Hafnium data for description of criticality of FRM II reactor with control and safety rods

A. Röhrmoser, FRM II

Technische Universität München, FRM II, Lichtenbergstr. 1, 85747 Garching – Germany

ABSTRACT

The neutron source FRM II operates as a critical reactor and is controlled by a single hafnium rod (CR) inside the light water cooling channel. The safety system is composed of five safety rods (SRs), which are also of material Hf at 10mm wall thickness and approach the core in a heavy water environment. For description of criticality of the reactor under several situations it is of clear importance to work with best estimate data sets for the strong thermal absorber material Hf with six natural isotopes, that all contribute to a relevant absorption also in the resonance region. At reactor design time TUM organized an extra Hf benchmark to trap this shutdown topic.

This contribution compares some critical and subcritical cases with a fresh fuel element and its description with best 3d-models for the real reactor with a very structured environment at inserted control or safety rods. Depending on the used Hf data collection the results for the calculated reactivity grasp $\Delta\rho$ of the rods straddle remarkably with older data. The ENDF/B-V(I) data set, which was used for final licensing work of the reactor safety in the late `90s, shows an outstandingly high -estimation of total $\Delta\rho_{sd}$ in contrast to former data sets, which seem to underestimate the contribution by resonance absorption. The total shutdown margins $\Delta\rho_{sd}$ for ENDF/B-V(I) differ relatively by more than +5% for the CR and +3% for the SR system compared to calculations with newer data sets. The CR sees a more fast, the SRs a more thermal spectrum. The subcritical and both critical cases can be described clearly better with the newer ENDF/B-VII or JEFF-3 Hf data, that all show up rather congruent in the intermediate results range between ENDF/B-V(I) and older data, but closer to the latter.

1 Introduction

The neutron source FRM II, a steady state research reactor, started its operation in 2004. It is based on a very compact single fuel element concept. The very narrow outer radius of ~13 cm of the cylindrical core inside a heavy water (SW) tank is a result of optimization for a high enriched uranium (HEU, 93%) fuel to provide sufficient operation time at moderate thermal power of 20 MW [FRM2des].

The reactor is controlled by one central Hf rod, which can be moved totally in and out of the inner space of the element. The emergency shutdown system consists of five identical rods, again of Hf material, approaching the fuel element in the heavy water around the core. For sure, the design estimations had to include some conservativeness for the shutdown margins.

Both shut down systems will be recapitulated here with a best actual core model and also newer neutron interaction data, particularly for the Hf material. And by comparing the results to the design estimations, this work must clearly confirm the former conservativeness for the shutdown margins, guarantying maximum multiplication for neutrons in the cold case clearly below $k_{eff}<1.0$ with at least '4of5 safety rods'. For the control rod the comparison will be performed the same way, although it was extremely dimensioned, in a way to bring the reactor by far subcritical, in fact to or below $k_{eff}<0.9$ even for the maximum k_{eff} situation with a fresh element in the reactor.

The main topic of this work is the comparison of the reactors shut down margins in the light of evolution of the nuclear data for Hf over more than two decades.

2 Hafnium absorption data in general

The very heavy-weight metal hafnium consists of 6 natural occurring isotopes. The distributed data suites with the here used 3d-neutron transport code MCNP did provide macroscopic data sets till ENDF/B-VI (72000.xxc). Since ENDF/B-VII isotopic collections are given (s. reference table in chapter I.6 of [MCNP]) and have to be assembled by their natural composition. The same is true for JEFF suites since JEF-2(.2), that can be collected complementary [JEFF]. Two examples for macroscopic data set are compared in Fig. 1 with the absorption cross section depending on the neutron energy in MeV ('mev' in the figure plotted from MCNP code). The one is for ENDF/B-V or VI (identical in later results); the second for the assembled JEFF-3.1 cross section data and some discrepancies appear evidently.

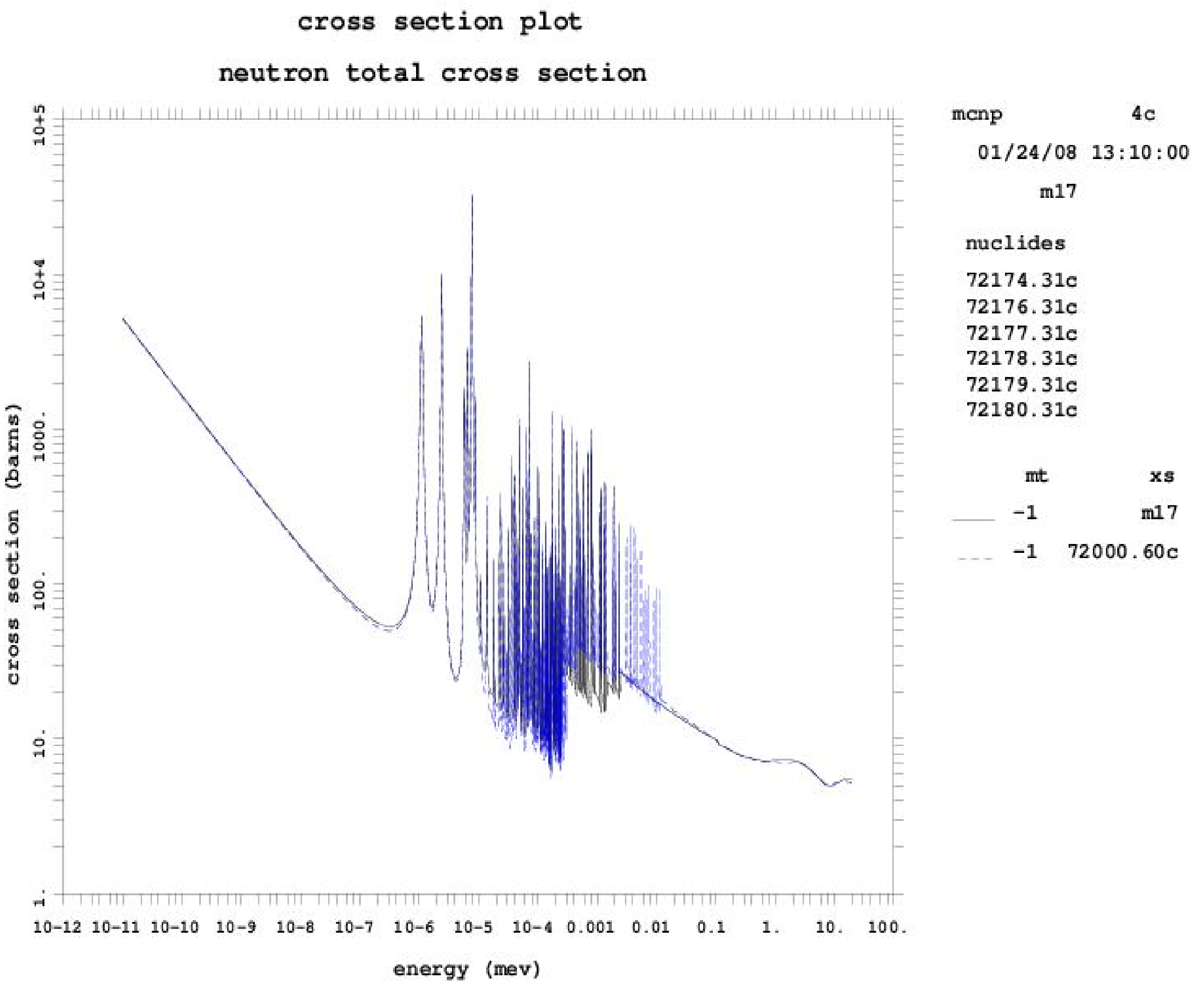


Figure 1:
neutron absorption cross section for hafnium with different data sets.

The lower part of the upper resonance region is missing in the ENDF/B-VI data set 72000.50/60c (and seems to have been exaggerated low with former ENDL Hf data) in comparison to newer data sets (here shown JEFF-3.1). This will be reflected later on the calculations with higher absorption contributions of 72000.60c (respectively lower with 72000.35c/42c) in the fast flux region in comparison to newer JEFF or ENDF/B-VII data. There seem to be scarcely differences outside the resonance region. Newer data sets are much more closer to the shown JEFF-3.1 data characteristics in the figure, and this will be also true for the later results on core reactivity.

3 Control rod and Emergency shut down rod system of FRM II

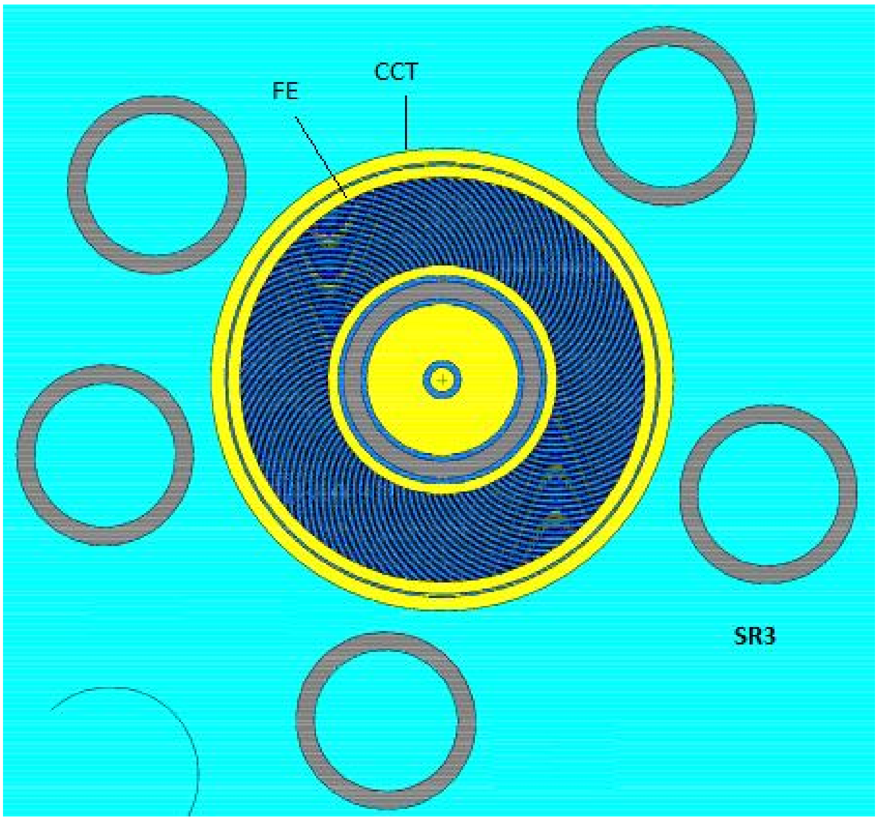


Figure 2:
Horizontal cross section view of compact FE inside the central channel tube (CCT, 26 cm diameter), that separates the primary coolant circuit from the heavy water in the tank (D_2O-vessel, light blue) at FRM II. The core is controlled through movement of the inner hafnium rod with a beryllium moderator follower. The fuel element (FE) with bent fuel plates is surrounded by the five massive safety rods (again Hf, diameter 10 cm), which approach rather vertical around the core in shut down case and which are shown here in their closest neighborhood location to the CCT. The most potent rod SR3 will be removed in the '4 of 5' calculation.

3.1 Safety tasks

Two main duties have to be maintained by shutdown systems:

a) Grasping sufficient reactivity when inserted, so that even in the most reactive situation with several failures supposed, the reactor will remain clearly subcritical
(while staying far away with negligible effect for the reactor in rest positon)

b) Very quick reaction to compensate any occasional reactivity feed into the reactor.

This work doesn't deal with technical aspects, but regards the first topic of 'reactivity grasp'.

The control rod brings the reactor subcritical below k_{eff}<0.9 even for the maximum k_{eff} situation with a fresh element in the reactor.

The second shutdown system of FRM II (the first is the control rod) consists of a bank of five identical hafnium safety rods, which permanently wait in a top position in the heavy water (HW) tank for signaling to move then down very quickly and cover the area around the core, that lives very much of back streaming neutrons from the heavy water tank surrounding. Consequently this acts like an absorbing curtain around the fuel element inside the central channel tube, what results again in a very high shut down margin even in the extreme case of a fresh fuel element and the control rod totally withdrawn with a new beryllium reflector (free of burn up poison). Postulating also failure of one of the five rods will still guaranty very sufficient high shut down margin.

With newer calculations differences can't be too high and hence the extreme conservativeness for both systems must be confirmed without doubt.

3.2 Brief history outline

3.2.1 First results for the strong absorber material Hafnium in FRM II

At design times for the reactor FRM II there had to be performed complicated data preparation procedures for any material, as there were cell calculations, 1d-spectra determinations and other approximations to produce adaptive data sets for at most times 2d-cyclinder symmetric core layout calculation. For the most absorbing material of the core design there was even seen the necessity to make a benchmark comparison in the early days (internal reports, FRM II project, 1987). Three independent teams didn't stop, before final calculations were acceptable close together and after some inadequate procedures with data preparation and application could be recognized; this was for the hafnium material of the control rod, which was also used for the emergency shutdown system layout nearly or approximately a decade later.

3.2.2 Design phase for safety layout

The calculation possibilities for complicated geometries had made a big step forward by highly developed 3d-MonteCarlo (MC) code systems without need for data preparation. And the former complicated data preparation work could be bypassed through use of ready-to-use (point) data sets. Especially reactivity questions for the five shut down rods of the FRM II core could be regarded now under control with a 3d-model of the aslope inserted rods.

The worst case supposed for the safety layout was the control rod totally withdrawn and an additional failure of the most absorbing shut down rod SR3 (here '4of5 SRs down' case) at a fresh fuel element (and new inner Be reflector follower). Including a big calculations-accuracy margin the results in the '90s were still fulfilling the request for values k_{eff}<1 for any '4of5 SRs down' case.

3.2.3 Modern shut down rod margin calculation with most precise 3d-model of FRM II

Sophisticated data preparation procedures and approximations can be bypassed by use of point data for cross sections and 3d models for MonteCarlo (MC) codes. As computer power has exploded in the last decades, the MC methods for individual particle transport can be exploited now very intensively. As a consequence results can be given now for a lot of details, with much less adjustment necessary and with more potential for doubtless high exactness.

An extensive review of the former FRM-II MCNP model of the '90s was done, since 2003 the core was calculated heterogeneous. In the HW tank, 11 beam tubes, one cold and one hot source and multiple irradiation channels penetrating from the top, were updated to the 'as-built'-situation. This MCNP model '3dMod_FRM2k' was used for instance to study azimuthal effects like disturbances to the 2d symmetric model in the power distribution [FrmMdl] and later on for 3d-burn up calculations [RRFM10], both with very fine results. There were used mainly ENDF/B-V/VI data sets for the former studies.

Here a variety of newer data sets will be used for calculating shut down margins of the hafnium rods, exactly in this environment.

4 <u>Results with newer data</u>

4.1 reactivity grasp of SR bank (maximum reactivity case)

Ahead of putting the reactor into operation (in 2004) the value for the emergency shutdown margin could be updated by the heterogeneous and improved 'as-built' reactor model at cold temperatures and using the ENDF/B-VI Hf.60c data set for hafnium.

The results confirmed the extreme reactivity grasp of the SR bank. With ENDF/B-VI Hf.60c data the grasp was even 5% higher than with the design data set Hf.35c (or Hf.42c). Newer data sets for Hf give results for the reactivity grasp in between (slightly closer to the older data) and are all very close together now (Hf.70c or later and also with JEFF-3.1 or JEFF-3.2 data; compare case CR below). The former JEF-2.2 data set for hafnium discloses also somewhat higher resonance absorption (documented also in [JEFF]).

Figure 3:
Total reactivity grasp of the safety rod bank at FRM II when inserted around the fuel element, calculated with different ENDF/B and JEF(F) data sets for Hf.

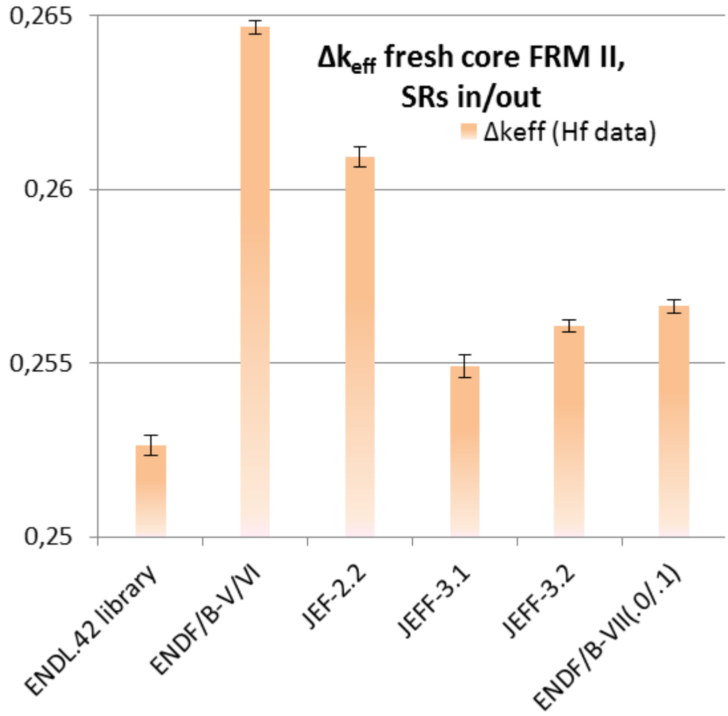
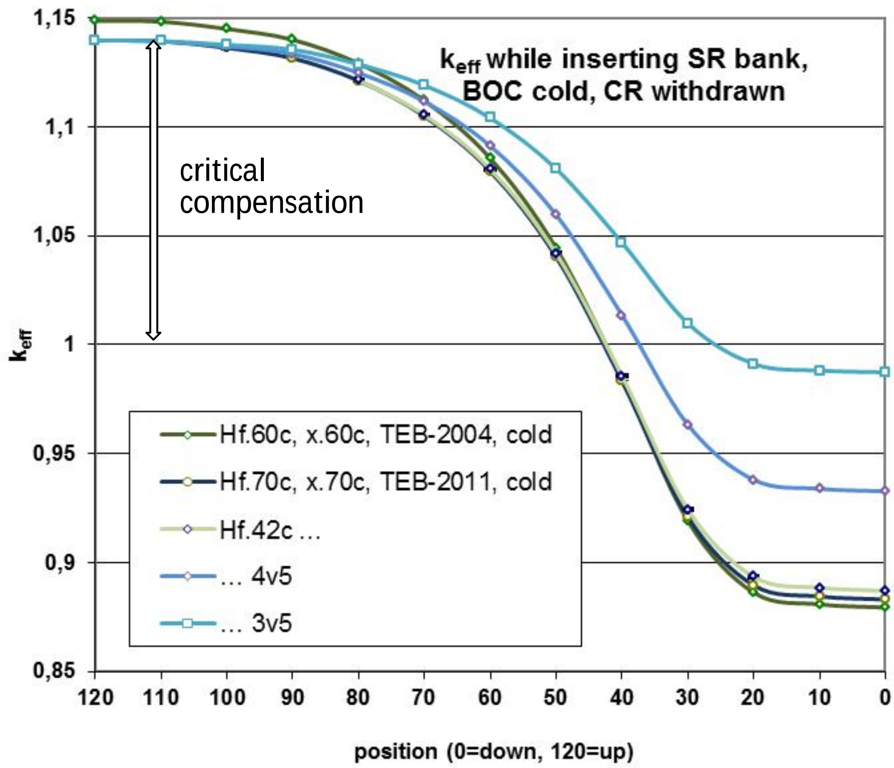


Figure 4:
maximum neutron multiplicity with fresh core and CR withdrawn (Be inside moderator in the core, here 'new'=not poisoned) as function of SR bank position. The most potent shutdown rod SR3 is removed in the '4 of 5' calculation and additionally SR4 in the '3 of 5' calculation.
The SR bank will compensate step by step the CR when moved out in the latter critical case of section 4.4 .



The chosen data set is of secondary importance for the aim of achieving clear sub-criticality for the fresh core with control rod stuck outside (see Figure 3).

The maximum reactivity for the fresh core with all hafnium rods removed is some ‰ higher calculated with ENDF/B-VI data (s. diagram; mainly due to U.60c), but since the ENDF/B-VI Hf.60c data set is also extreme giving higher reactivity grasp (in comparison to any other data set), k_{eff} for the case 'SR bank in' is then lowest. The absolute values can be stated always rather close together with 'SR bank in' or 'SR bank out' (and in between).

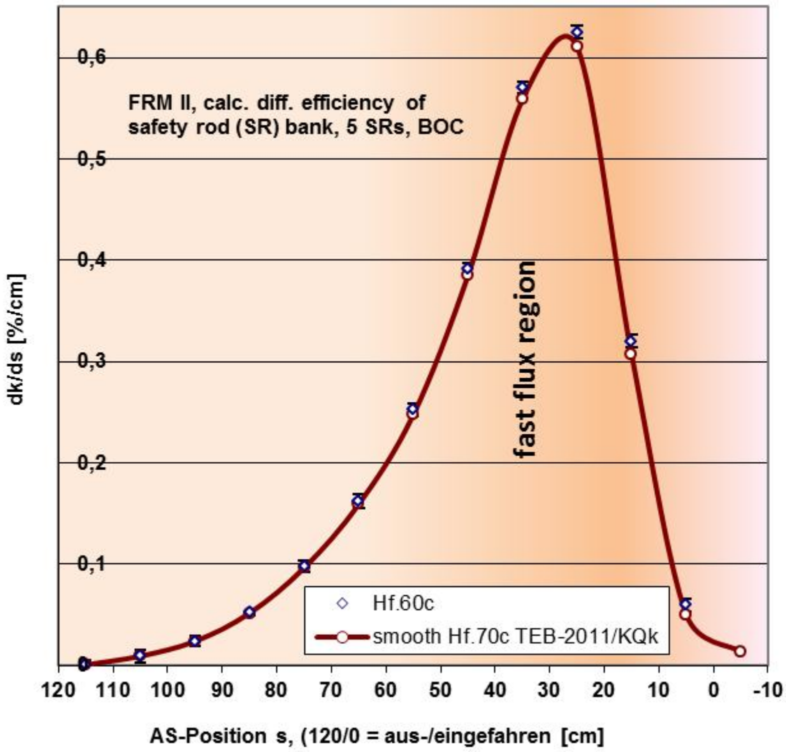
Regarding the worst case safety condition for the most reactive case imaginable (fresh cold core and cold source also cold ='filled with moderator', no Be poisoning) and CR failure with only 4of5

SRs down k_{eff} is in fact extremely far below 1 at about 0.933. Even any 3of5 SRs-down situation would satisfy this condition (k_{eff} < 0.987), calculated here with ENDF/B-VII data (Hf/x.70c) for the core.

When regarding the differential reactivity with fresh core and CR withdrawn as function of SR bank position at FRM II we obtain same background for the deviations with the Hf data base.

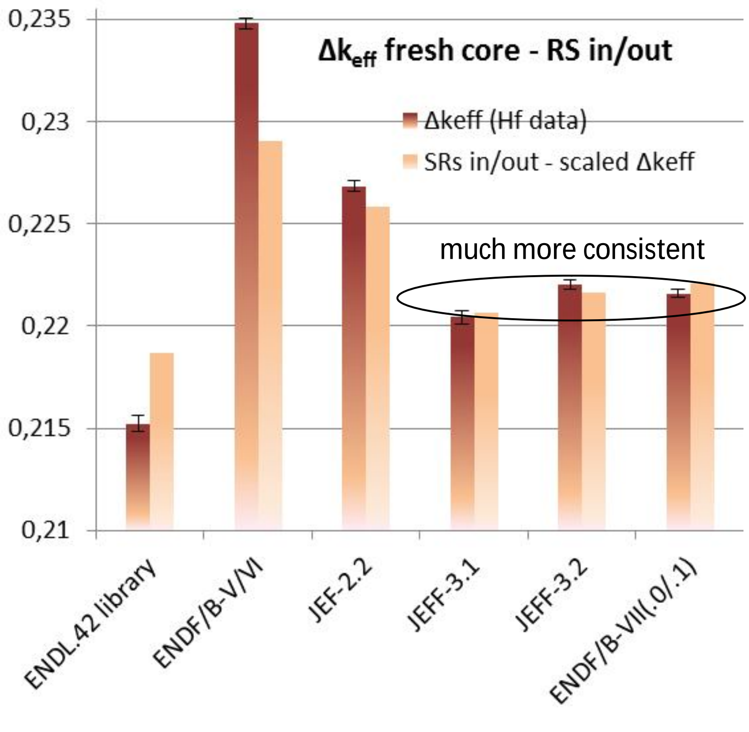
Comparing the differential reactivity grasp calculated for Hf.60c and Hf.70c (Fig. 5) reveals that the deviance can be assigned to the movement of the safety rods into the fuel element close region with fast flux contribution. This is fully consistent with the comparison of the neutron absorption cross section (Fig. 1) for Hf.60c and newer data, the latter coming along much more consistent.

Figure 5:
differential reactivity (dk_{eff}/ds) with fresh core and CR with-drawn as function of SR bank position at FRM II for different data bases.



4.2 reactivity grasp of control rod

Figure 6:
Comparison of the total reactivity grasp of the control rod, when moved 82 cm from fully down (inside fresh element, SRs withdrawn) to fully up (out) position. The former case for the SRs (then CR withdrawn) is shown scaled down for comparison, where the same ENDF/B and JEF(F) data collections were used.



The aim of achieving clear sub-criticality for the fresh core with all safety rods outside is by far fulfilled for any data set with all k_{eff} values between 0.89 ↔0.91.

And the trend for the reactivity grasp of the control rod (Fig. 6) calculated with different data sets for hafnium is very the same as for the safety rod bank (shown also in Fig. 6, but scaled down by factor ~ 6/7 for direct comparison). With ENDF/B-VI Hf.60c data (the Hf.50c data set seems to be identical) the grasp is again clearly highest and lowest with the design data set Hf.35c (or Hf.42c). Newer data sets for hafnium give results for the reactivity grasp in between (slightly closer to the older data) and are now all close together (Hf.70c or later and also with JEFF-3.1 or JEFF-3.2 data). But the absolute variance at the very same trend is higher due to more fast flux contribution inside the element. The results for the older data Hf.60c and Hf.42c differ by 9% for the absolute reactivity grasp of the control rod, what is reasonable and one could search for critical cases of the reactor, where a specific Hf data set gives a better description. Some cases will be discussed next.

4.3 First critical multiplication case (with control rod)

First criticality for the cold reactor at empty cold source was achieved on 2.3.2004. The only Hf rod in intervention was there the control rod (CR). The critical position of the rod was calculated to be 340 mm for exactly this case; the transition region of the control rod was refined in the model the days before startup to be most precise from the geometrical side. The later measurement was consistent with 341 mm at total possible driveway of 820mm.

Hence the agreement was excellent but clearly too precise; a statement that has to be given with respect to variances with the underlying data sets, as shown already here for Hf. But the same is true for other materials of the reactor; some remarkable deviations can be found with newer data for uranium, but also for heavy water.

When regarding results for the full suite of data sets with let's say 'all data 50c/60c/70c' or 'all data JEFF.31', than the variance appears to be rather moderate for FRM II. Particularly of interest is now the case of taking a newer Hf data set also for the first two cases instead of Hf.50/60c and very consistent Hf data sets

Figure 7:
Calculated k_{eff} values with different data set suites for the case of first criticality with CR moved 341 mm upward for the new reactor (CNS warm, cold temperatures, thermal scatter data for 20°C). Some extra absorption in the structures is supposed for material impurities. The cases ENDF/B-V and –VI are also given with less absorbing Hf data (exchanged to Hf.70c).

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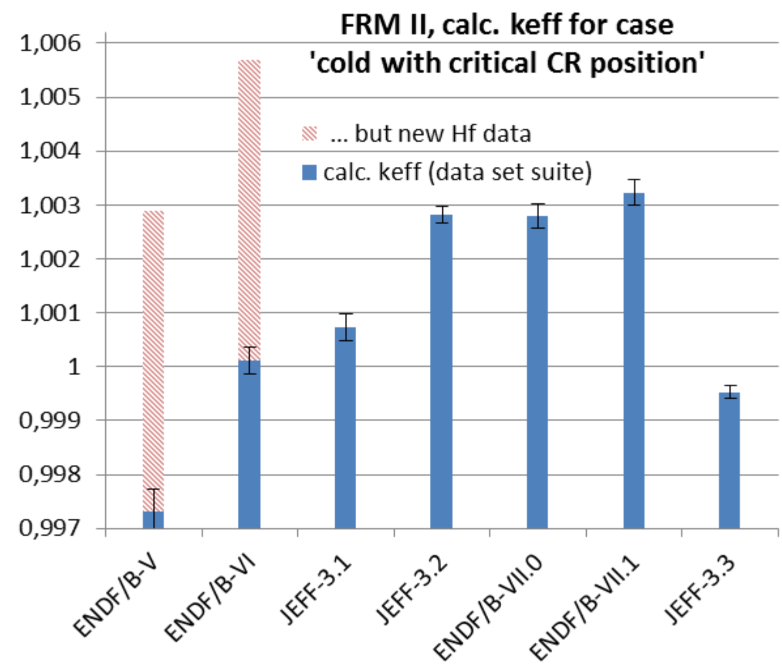


Recent evaluations of trends gathering all critical start up cases (44 ones till Jan. 2018) suppose a grasp of about Δk =-0.0045 in the first cycles by fast burnable impurities like B-10 and Li-6 in the structures[1]. This is respected in the figure as well as very small corrections for real temperatures of 23°C[2] at start-up and the measured H/D-ratio in the heavy water of 0.135 at-% (all calculations 0.2%).

All newer data suites since JEFF-3.1 give then rather consistent results between $0.9996 < k_{eff} < 1.0031$. The first two ENDF/B-cases were obtained with the Hf.50c/60c data set, which gives outstanding high absorption. With solely new Hf data the ENDF/B-V case arises consistent, but the ENDF/B-VI case is then again outstanding due to uranium data that tend to give too high k_{eff} values for a thermal reactor with high enriched U (a statement which would be confirmed by considerations for FRM II with burnt fuel element).

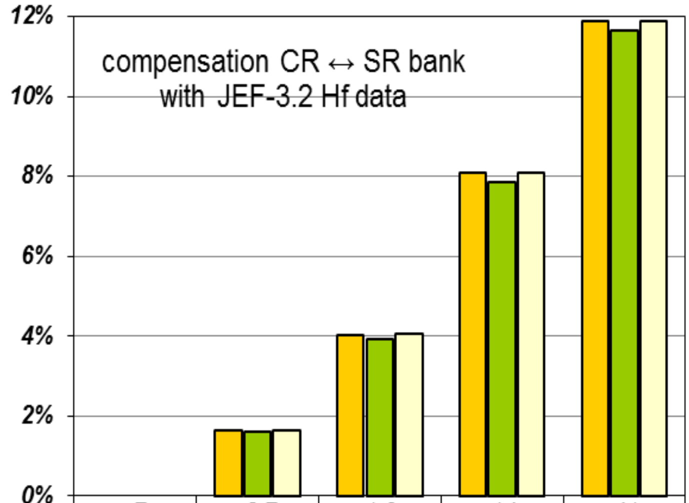
Conclusion: the start-up case seems to be really better described with the newer, less absorbing Hf data for the CR driven inside the element, giving indication for a very small fraction of extra absorption by slow burning structure impurities at start-up.

Next will be discussed the quality of description for the rods in the heavy water tank with different Hf data.

4.4 Reactivity compensation safety rods ↔ control rod

By comparing several critical cases at nuclear start-up in 2004, very precise measurements exist for the compensation of the CR in the element against a coordinated movement of the safety rods outside in the heavy water tank.

Those real critical cases were also post-calculated, modelling exactly the given positons of the CR as well as the SR rods, which move down with their lower end step by step to about core mid plane (cmp. Fig. 4).



RS position [cm]	-7	-3,7	1,6	14	41
RS reactivity control	0,00%	1,63%	4,03%	8,10%	11,88%
AS compensation uncorr.	0,00%	1,59%	3,93%	7,85%	11,66%
AS compensation with 5 mm down-correction	0,00%	1,66%	4,06%	8,08%	11,89%

Figure 8: calculated compensation of reactivity ρ=(k-1)/k by control rod against safety rods for real critical cases of the reactor at start-up in 2004. RS edge positions -7cm respectively +41cm mean SRs or CR are driven totally out.

It was taken now one of the newer Hf data sets, which seem to give an appropriate description for the CR inside the element and the compensation of the CR against safety rods is reflected quite well by the calculation with intermediate absorbing Hf data like the one for JEFF-3.2. It is not ruled out that the SRs could hang in fact a few mm lower than given by the official height for the Hf safety rods, staying about 1m above the core in rest position. Taking into account a postulated, generally 5 mm lower position, the agreement could become prefect as shown. And even a 9 mm lower position is possible, which would give exact compensation when supposing again a grasp of about Δk =-0.0045 (case SRs removed) in the first cycles by impurities in the Al structures like B-10 and Li-6 (which are less potent

[1] the specifications would allow those impurities yielding a maximum influence Δk =-0.0060

[2] The spectral temperature effects for water (LW and HW) could be evaluated by comparing to results with 50°C water data, each. The density effect can be tracked by far easier by pure density variations in the calculations.

in the case ‘SRs down’). A lower position of a few mm of the hafnium SR rods would be without any relevance for the reactor.

Supposing the quite well description of the reactivity influence of the inner CR by newer, intermediate absorbing Hf data like the one of the JEFF-3.2 or ENDF/B-VII suite, it is then rather well verified that the influence on reactivity of the Hf rods in the heavy water is also given very exactly. With Hf.50c/60c data the compensation would be less appropriate for all cases.

4.5 First subcritical multiplication case with safety rods in

To derive the very first evidence for the core reactivity at startup, although still clearly subcritical, one can try to back on the relative gain g_i in detector counts when introducing uranium into the fuel element. This comparison without/with FE [Anim-09] is based on the case ‘SRs in down position/CR withdrawn’ with the HW tank (already) totally filled.

The n detection of the reactor is accomplished by three online wide range detectors_(WDs), that are arranged nearly equidistantly outside the moderator tank at about 2m distance to the core (see Fig. 9). Two sources are evident at this first situation with multiplied neutrons:

i. The ^{252}Cf primary start-up source PNS for FRM II is given with accuracy for n-strength of better than 1%. It was located aside from the core and at a distance of about 1.5 m to its nearest WD in the horizontal plane of the core 1m above the WDs; the source was modelled exactly in the position 5-6 cm above core mid plane (CMP) at 34 cm distance to the central core axis.

ii. multiplied by fission events (uranium of the FE)

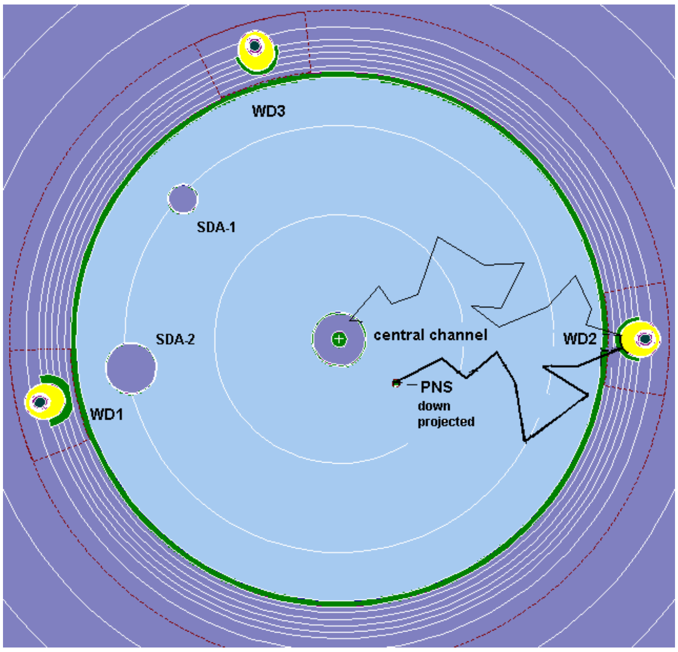


Fig. 9:
Horizontal cut through the HW moderator tank and its environment at height of the bottom of the tank (thus 115 cm below CMP); here all three WDs (WD1,2,3) were cut as well as the central channel for the primary coolant. Ring segments in the range of the WDs and other segmentations are introduced for variance reduction reasons in the calculation. The red dotted regions covering the WDs show volumes of flux detection with better statistical accuracy. Two possible neutron histories from core and PNS to WD2 are illustrated.

4.5.1 Measurement

A rather small increase of only 1.12 is seen on the detector WD2, which was positioned in the tank in an angle segment close to that of the PNS. In other words, the other two detectors are much more sensitive on neutrons originating from the fuel elements in comparison to the PNS neutrons and thus preferable for the task here. The measurements show only a small statistical noise.

4.5.2 MCNP prediction

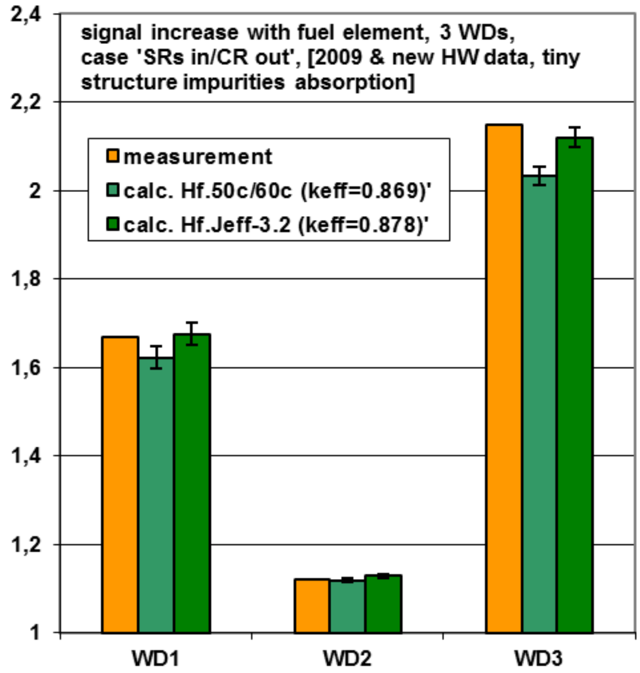
The 3D-core model calculations without and with the fuel element inserted are an image of corresponding measurements, both with primary neutron source. For the case with fuel there was also determined the multiplication factor to be at k_{eff}=0.87 using the cross section libraries Z_A.50c/60c. Taking JEF-3.1 data for Hafnium the result was at k_{eff}=0.88, meaning there is a greater discrepancy for the Hf data set, especially with respect to the outer shut down rod curtain. All other data were taken with ENDF/B-V/VI.

4.5.3 Comparison ‚measurement ↔ calculation'

The calculated relation in detector count rates could be given precisely enough by use of some error reduction ideas. The values are quite consistent to the measurement what is the best confirmation for the very good tracing of neutron histories both from the PNS as well as from the fuel element on the long and quite different paths to the three detectors.

Measured gain factors and calculated ones are compared in the diagram of Fig. 10.

Fig. 10:
Measured and calculated gain in count rates at the three WDs; error bars on the relative values of the MC calculations are also given.



A modified point kinetics formula is valid here for the the gain factors at the detectors and the gain is dominated by the value k_{eff} when approaching the value 'One'. Hence it can be derived that this close agreement is also an indication for the correctness of the k_{eff} value given with MCNP for the same case, lying rather exactly at k_{eff}=0.88.

This is the value achieved with newer Hf data for the case with the safety rods fully inserted. With a small down correction of k_{eff} due to new HW data and the tiny start absorption for structure impurities (compare 4.3) the agreement is still improved against [Anim-09] and it appears worse with the Hf.50c/60c data.

SUMMARY

This contribution compares 3d-calculations for well-defined cases at FRM II reactor with a fresh fuel element and driven critical by hafnium rods. The results were achieved with reactor core description by best 3d-models for the real reactor with a very structured environment at inserted control or safety rods. Case one is the startup situation before going first time to power in 2.3.2004, case two are other critical cases, accomplished the next days with partly inserted safety rods, while the control was moved out. Finally an early subcritical situation is regarded with only SRs inserted in the HW tank.

Depending on the used Hf data collection the results for the calculated reactivity grasp $\Delta\rho$ of the rods straddle remarkably with older data. The ENDF/B-V(I) data set, which was used for final licensing work of the reactor safety in the late `90s, shows an outstandingly high estimation of total $\Delta\rho_{sd}$ in contrast to former data sets, which seem to underestimate the contribution by resonance absorption. The total shutdown margins $\Delta\rho_{sd}$ for ENDF/B-V(I) are relatively up by more than +5% for the CR and +3% for the SR system compared to calculations with newer data sets. The CR sees a more fast, the SRs a more thermal spectrum. The values $\Delta\rho$ for the subcritical and both critical cases of FRM II with inserted Hf rods in the core and outside in the HW can be clearly better described with the newer ENDF/B-VII or JEFF-3 data, that all show up rather congruent in the intermediate results range between ENDF/B-V(I) and older ENDL data, but closer to the latter.

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LEGEND

HEU	very high U-235-enriched fuel
FE	fuel element
CC(T)	central channel (tube)
LW/HW	light/heavy water
CR	control rod
SRs	safety rods
WDs	wide range detectors
CMP	core mid plane
MC	Monte Carlo simulation
MCNP	MCNP, program code for particle transport by the Monte Carlo method for n/e/γ …
n	neutron
BOC	‚begin of cycle', cycle start, fresh FE, lowest control rod position at operation
Δρ	reactivity grasp (by rods)

REFERENCES

[FRM2des] K. Böning, W. Gläser, A. Röhrmoser, „Physics of the Munich compact core design",Proc. 1988 International Meeting on Reduced Enrichment for Research and Test Reactors RERTR, San Diego, Ca. (USA); Report ANL/RERTR/TM-13 CONF-8809221, 393 – 403 (1993)

[MCNP] "MCNP - A General Monte Carlo N-Particle Transport Code, Version 5", LA-UR-03-1978 (4/2003,10/2005), X-5 Monte Carlo Team, Los Alamos National Laboratory

[JEFF] "JEFF Nuclear data Library", NEA, Nuclear Energy Agency, f.i. ISBN 978-92-64-99074-6

[FrmMdl] A. Röhrmoser, "Core Model of new German Neutron source FRM II", Nuclear Engineering and Design, June 2010

[RRFM10] A. Röhrmoser, "FRM II, New burn up calculations", Proceedings of RERTR meeting 2010, Lisboa, Portugal

[Anim-09] A. Röhrmoser, "Evaluation of in-pile neutron signals during the start up phase of the FRM II compact core reactor", Proceedings of the ANIMMA 2009 conference 2009, Marseille, France