawal from a proven nonproliferation policy and unnecessarily jeopardizes the successful international efforts to ban the use of HEU for civilian purposes.

ACKNOWLEDGMENTS

I owe a special thanks to my colleagues at Darmstadt University of Technology, namely Christoph Pistner and Wolfgang Liebert, for support of and contributions to this project. I also wish to thank the staff from the RERTR program who established the basis of this work by providing the underlying concepts for conversion of the FRM-II reactor. Finally, I gratefully acknowledge the financial support for this project by the Berghof Foundation for Peace and Conflict Research, the Interdisciplinary Research Group in Science, Technology, and Security (IANUS), and the Social Science Research Council (SSRC).

NOTES AND REFERENCES

1. In the civilian sector, HEU is also used in research reactor targets (in minute quantities) for radioisotope production and in the fuel of Russian nuclear-powered icebreakers.

2. D. Albright, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies*, SIPRI (Oxford University Press, 1997), in particular, chapter 8 and appendix D.

3. See, for example, W. Krull, “Progress and Pain with RERTR—20 Years on,” *Nuclear Engineering International*, December 1998, pp. 26–28, and A. Travelli, *Status and Progress of the RERTR Program in the Year 2000*, 23rd International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR), October 1–6, 2000, Las Vegas, Nevada.

4. *International Nuclear Fuel Cycle Evaluation* (INFCE) (International Atomic Energy Agency (IAEA), Vienna, 1980), Cf., in particular, Vol. VIII, p. 142.

5. It must be stressed that the uranium densities achievable today are an explicit result of the research and development initiated and funded by conversion activities. The fact that such a fuel type would be used in the FRM-II (discussed below) in conjunction with highly enriched uranium, is therefore highly problematic.

6. Information on operational research reactors has been extracted from *Nuclear Research Reactors in the World*, (International Atomic Energy Agency, Reference Data

Series No. 3, September 2000 Edition, Vienna, 2000). The information on the conversion status of the relevant facilities is mainly based on J. E. Matos, *LEU Conversion Status of U.S. Research Reactors, September 1996*, 19th International Meeting on Reduced Enrichment for Research and Test Reactors, October 7–10, 1996, Seoul, Korea. Additional, updated information was provided by J. E. Matos (ANL) in private communications. More detailed information on the individual facilities (represented in Figure 1) is available at www.inesap.org/rr.html

7. The following converted reactors do not appear due to the restrictions applied: four reactors which, in the meantime, have been shut down and four reactors with a thermal power <1 MW.

8. Exceptions are the Russian research reactors. For most of the 12 Russian HEU-fueled reactors listed by the IAEA (operational in 2000, thermal power ≥ 1 MW), information on the preconditions for conversion is sparse, however, a more comprehensive collaboration with the RERTR program is currently emerging.

9. See note 6 for references.

10. The IAEA lists one Russian HEU-fueled research reactor built after 1980 (RU-0021, RBT-10/1) as shut down.

11. FRM-II stands for *Forschungsreaktor München II*.

12. The US-American Advanced Neutron Source (ANS) project, which was also based on HEU fuel, was canceled in 1996, mainly because of nonproliferation concerns.

13. China began as late as 1985 with the construction of a HEU-fueled reactor (MJTR, 5 MW); France is still operating four older HEU-fueled reactors.

14. S. C. Mo, N. A. Hanan, J. E. Matos, *Comparison of the FRM-II HEU Design With an Alternative LEU Design*, 18th International Meeting on Reduced Enrichment for Research and Test Reactors. September 18–21, 1995, Paris, France.

15. N. A. Hanan, S. C. Mo, R. S. Smith, J. E. Matos, *An Alternative LEU Design for the FRM-II*, 19th International Meeting on Reduced Enrichment for Research and Test Reactors. Seoul, Korea, October 7–10, 1996.

16. For additional information on the design of the reactor see, for instance, A. Röhrmoser, *Neutronenphysikalische Optimierung und Auslegung eines Forschungsreaktors mittlerer Leistung mit Zielrichtung auf einen hohen Fluss für Strahlrohrexperimente*, dissertation, Department of Physics, Technical University of Munich, July 25, 1991, or K. Böning, A. Axmann, W. Petry, *Der FRM-II: eine umfassend optimierte Neutronenquelle für die Forschung*, Technical University of Munich, Opa 00229, April 1999.

17. See, for instance, W. Liebert, Open letter concerning the planned research reactor FRM-II using highly enriched uranium, *INESAP Information Bulletin*, No. 2, July 1994, pp. 16–18.

18. See, for example, N. A. Hanan, R. S. Smith, J. E. Matos, *Alternative LEU Designs for the FRM-II With Power Levels of 20–22 MW*, 22nd International Meeting on Reduced Enrichment for Research and Test Reactors. Budapest, Hungary, October 3–8, 1999.

19. As mentioned earlier, this conversion strategy was already published by ANL in 1995 before construction of FRM-II actually began.

20. Federal Ministry of Education and Research (BMBF), *Bericht der von der Bundesregierung eingesetzten Expertenkommission zur Prüfung der Umrüstbarkeit des Forschungsreaktors München II von HEU auf LEU* (Bonn, June 1999).

21. Federal Ministry of Education and Research (BMBF), *Vereinbarung über FRM II vorgestellt*, Press release No. 169/2001, October 25, 2001.

22. More detailed information can be found in A. Glaser, C. Pistner, W. Liebert, *Verifizierung und Präzisierung der Informationen zu den Brennstoff-Varianten für den Forschungsreaktor München II*, IANUS Working Paper 2/2000 (Darmstadt, February 2000).

23. J. Briesmeister (editor), *MCNP—A General Monte Carlo N-Particle Transport Code, Version 4B* (Los Alamos National Laboratory, LA-12625-M, 1997).

24. *Mathematica* 4.0.1 for Linux. Wolfram Research, Inc., and S. Wolfram, *The Mathematica Book*, Fourth Edition (Cambridge University Press, 1999).

25. A low content of hydrogen has been added in order to account for light-water impurities (ratio hydrogen to deuterium: 0.2 at%).

26. See K. Gobrecht, *Progress on the Cold Neutron Source of the Garching Neutron Research Facility FRM-II*, Proceedings of the 6th Meeting of the International Group on Research Reactors. KAERI/GP-128/98. April 29–May 1, 1998. Taejon, The Republic of Korea, pp. 377–390.

27. Due to the limited availability of information on the design of the cold neutron source, precise estimates of the absolute values of the neutron and gamma heating are difficult to make. However, a relative comparison of the heat deposited in the cold neutron source under equal simulation conditions provides a good assessment of the general situation.

28. Results of burnup calculations are not discussed in this article. However, one of the main findings is that the cycle length for conversion variant 2a is at least as high as for the original HEU design, which is approximately 52 days.

29. See note 18 for reference.

30. A recent publication by TUM suggests that the controversy regarding a possible increase in the heating of the cold neutron source may have been overemphasized. Apparently, it is possible to achieve significant additional cooling if required: "The refrigerator [...] can be upgraded [from 5 kW] to 8 kW refrigeration power by adding an extra compressor and further expansion turbines, in case of additional needs of refrigeration near the core (e.g., for a second CNS)." (E. Gutsmiedl and K. Gobrecht, *Status Report on the Cold Neutron Source of the Garching Neutron Research Facility FRM-II.* IGORR 8 Meeting, April 17–20, 2001, Munich, Germany.)

31. According to the second reference in note 16, the utilization factor of beam tube 1 will be 42.5%.

32. It is assumed that for a given experiment, the measuring time has to be extended such that the total number of neutrons remains constant, i.e., $\phi_1 t_1 = \phi_2 t_2 = const.$

33. See references in note 3.

34. U.S. Department of Energy, *Savannah River Site, Spent Nuclear Fuel Management Final Environmental Impact Statement*, DOE/EIS-0279, March 2000, and *Record of Decision for the Savannah River Site Spent Fuel Management Final Environmental Impact Statement*, Federal Register, Vol. 65, No. 152, August 7, 2000.