FRM-II Conversion Revisited

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Abstract. The possibilities for a conversion of the currently constructed research reactor FRM-II has been extensively discussed at various RERTR meetings over the past years. In order to support the ongoing decision-making process in Germany, we prepared computer simulations providing extra information on the scientific usability of the converted reactor based on designs proposed by ANL and TUM. The most important results of these calculations are presented and discussed. Special attention is thereby given to the specific German context.

The conversion variants for the FRM-II

The research reactor FRM-II is currently under construction in Garching (Germany) and will be operated by Munich University of Technology (TUM). The reactor is designed for a thermal power of 20 MW and would realize a peak unperturbed thermal neutron flux of $8 \times 10^{14}\,\mathrm{n/cm^2\,s}$ [Böning et al., 1999]. One single fuel element is employed containing a total uranium inventory of 8,1 kg enriched to 93% in 113 involute-shaped fuel plates (figure 1, 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 2).

The fact that HEU will be used as fuel for the reactor was strongly criticized from the very beginning on a national and international level. 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 German Federal Government, an expert commission was established by the 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 which consequences the use of HEU would have with respect to aspects of nuclear nonproliferation. Three conversion variants were defined during the discussion. All of them are essentially based on models developed by ANL (cf. for example [Hanan et al., 1999]).

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 would realize the same thermal neutron flux and cycle length as with 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.[1]

Variant 2: Conversion of the reactor prior to completion. While maintaining the 20 MW power level and the cycle length, this would equally imply the use of a fuel element with an increased radius and, hence, reconfiguration and partial modification of the components in the moderator tank. Two different options are considered (variants 2a and 2b, cf. table 1 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 ultra-high uranium densities are available, presumably around 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 modifications (variant 3b, cf. table 1).

1 It should be noted, however, that this conversion strategy was already published by ANL in 1995 before construction of FRM-II actually began [Mo et al., 1995].

The report of the commission 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 [BMBF, 1999]. 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.

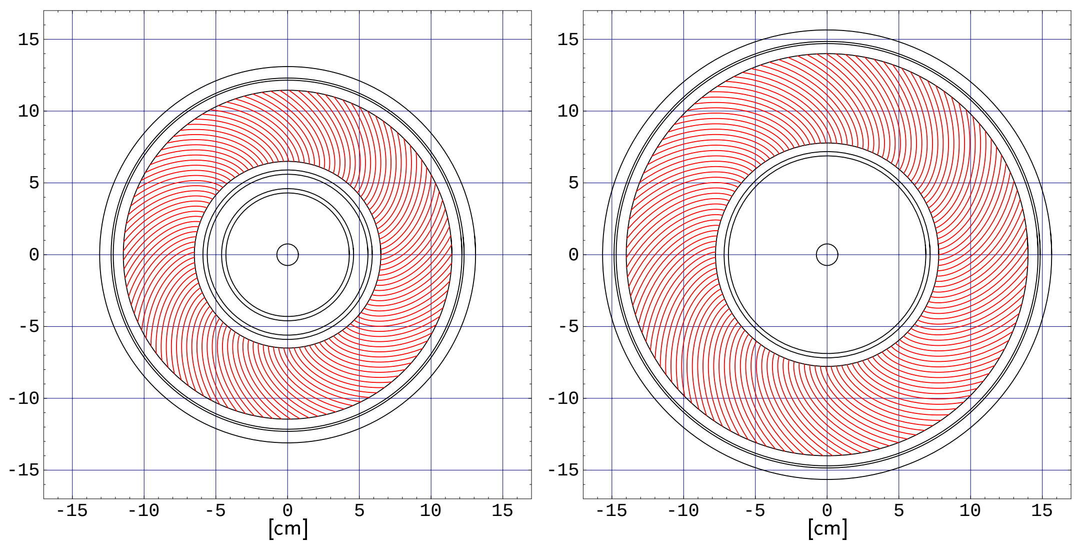

Figure 1: Geometry of the two alternative fuel elements for the FRM-II: HEU design (left) and LEU design as proposed by ANL (right). xy-plane at $z = 0$. The active height is 70 cm for both designs.

		Variant 2a	**Variant 2b**	**Variant 3a**	**Variant 3b**
Start ($\geq$ 2001)	Fuel type Enrichment Uranium density	U_3Si_2 24–26 wt% 4,8 g/cm^3	U_3Si 19,75 wt% 6,2 g/cm^3	No action !	No action !
Goal ($\geq$ 2006)	Fuel type Enrichment Uranium density	UMo 19,75 wt% 7–9 g/cm^3			UMo 40–70 wt% max. 8,0 g/cm^3

Table 1: Data for FRM-II conversion strategies.

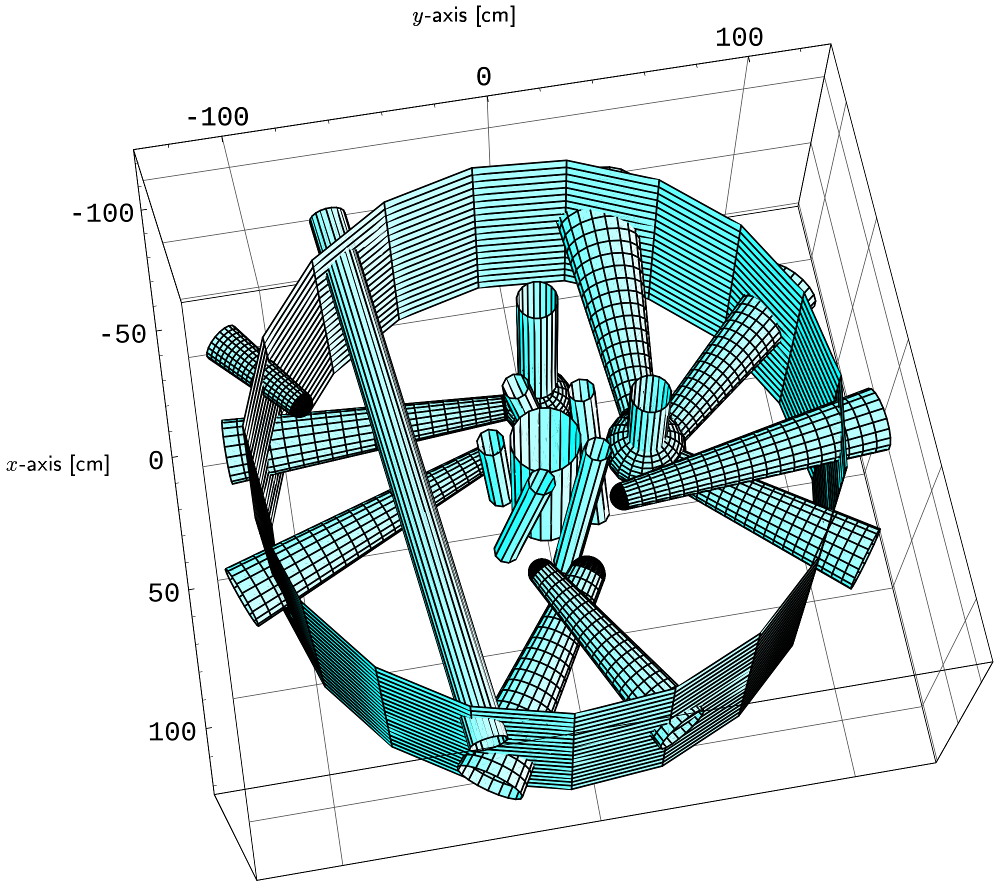

Figure 2: Illustration of the main components in the moderator tank: beam tubes 1 to 10, cold and hot neutron source and safety rods 1 to 5. The axes being defined as indicated, beam tube 1 runs parallel to the x-axis and is directed on the cold neutron source centered around $(x, y, z) = (-5, 40, 0)$ cm.

Method of calculation

Based on a three-dimensional model of the reactor core,[2] the Monte Carlo neutron transport code MCNP (Version 4B, cf. [Briesmeister, 1997]) has been used to determine all neutron-physical quantities which 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, cf. [Mathematica, 1999]). 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 plates which cannot be directly modeled in MCNP, is shown in figure 3. 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.[3] More details on the structure and the functionality of the system of calculation are given in the appendix.

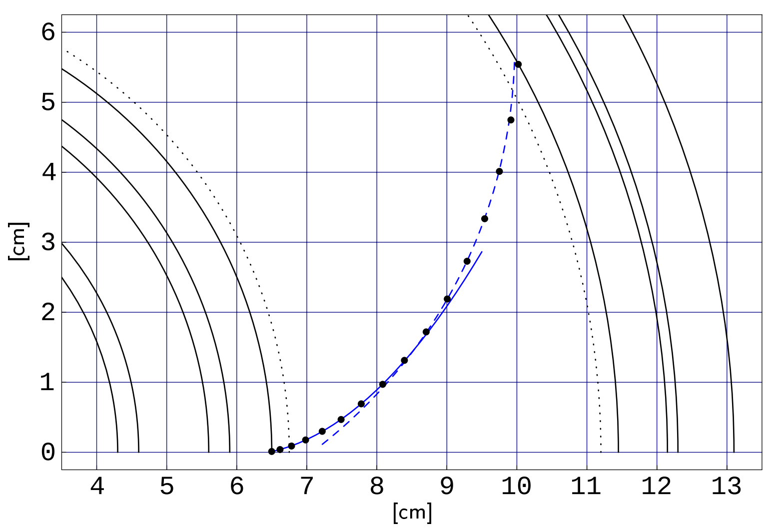

Figure 3: Representation of involute-shaped fuel plate in the simulations by appropriate approximation functions: parabola (—) and circle (- -) in xy-plane. Bullets indicate the exact coordinates of the involute. The dotted lines limit the active zones of the fuel plates.

2 More detailed information can be found in [Glaser et al., 2000].

3 *Mathematica* has also been used for specific calculations, in particular for burnup calculations.

Results of the calculations

The most important results obtained for the different conversion variants are listed in table 2. Only variant 2a, presumably the most attractive conversion option, is discussed below in some detail.[4]

The radial distribution of the thermal neutron flux for the unperturbed situation, i. e. without additional experimental components in the moderator tank, is shown in figure 4. 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: it reaches 87% of the HEU reference value.

In more complex simulations, the most important experimental components have also been modeled (cf. figure 2). Especially, 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 claimed by the 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 confirmed by the simulations which, rather, support results published by ANL. In case of the variants 2a and 2b, the heat deposited in the cold source increases by less than 1%, in all other cases heat deposition decreases.

The neutron spectrum in beam tube 1, which alone will be responsible for more than 40% of the scientific usability of the facility,[5] is shown in figure 5. The maximum value of the cold neutron flux is reduced by slightly less than 10%. The fast neutron flux which is considered an undesired background signal, increases (between 1 eV and 10 MeV) by 17% on average.

4 Variant 2b is based on U_3Si fuel which is characterized by an inferior irradiation behavior. Although it is supposed to behave well under FRM-II conditions, additional licensing procedures would probably become necessary. Thereby, the attractiveness of conversion option 2b is, to our opinion, significantly reduced compared to option 2a based on U_3Si_2 fuel.
Variant 3a requiring modification of the activated reactor can be considered an extremely unrealistic option, whereas variant 3b equally relies on HEU fuel and would basically have no advantage from the perspective of nonproliferation.
Results of burnup calculations are not discussed in this paper. However, one of the main findings is, that the cycle length for conversion variant 2a is at least as high as for the standard HEU design, that is approx. 52 days.

5 According to [Böning et al., 1999], the utilization factor of beam tube 1 will be 42,5%.

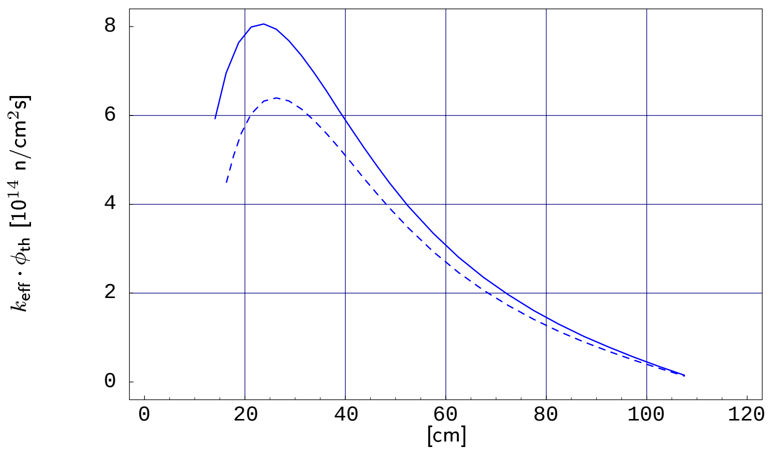

Figure 4: Radial distribution of thermal neutron flux for the HEU design (—) and for the conversion variant 2a (- -). The maximum value of the conversion variant reaches 79%, the thermal neutron flux at $r = 40$ cm reaches 87% of the HEU reference value. Distance is measured from the core centerline.

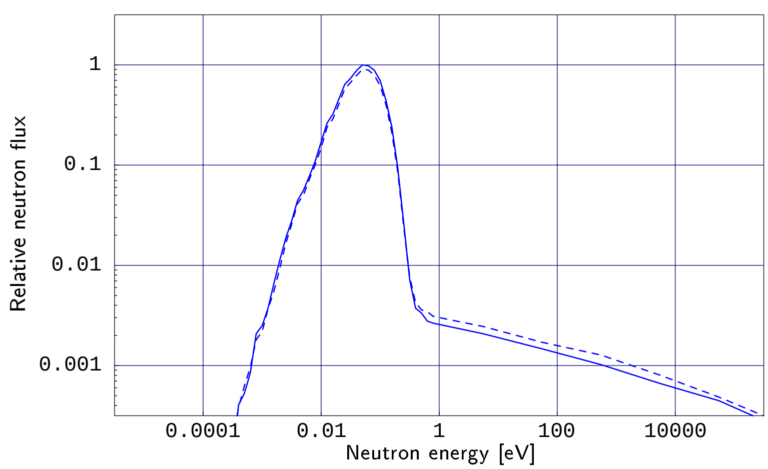

Figure 5: Neutron spectrum in beam tube 1 at $x = -70$ cm, axis as defined in figure 2. Standard HEU design (—) and Variant 2a (- -). Relative maximum value of LEU design: 90,7% of HEU value. Each spectrum is based on evaluation of 40 million neutron histories.

	HEU	Variant 2a (Start)	Variant 2b (Start)	Variant 2 (Goal)	
Fuel type	U_3Si_2	U_3Si_2	U_3Si	UMo(6wt%)	
Enrichment	ca. 93	26,00	19,75	19,75	[wt%]
Uranium density	3,0/1,5	4,8	6,2	7,1	[g/cm^3]
Unperturbed case					
$\phi_{\mathrm{th,max}}$	8,060	6,395 (79,3%)	6,437 (79,9%)	6,269 (77,8%)	[10^{14} n/(cm^{2}s)]
$\phi_{\mathrm{th,cns}}$	5,685	4,926 (86,6%)	4,948 (87,0%)	4,808 (84,6%)	[10^{14} n/(cm^{2}s)]
Perturbed case					
$\dot{Q}_{\mathrm{cns}}$	2,444	2,463 (100,8%)	2,464 (100,8%)	2,413 (98,7%)	[kW]

	HEU (Start)	Variant 3a (Goal)	Variant 3b (Goal)		
Fuel type	U_3Si_2	UMo(6wt%)	UMo(6wt%)		
Enrichment	ca. 93	19,75	50,00		[wt%]
Uranium density	3,0/1,5	7,1	8,0/4,0		[g/cm^3]
Unperturbed case					
$\phi_{\mathrm{th,max}}$	8,060	6,269 (77,8%)	7,626 (94,6%)		[10^{14} n/(cm^{2}s)]
$\phi_{\mathrm{th,cns}}$	5,685	4,808 (84,6%)	5,452 (95,9%)		[10^{14} n/(cm^{2}s)]
Perturbed case					
$\dot{Q}_{\mathrm{cns}}$	2,444	2,413 (98,7%)	2,323 (95,1%)		[kW]

Table 2: Basic results of the calculations for the FRM-II conversion variants 2 and 3. Quantities for the unperturbed case: maximum thermal neutron flux $\phi_{\mathrm{th,max}}$ and thermal neutron flux at position of cold neutron source $\phi_{\mathrm{th,cns}}$. The absolute values given for the heating of the cold neutron source $\dot{Q}_{\mathrm{cns}}$ which has been determined with all major experimental components placed in the moderator tank (perturbed case, cf. figure 2), is valid for a slightly simplified model of the device. In particular, the re-entrant hole has not been modelled. All values given in percent are relative to the standard HEU design (100%).

Short assessment of the conversion variants

Different aspects have to be considered when assessing the overall impact of the conversion variants proposed for the FRM-II. Besides the scientific usability of the converted reactor and nonproliferation aspects associated with the different conversion options, reliability of fuel supply, spent fuel disposition options, delays and economic aspects equally deserve attention.

Scientific usability

Due to the reduced neutron flux in all LEU conversion variants, slightly extended measuring times have to be accepted. Based on the calculations performed and comparing the values at the position of the cold neutron source, an extended measuring time of approx. 15% (for variant 2a) is resulting. 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

The FRM-II in its current design would set a precedence and allow other countries to follow a similar strategy, i. e. to use HEU fuel (again) and, eventually, even the high density fuels which were originally developed for conversion to low-enriched fuel. In a situation where other important high flux reactors are prepared for conversion to LEU (like the facilities in Grenoble or Petten), Germany would set a counterproductive example for the international community. This would probably be the most negative lesson learned from the case of the FRM-II and could risk the remarkable progress of RERTR achieved over the last decade [Travelli, 1999].

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 approx. 87,5%, i. e. by only 5,5%. Since the total uranium inventory per fuel element also remains rather high (approx. 7 kg), the spent fuel equally represents a serious proliferation hazard.

A preliminary analysis of the weapon-usability of uranium at different enrichment levels suggests that an enrichment of 20% is indeed extremely unattractive for weapons-use whereas an enrichment of 50%, as proposed for conversion variant 3b, probably cannot be categorized as proliferation proof.[6] Conversion of the reactor along this option would not lead to a significant improvement in proliferation resistance, especially because it is considered as a permanent solution.

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6 Cf. for example [Glaser, 2000].

Fuel supply and disposition

The HEU annually required for operation of the FRM-II amounts to approx. 40 kg (five fuel elements with an uranium inventory of 8,1 kg each). According to the *Schumer Ammendment* from 1992, the US will not supply fuel for the FRM-II. For this reason, the reactor operator is planning to cover the long-term fuel supply with HEU provided by Russia. For about 40 years, the project would rely upon the availability of a material which is internationally proscribed. It has to be emphasized that variant 3b would not solve the supply 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 for fuel suppliers, in particular, because it is only foreseen as a temporary solution.

Unexpected problems may also emerge at the back-end of the fuel cycle. Since cooperation with the US *Spent Fuel Acceptance Program* is excluded and reprocessing services for uranium-silicide fuels are not available, Germany will have to develop and implement a disposition strategy for HEU, eventually, specially designed for FRM-II fuel which could be an extremely expensive venture. For instance, the US is currently developing the *Melt & Dilute* technology in a two billion dollar program [US DoE, 2000].

Delays and costs

Except for variant 3b where almost no significant down-time would have to 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 down-time would be most acceptable. An analysis of the availability of European neutron research facilities suggests that a delay now would have a smaller impact than a several year down-time for converison in 10 years or so when some other facilites 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).

Supplementary costs which would be due to modifications or down-times 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 financial volume of the project. Within this context, it would have been wiser to decide on the conversion strategy shortly after the commission had published its report in June 1999 and 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 US programs will certainly entail substantial financial burdens at the back-end of the fuel cycle.

Conclusion

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

Our calculations are focussed on the FRM-II conversion scenarios identified by a BMBF expert commission in 1999 and confirm, in essence, the data previously published by ANL.

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 completion and is only temporarily based on a fuel slightly above the LEU limit (24–26% enrichment). Our simulations predict that the measuring times would have to be extended by 10–15% compared to the current HEU design.

Conversion of the reactor at a later time would either imply modificiation of the activated reactor or the use of a fuel enriched to 40–60%. A preliminary analysis of the weapon-usability of uranium at different enrichment levels suggests that a value of 50% apparently has to be considered as weapon-usable. Conversion of a research reactor to such a fuel does not constitute a satisfactory option from the perspective of nonproliferation, especially if this conversion is understood as a permanent solution. This is exactly the case for FRM-II variant 3b, the conversion variant obviously preferred by the project management. The temporary use of medium-enriched fuel, however, may be an acceptable and even reasonable solution provided that it is an intermediary step towards final conversion to a LEU design.

Unfortunately, in practice, it is extremely difficult to weigh a loss in scientific usability of a facility, though marginal, against the improvements received with respect to nonproliferation. For this reason, from a global perspective, increasing the public and political awareness regarding nuclear proliferation and the possibilities to prevent it, would be equally important.

It may turn out that the case of the FRM-II will make a fateful example. In a worst case scenario, it may encourage other countries to opt for HEU fuel, against the established nonproliferation policy. The case of the FRM-II, while benefitting from progress made possible by the international conversion activities, would at the same time put at stake the perspectives of the entire RERTR program.

APPENDIX

Short description of the system of calculation

In figure 6, the structure and functionality of the system of calculation which has been used to acquire the results presented in this paper, is visualized. According to their specific functions, the individual notebooks are organized at various (hierarchic) levels. These levels can be subdivided into two basic categories: the first class of notebooks is used to prepare a new model from scratch (levels 1, 2 and 3), whereas the second class expects a MCNP output or tally file in order to extract specific raw data for subsequent calculations (levels A and B). Only at level 1, design information is acquired by the program.

A couple of notebooks do not directly contribute to the preparation of the model. They provide extra information such as general properties of high density fuels or three-dimensional plots of the moderator tank including its experimental components (as in figure 2) and support data acquisition at the top level of the simulations.

Due to the differences in core design between the HEU-core and the LEU-core, i. e. the TUM-design and the ANL-design, two separate notebooks (Lev1.TUM.Prep and Lev1.ANL.Prep) are used for preparation of the MCNP input syntax of the core.[7] Based on these results, a generic MCNP input file is produced by Lev2.UNI.Outp. This file, in turn, is extended and finished by the notebooks of the following level which append special purpose input sections in order to tailor the file for specific tasks: this includes, for instance, preparation of burnup calculations or sections allowing the analysis of the neutron flux distribution in the fuel plates, in the moderator tank or in the beam tubes. Equally, an analysis of the heating of the cold neutron source due to neutrons and photons is prepared at this stage.

The burnup calculations require a more complex, iterative approach. At level A, the MCNP output file is read and the physical quantities derived from this data are written to formatted ASCII-files. This includes the spectrum-averaged cross-sections for all relevant nuclides and reaction types in all spatial segments of the fuel plate as well as the neutron flux and relative power density distribution. Based on this information, the burnup calculations are realized by LevB.UNI.Burn for a predefined time step. The resulting material composition for each segment is written to a file in MCNP syntax. This fragment is used to prepare the next burnup step. The results are finally analyzed with further notebooks (level C) which are not indicated in the figure below.

7 The different scaling of the cores is easily handled with the same mathematical techniques. However, the graded uranium density used in the fuel plates of the HEU-core and the different secondary core components (boron ring below HEU-core and design of central control rod) suggest a treatment in separate procedures.

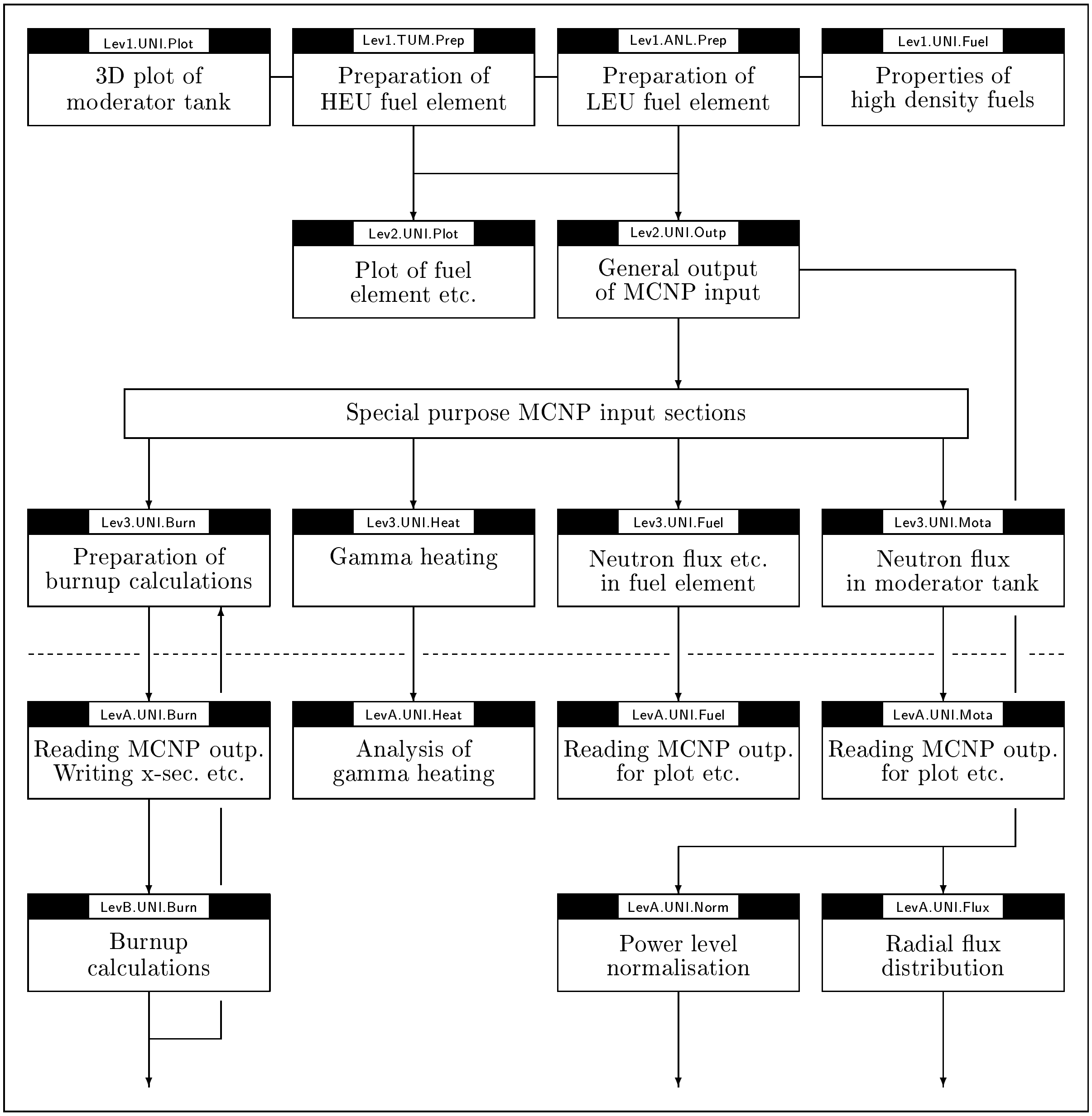

Figure 6: *Mathematica* notebooks for research reactor analysis.

References

[BMBF, 1999] Bundesministerium für Bildung und Forschung: *Bericht der von der Bundesregierung eingesetzten Expertenkommission zur Prüfung der Umrüstbarkeit des Forschungsreaktors München II von HEU auf LEU.* Bonn, June 1999.

[Böning et al., 1999] K. Böning, A. Axmann, W. Petry: *Der FRM-II: eine umfassend optimierte Neutronenquelle für die Forschung.* Technische Universität München, Opa 00229, April 1999.

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

[Glaser, 2000] A. Glaser: *The Conversion of Research Reactors to Low-Enriched Fuel and the Case of the FRM-II.* Paper presented at the XIIth International Summer Symposium on Science and World Affairs. August 23–31, 2000, Moscow, Russia.

[Glaser et al., 2000] 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.

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

[Mathematica, 1999] Mathematica 4.0.1 for Linux. Wolfram Research, Inc. Also: S. Wolfram: *The Mathematica Book.* Fourth Edition, Cambridge University Press, 1999.

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

[Travelli, 1999] A. Travelli: *Progress of the RERTR Program in 1999.* Presented at the 22nd International Meeting on Reduced Enrichment for Research and Test Reactors. October 3–8, 1999, Budapest, Hungary.

[US DoE, 2000] US Department of Energy: *Savannah River Site, Spent Nuclear Fuel Management Final Environmental Impact Statement*, DOE/EIS-0279, March 2000.