Reduced Enrichment Program for the FRM-II, Status 2004

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ABSTRACT

The new research reactor FRM-II of the Technische Universität München (TUM) has been designed to provide a maximal thermal neutron flux at mere 20 MW power. The single element design uses silicide fuel of densities 3.0 and 1.5 g/cm^3 of highly enriched uranium (HEU, 93 % U-235). With the nuclear license, that was granted in May 2003, a condition was imposed to reduce the enrichment of FRM-II to medium enriched uranium (MEU) with not more than 50 % U-235 until the end of the year 2010. The TUM has established an international working group to meet this target. This paper presents the backgrounds and the results and plannings for the first of three 2½ year periods to reach the conversion in time.

1 FRM-II's tour from first idea to full operation

1.1 Design Phase

The new research reactor FRM-II has been designed as a high performance neutron source. It is optimised as a multi purpose reactor, primarily for beam tube experiments in fundamental research but also for various technical, medical and industrial applications. The general features of this novel design have been established already in the 80's. A presentation of the actual core design was given early at RERTR 1988 [1]. Exactly that core design went into operation 16 years later[1].

The core should provide a thermal neutron flux as high as possible in a large volume outside the reactor core to be accessible for the experiments at the moderate thermal power of 20MW. The total power was fixed to a rather low value for reasons of minimizing the radioactive inventory and the environmental impact. These requirements have been met by the compact fuel element of FRM-II which uses silicide fuel of relatively high uranium densities (3.0 and 1.5 g/cm^3) of highly enriched uranium (HEU, 93 % U-235).

1.2 Core design in shortness

The compact core of the FRM-II consists of only one cylindrical fuel element (24.3 cm outer diameter, 70 cm fuel zone height), which contains 113 fuel plates that are cooled by light water and placed in the center of a large heavy water moderator tank. The element contains 8.1 kg of HEU (with 93 % U-235) in the plates which each include uranium-silicide dispersion fuel (U_3Si_2/Al) between two Al cladding layers. These fuel plates are 1.36 mm thick and welded to the inner and outer core tubes; they have involute geometry to provide cooling channels of constant width (2.2 mm). Because of the extremely strong gradient of the thermal neutron flux between the highly absorbing fuel zone and the virtual absorptionless D_2O moderator it is necessary to reduce the power density peaking effects at the outer edge of the fuel zone by grading the fuel density in each plate: the density of uranium is 3.0 g/cm^3 inside and only 1.5 g/cm^3 outside of a "grading radius" r_g = 10.56 cm.

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[1] What was not fixed at that time were the exact operational conditions. Thus minor core modifications have been added later mainly to increase safety margins, such as the doubling of the wall thickness of the Hf control rod from 5mm to 10mm or an accelarated water flow in the core.

The unperturbed maximum of the thermal neutron flux in the D_2O moderator is as high as $8.0 \cdot 10^{14}$ $cm^{-2} \cdot s^{-1}$ at 20 MW reactor power and for a reactor cycle length of at least 52 full power days. A horizontal cut through the inner part of the moderator tank with the fuel element is shown in Fig. 1.

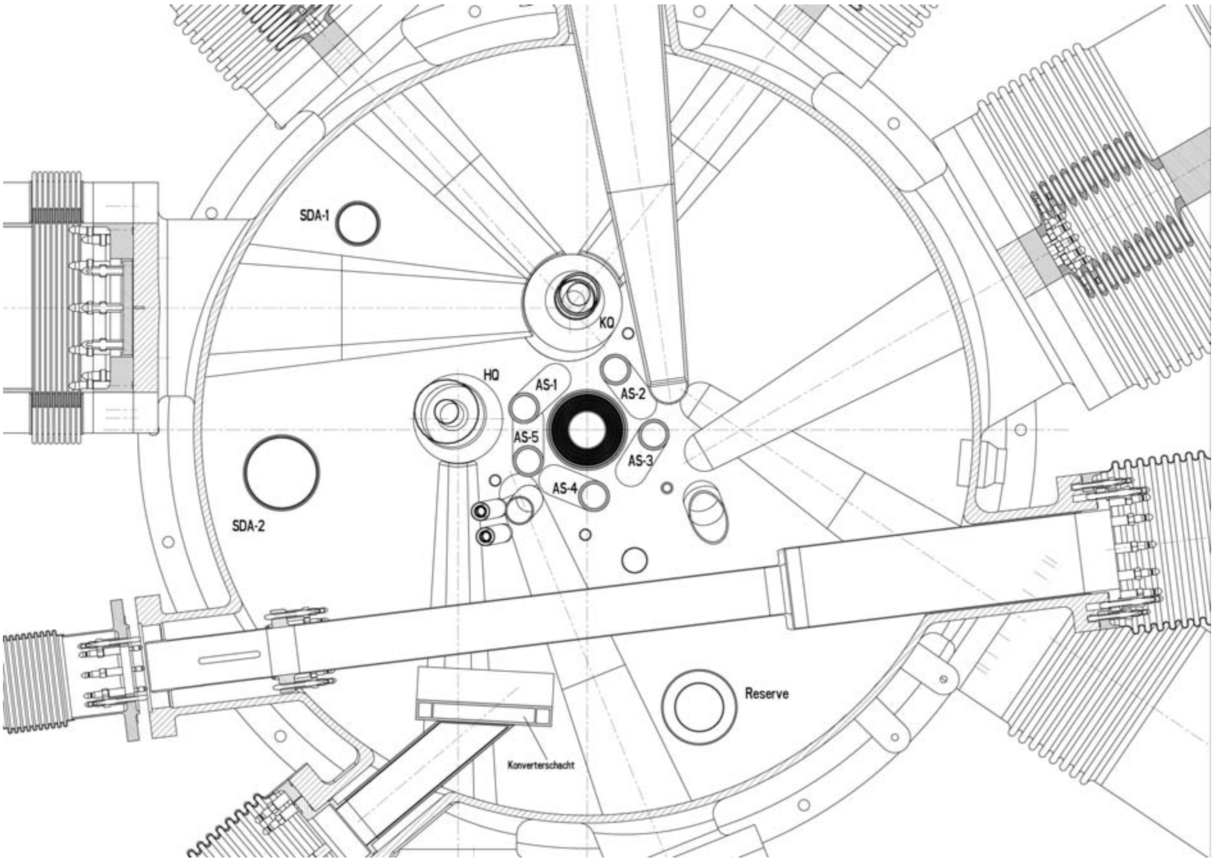

Fig. 1. Perspectively view from above down into the core midplane; one can see the inner part of the moderator tank with the fuel element in the central position. The control rod (not shown) moves in the inner space of the fuel element. The 5 shutdown rods (AS-1 through AS-5) are shown in their shutdown positions. One further recognizes some of the 10 horizontal and 2 inclined beam tubes as well as some vertical irradiation facilities. KQ indicates the cold source and HQ the hot source.

As can be seen from Fig. 1, the fuel element is placed in the central core tube which separates the H_2O cooling circuit from the D_2O moderator. The control rod which also serves as one of the two fast shutdown systems moves in the free inner space of the fuel element (not shown). The other of the two fast shutdown systems consists of 5 shutdown rods which are arranged in the D_2O tank as close as possible to the core tube with a safety margin of 1 cm (closest distance). They are shown in Fig. 1 in their shutdown position (at operation withdrawn). One further recognizes some of the 10 horizontal and 2 inclined beam tubes as well as some vertical irradiation facilities.

1.3 Realisation / Operation

The construction of the new neutron source began in 1996 adjacent to the old ‘atomic egg’. In spite of a delay of two years with the operation license due to a extensive review by the ‘Federal ministry of Environment and reactor safety’ the startup phase began in 2003 and on 2.3.2004 the first criticality was achieved. Full power of 20MW was reached for the first time in august 2004. 52 full power days – i.e. the time projected for one fuel cy cycle – was reached on 21.10.2004. The first fuel element had demonstrated that it provides a cycle length as already predicted as a minimum in the calculations some 16 years before. The start of routine operation of the FRM-II is scheduled for december 2004.

2 Reduced Enrichment for FRM-II

2.1 General background

At present many of the low or medium flux reactors and all of the high flux reactors in the world use HEU fuel. The International Nuclear Fuel Cycle Evaluation (INFCE) Conference of 59 States and 6 International Organisations stated during the years 1978–1980 with respect to a conversion from HEU to LEU (low enriched uranium) that "… the agreed criteria are that safety margins and fuel reliability should not be lower than for the current design based on HEU and that neither any loss in reactor performance, e.g. flux per unit power, nor any increase in operating costs should be more than marginal" [2]. It is widely understood that the term 'marginal' means about 5%.

In cases where the discussion of nonproliferation has led to the conversion of a research reactor from HEU to LEU, the following principal has to be persued: to reach comparable criticality conditions when reducing enrichment by compensation with uranium density the fissible mass must be at least increased by a certain degree. The reason for this overcompensation of enrichment by density is the increased concentration of the isotope U-238, which acts as a "neutron poison". The FRM-II fuel element actually contains 7½ kg U-235 and ½ kg U-238. Would it contain 20% enriched U at the same U-235 mass the U-238 mass would be 38 kg. Nearby, that is why the production of plutonium by the U-238 isotope is drastically lower in the first case.

2.2 Enrichment discussion for FRM-II / results in 80'ies and 90'ies

Already in the 80'ies enrichment studies for a new FRM were performed by TUM. The maximum uranium density with the fuel U_3Si_2 was assumed to be not higher than 4.8 g/cm^3. In comparison to a LEU variant the FRM-II HEU element achieved a maximum flux level that was 35% higher [3]. In 1995/96, nearly one decade after the final TUM design of the element and at beginning of the construction phase for FRM-II there were presented alternative designs for FRM-II by the RERTR group at Argonne [4]. It was shown that a conversion to LEU was impossible without severe geometry changes and an increase of the reactor power to 32 MW, even with unrealistic uranium metal densities of 19 g/cm^3.

2.3 New Initiative

In 1998 the new "red-green"-Federal Government expressed its wish to take the FRM-II into operation with a fuel element with reduced enrichment – so far the scientific aims are met. Hearings with experts about the feasibility of the conversion have been organized by the Federal Ministry of Science and Education. In October 2001 an 'Agreement between the Federal Republic of Germany and the Free State of Bavaria on the conversion of FRM-II' has been written down and finally signed after granting the final license in May 2003. The compromise settled in this agreement is part of the final nuclear license – development of a new medium enriched (MEU, with not more than 50 % U-235) fuel element until the end of the year 2010 [5]. It is understood that the conversion should neither reduce the reactor safety nor degrade the neutron flux and reactor cycle time more than marginal.

2.4 Actual Schedule

Already in November 2001 TUM had established an international working group to study the possibility of a new fuel with up to now not qualified densities and reduced enrichment. The group consisted of representatives of the TUM (FRM-II), the fuel element manufacturer CERCA and the constructor of FRM-II, Framatome-ANP (formerly Siemens-KWU). In its kick-off meeting in July 2003 the group declared to accept the technological challenge of the development of a fuel with densities in the order of 8 g/cm^3 within the very short time limit of 7½ years.

The project was broken down into three phases of 2½ years duration each:

I. search for the fuel type, test irradiations
II. further test irradiations, final decision on the fuel type and design of the fuel element

III. fabrication of the fuel element and licensing

3 MEU Conversion FRM-II, Phase I

In program phase I the high density fuel shall be chosen or at least done a preselection. This first 2½ years phase spreads from 7.2003 till 12.2005 and the following tasks are assigned to phase I:

a) calculations for the high density fuel(s) for FRM-II geometry
b) irradiations of MEU full size fuel plates
c) participation in international research programs

3.1 Calculations with UMo dispersion fuel, first results

Any scenario to convert the FRM-II has to keep the reactor power constant at 20 MW. Without changing the whole D_2O moderator tank with all its installations and its shutdown rods the core geometry must remain unchanged. This is necessary not only to avoid a complete new licensing procedure but also a reactor shutdown period of many years and costs of more than 150 million Euros as stated by a sharp estimation.

For an enrichment of 50% an advanced fuel with high density is required when maintaining the dimensions of the HEU compact core fuel element of the FRM-II. The new uranium-molybdenum dispersion fuel (UMo-Al) presently under research worldwide promises realistic uranium densities of up to 8.0 g/cm^3. TUM did actual neutronics calculations for this fuel with the same procedures that led to the HEU design of FRM-II (criticality, burn up …). The result was now that the density in the fuel must be at least 7.75 g/cm^3 with an enrichment of 50% U-235. When taking into account other aspects like the less fortunate power density distribution with UMo, the minium density can hardly be below 8.0 g/cm^3. The core contains then 10.8 kg U-235 instead of 7.5 in the actual HEU case. The total U mass is 22 kg instead of 8 kg now. All efforts to flatten the power distribution will reduce criticality.

One key point is the maximum of the fission density (FD) in the fuel. Because of the very inhomogeneous power and fission density in the plates maxima are reached only in very small areas of the plate. This is different from irradiation tests, where the plates are much more homogeneously irradiated. The relevant maximum of the value in FRM-II must be assigned to the inner part of the plate and possibly to the plate ends. The result of these preliminary calculations is that the maximum of fission density in the meat is up to $2.0 \cdot 10^{21}$ cm^{-3} in a narrow area at the inner and outer border of the high density region (see Fig. 2). Test irradiations have to show whether the new fuel withstands the mentioned fission densities.

Still the thermal flux is depressed by about 8.0% when compared to the actual HEU fuel, i.e. the aim of only marginal consequences for the scientific use is not yet met.

3.2 Irradiation Program

For Phase I it was decided to plan an irradiation of four test plates of full size: For this, six plates are already produced by CERCA with UMo/Al dispersion fuel (8% wt. Mo) and wait to be irradiated.

The uranium densities are 8.0 g/cm^3 for 4 plates and 7 .0 g/cm^3 for the two other plates. Two of the 8.0 g/cm^3 plates contain the additive of a possible considerable “diffusion blocker”. Those blockers are presently object of research and development worldwide. We used 2% of silicon additive in the Al matrix. Including a safety margin a FD of $2.3 \cdot 10^{21}$ cm^{-3} shall be reached by the test irradiations. According to calculations of CEA this will be reached in a remarkable area of the plates within four cycles of the MTR reactor OSIRIS at CEA-Saclay.

In case any of the 8.0 g/cm^3 plates will fail during the irradiation, it can be replaced by the two 7.0 g/cm^3 plates in the test facility.

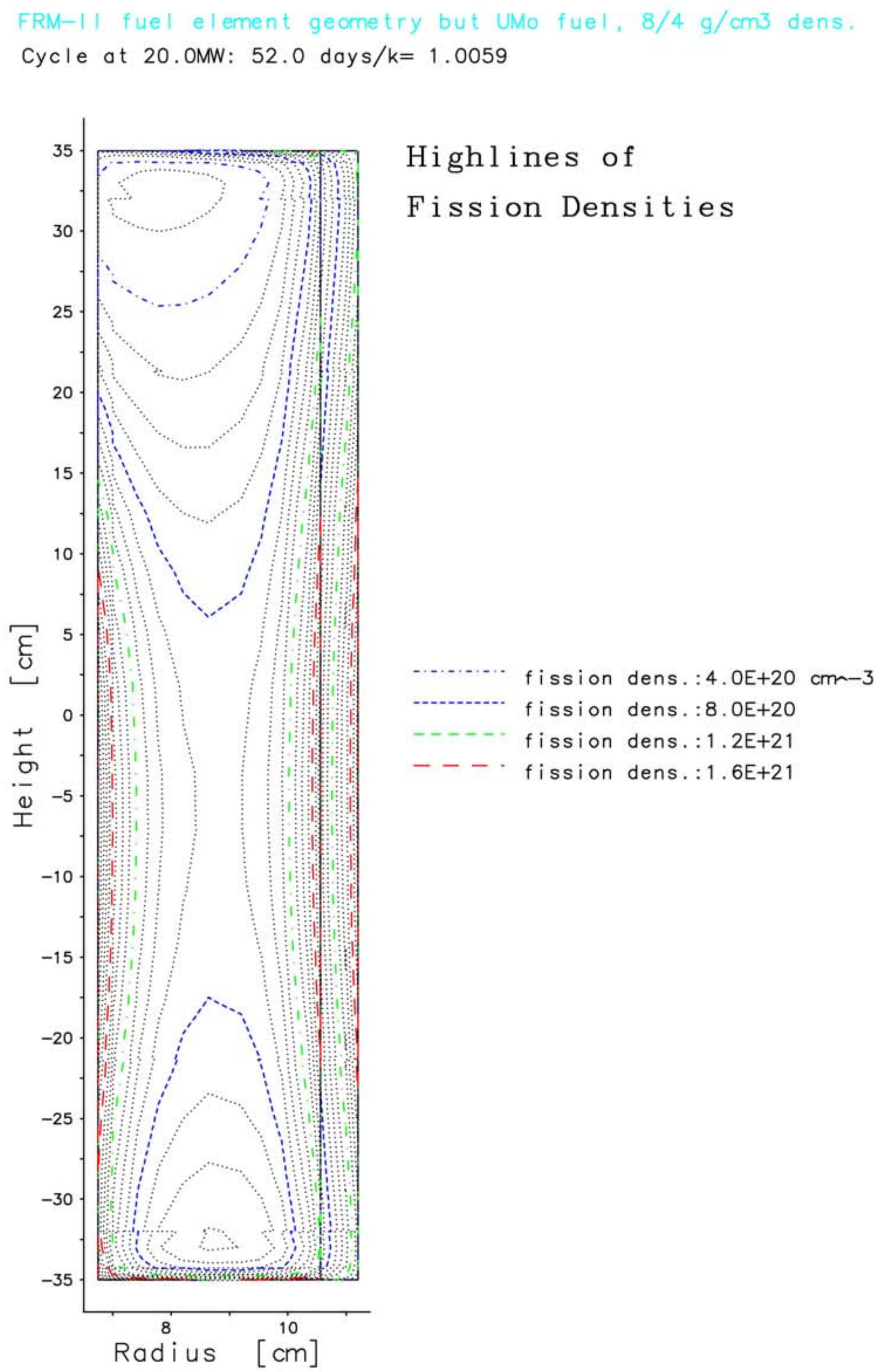

Fig. 2. Calculated distribution of the fission density (FD) in a FRM-II fuel plate with UMo dispersive MEU fuel. The uranium density must be of 8.0 g/cm^3 in the meat to achieve the same cycle length as with the current HEU element.

Great attention is given to the request to have similar conditions during the irradiations as close as possible to those in the future FRM-II core. Specifically the maximum temperatures in the meat should be comparable. To do so OSIRIS needs an extension of its irradiation license for heat flux values in the order of 280 to 300 W/cm^2. The decision from the French safety authority is expected for March 2005. The irradiation of the plates will start immediately after the authorization is granted.

3.3 Cooperations in highest density fuel research

The alternative of monolithic UMo fuel is presently under study at the US RERTR Program. One of the main challenges with this very high density fuel is the fabrication of full size plates. So far only two test irradiations of small mini-plates have been performed.

CEA, CERCA and TUM agree in a ‘Memorandum of Understanding’ about their cooperation in feasibility studies of the fabrication and the irradiation behavior of monolithic fuel plates of full scale.

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