FRM-II PROJECT STATUS AND SAFETY OF ITS COMPACT FUEL ELEMENT

M. NUDING, M. ROTTMANN, A. AXMANN and K. BÖNING
Technische Universität München
ZBE FRM-II-Bau
D-85747 Garching - Germany

ABSTRACT

The construction of the new research reactor FRM-II is close to completion and the nuclear start-up is scheduled to begin in January 2001. This contribution provides an overview about the concept of the facility and the safety features of the reactor. It also describes some of the tests performed during the licensing procedure of the compact fuel element and their results. At the end a short status report is given.

1. Introduction

The Technische Universität München (TUM) is presently building a new high-flux reactor, the FRM-II. This new reactor shall replace the existing "Forschungsreaktor München" (FRM) which has been operating very successfully for about 43 years now.

The FRM-II was developed with first priority for beam-tube experiments, but it will also provide excellent possibilities for irradiation experiments or isotope production. For this reason the reactor was designed in a way that a high and spectrally pure thermal neutron flux is available in a large volume outside of the reactor core, where it is accessible for experimental use. In addition to beam-tubes which will end in the thermal neutron field there will be beam-tubes that will provide - with the help of "spectrum shifters" - cold, hot and fast neutrons.

Even though the thermal power of the FRM-II was limited to 20 MW a maximum thermal neutron flux of about $8 \times 10^{14}\ cm^{-2}s^{-1}$ will be reached. Because of its "compact-core-concept" which represents a further development of the concepts of the HFR (Grenoble, F) and the HFIR (Oak Ridge, USA) the FRM-II will have the best flux-to-power-ratio worldwide. This is a big advantage with regard to the background radiation at the experimental facilities, reactor safety, nuclear waste and costs. For all these reasons and because of the progress in the optimization of the user installations that has been made in the last decades the FRM-II will be one of the most efficient research reactors in the world.

2. The compact core concept

The unique characteristics of the FRM-II - such as high thermal neutron flux, a high spectral purity of the energy distribution of the neutrons and a large usable volume outside of the reactor core - are obtained due to a small core cooled with light water (H_2O) that is placed in the center of a moderator tank filled with heavy water (D_2O). Due to the fact that the thermal power should be limited to 20 MW the reactor core was designed as a particularly small "compact-core". It consists of only one cylindrical fuel element that contains the U_3Si_2-Al-dispersion fuel in combination with high-enriched uranium (about 93 % ^{235}U). The fuel contains about 8.1 kg uranium and is placed in 113 involutely curved fuel plates. Because of this involute shape the coolant channels between the plates have a constant width of 2.2 mm. The plates themselves have a thickness of 1.36 mm (fuel 0.60 mm, cladding

0.38 mm). The outer diameter of the active zone of the fuel element is 243 mm and its height is 700 mm.

Since the reactor core is very small the leakage of fast neutrons out of the core is very high (more than 50 %) and neutrons which have been thermalized in the D_2O and diffuse back into the core make a big contribution to the nuclear chain reaction. However, they would cause a big peak in the distribution of the power density at the outer edge of the core. This peak is reduced in the FRM-II using the concept of fuel grading: the uranium density in the fuel meat is 3.0 gU/cm^3 in the inner part of the fuel element and 1.5 gU/cm^3 in the outer part. The peak at the lower end of the active zone caused by the reflector-maximum of the thermal neutron flux in the H_2O of the primary circuit is reduced by a boron-ring in the outer tube of the fuel element. The power density at the upper end of the core is considerably lower, because of the close proximity of the hafnium absorber of the central control rod.

3. Inherent safety features

As mentioned above the thermal neutrons diffusing back from the moderator tank play an important role in the reactivity balance of the reactor. As a consequence the FRM-II has some essential inherent safety features. For example, the reactor would become subcritical if the D_2O in the moderator tank would be replaced by H_2O or if a substantial fraction of H_2O would be mixed into the D_2O. If the H_2O in the fuel element would be replaced by D_2O - this would lead to a worse slowing down of the neutrons in the core - and of course if the H_2O would be totally removed from the core the reactor would become subcritical. An essential safety feature concerning the handling of the fuel element is that the fuel element is highly subcritical in pure H_2O without any additional absorber.

4. The designed safety features

The most important safety aim in designing a reactor is to avoid under all circumstances inadmissible radioactive exposures for the population and the personnel. In order to reach this target the release of fission products is avoided by three barriers: fuel matrix, pool water and reactor building confinement. Furthermore it is guaranteed that the reactor can be shutdown under all circumstances and the decay heat can be safely removed [1].

The reactor building and the reactor pool (including the storage pool) were designed in a way that the pool water is kept under all accident conditions - even in the case of an earthquake or of an aircraft crash (the latter would represent a beyond design basis accident). This aim is met by building the pool out of watertight concrete (1.8 m thick) with an additional stainless steel liner. Moreover, the ceilings of the 0 m- and the 11.7 m-floor of the reactor building are connected with flexible joints to the pool structure in order to keep shockwaves away from it. The beam tubes have two barriers for avoiding the loss of pool water. In addition the primary circuit and the primary cell are designed in a way that a complete loss of the pool water is impossible even if there would be a leak in the primary cooling circuit.

A release of fission products would be possible only in the case of a damage of the fuel element. Since the pool water does not retain all of the fission products (even though in most cases a very high fraction is retained) the ventilation system of the reactor hall is designed to filter and control the low flow rate of air released through the stack [1].

Two independent shutdown systems guarantee that the reactor can be shutdown under all circumstances and that the fuel element will not be damaged. Each of the two systems is sufficient to scram the reactor and keep it subcritical. The first shutdown system consists of five shutdown rods in the moderator tank. These rods are totally withdrawn during the normal operation of the reactor. Four

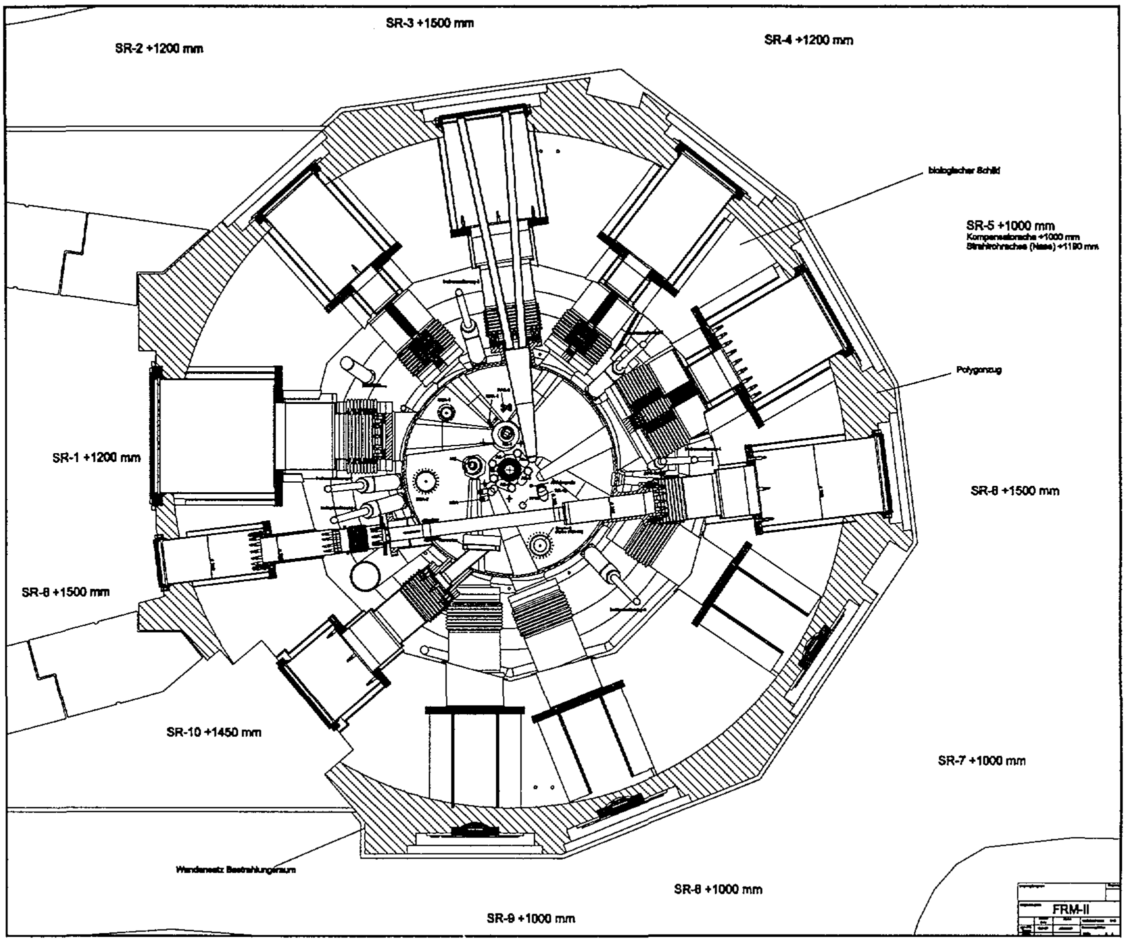

Figure 1: Horizontal cross section through the reactor pool. One can see the cylindrical reactor core in the center of the moderator tank surrounded by the five shutdown rods shown in their shutdown position. Three of the ten horizontal beam tubes begin at the Cold Neutron Source, one at the Hot Neutron Source and one at the converter facility. The heavy water tank of 2.5 m diameter is located in the reactor pool made of heavy concrete (not shaded in this figure) and filled with light water.

of the five rods would be sufficient to shutdown the reactor even if the central control rod were totally withdrawn. This control rod is located inside the inner tube of the fuel element and is moved upwards during the cycle. The control rod is coupled to its drive with a magnetic clutch which can be released if necessary.

5. Installations in the reactor pool

The reactor pool is 14 m deep with a nearly circular cross section (diameter about 5 m) at its lower part. Figure 1 shows a horizontal cross section through the reactor pool. In the center one can see the moderator tank and the fuel element. Ten big horizontal beam tubes lead the neutrons into the experimental hall or - as in one case - into the "neutron guide hall" that is connected to the reactor building. Three of the beam tubes begin at the Cold Neutron Source, one at the Hot Neutron Source and one at the converter facility for the production of fast (fission) neutrons. Moreover, in figure 1 one can see some vertical irradiation channels and - in the direct vicinity of the fuel element - the five shutdown rods in their shutdown position.

6. Tests within the scope of the licensing procedure

The fuel element and the U_3Si_2-Al-fuel were intensively tested during the licensing procedure of the FRM-II.

Dummies of the fuel element with depleted uranium were tested in experimental facilities which very closely represented the central part of the primary cooling circuit of the FRM-II. Within the scope of this "hydraulic test" the stability and the vibration behavior of the fuel plates were tested. The long-term behavior of the fuel element was tested for 60 days (the planned cycle length of a fuel element of the FRM-II is about 52 days) with an enhanced flow rate. The test showed that there is no deviation from the expected vibration behavior. The measured values of the thickness of the cooling channels were as before and also the US-inspection of the welds did not give any indication of defects. Following these inspections artificial defects at some welding points were produced and a part of the flow test was repeated. As expected there was no change in the vibration behavior of the fuel plates.

The U_3Si_2-Al dispersion fuel that will be used in the FRM-II was developed and intensively tested by the RERTR-program and so can be considered as qualified up to uranium densities of 4.5 gU/cm^3 to 4.8 gU/cm^3 in the fuel meat. For the FRM-II, the swelling behavior and the increase of the thickness of the fuel zone was deduced from the data given in the literature [2]. According to this the thickness increase due to swelling at the maximum fission densities in the fuel particles is about 10 % in the 3.0 gU/cm^3-zone and about 9 % in the 1.5 gU/cm^3-zone. The calculated maximum fission densities in the fuel particles at the end of the cycle (i. e. after 52 days) are 7.8×10^{21} f/cm^3 and 12.2×10^{21} f/cm^3 for the 3.0 gU/cm^3-zone and for the 1.5 gU/cm^3-zone, respectively. The occurrence of these fission densities is limited to some few mm^2 of the fuel plate which has a total active area of about 43000 mm^2. As one can see from these data the fuel particles in the 1.5 gU/cm^3-zone are stressed more than the ones in the 3.0 gU/cm^3-zone. For this reason the TUM has decided to irradiate a test-plate containing fuel with 1.5 gU/cm^3 at the SILOE-reactor of the CEA-Grenoble. After each of ten irradiation cycles the thickness of the fuel plate was measured allowing a detailed analysis of the swelling behavior. As expected the increase of the plate-thickness was small and continuous (see figure 2). In contrast to that a sudden increase of the swelling rate would have been indicative of "breakaway swelling" and of a failure of the plate. So the data used in designing the fuel element and the cooling systems were fully confirmed by the irradiation experiment.

Following this irradiation experiment Post Irradiation Examinations (PIE) were performed in the Hot Cells LAMA of the CEA-Grenoble in order to obtain information about the fine structure of the U_3Si_2-grains and the thickness of the U-Al interdiffusionlayer that is formed at the grain-boundaries. The microscopic pictures (one of them is shown in figure 3) demonstrate that the morphology of the fission gas bubbles is as expected. One substantial aim of the PIE was to confirm also the qualification of the fuel with an uranium density of 3.0 gU/cm^3 in the meat for the use in the FRM-II. The essential condition for this is that there is enough "free" aluminum[1] left at the end of the irradiation. In [4] a conservative value of 15 *vol.%* for the minimum Al-content has been established for stable fuel swelling. In order to calculate the Al-content in the fuel with 3.0 gU/cm^3 at a fission density in the particles of about 8×10^{21} f/cm^3 out of the data obtained from the test-plate with 1.5 gU/cm^3 a relation was formulated [5]. The applicability of this relation was tested by means of a quantitative analysis of the microstructure. The knowledge of the thickness of the interdiffusionlayer is necessary for determining the loss of "free" Al; it was calculated with the help of correlations taken from the literature ([6], [7]) and tested against the results of the microscopic examinations. The analysis showed that at a fission density in the particles of 8×10^{21} f/cm^3 the fuel with a uranium density of 3.0 gU/cm^3 still contains between 50 *vol.%* and 68 *vol.%* of "free" aluminum - this value is far above the required 15 *vol.%*. As a consequence it is proved that both fuels are qualified for the use in the FRM-II.

[1] The term "free" means that the aluminum in the U-Al interdiffusionlayer is not taken into account.

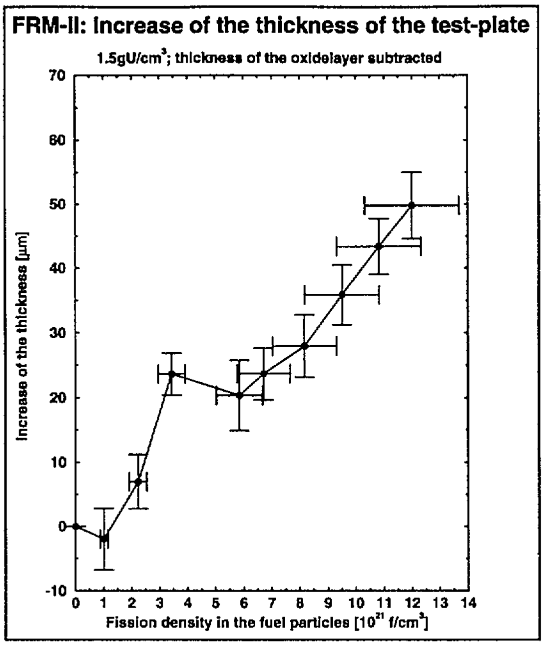

Figure 2: Increase of the thickness of the test-plate with an uranium density of 1.5 gU/cm^3 as a function of the fission density in the fuel-particles. The thickness of the oxidelayer has been subtracted. The error bars for the thickness represent the statistical error obtained from taking the mean value in a small area of the test-plate; the error bars for the fission density are related to the inaccuracy of the γ-scanning-measurements [3]. The exceptional point at about 3.4×10^{21} f/cm^3 was caused by problems with the electronic equipment which have been solved in the course of the irradiation test, and therefore is not due to irradiation effects.

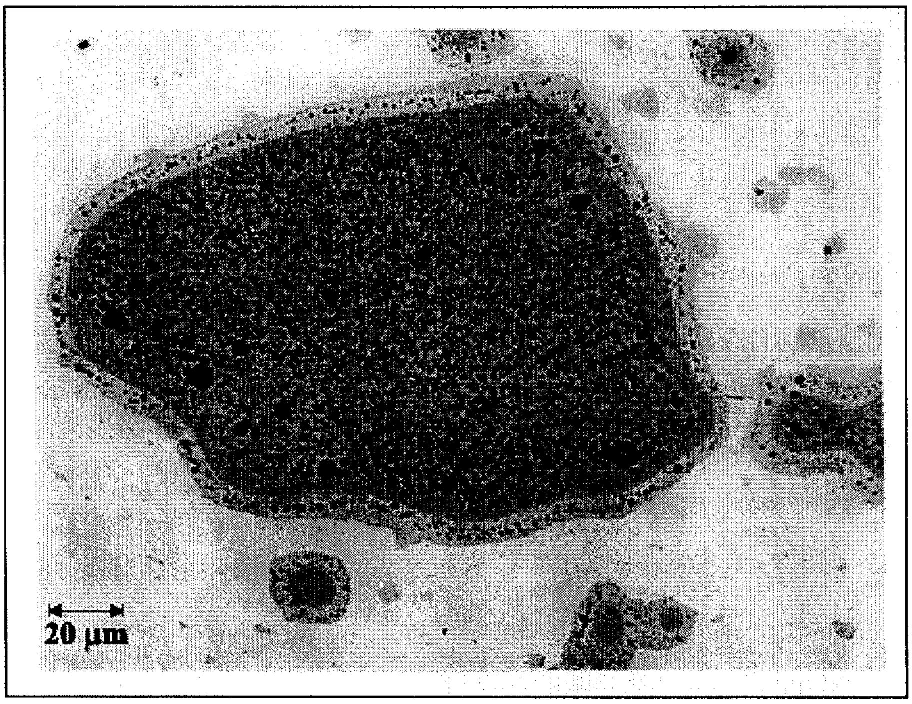

Figure 3: Picture of a U_3Si_2 particle taken in the region of the test-plate with a fission density of 12×10^{21} f/cm^3 in the fuel particles. The morphology of the fission gas bubbles is as expected. Moreover, the thickness of the U-Al interdiffusionlayer (light-gray area at the grain-boundary) is of the order of 6 µm and in good accordance with the theory [5].

In addition to that test the TUM started the irradiation of two more plates in the OSIRIS-reactor of the CEA-Saclay. One plate contains the fuel with a uranium density of 3.0 gU/cm^3, the other one contains fuel with both uranium densities, 1.5 gU/cm^3 and 3.0 gU/cm^3. The results of this test are expected for the second part of this year 2000.

7. Status of the FRM-II project

The first design considerations of the Technische Universität München (TUM) started even before the year of 1980. The project team FRM-II ("Projektgruppe FRM-II") of the TUM was established in 1987, after the project had gained the necessary support. After affirmative statements e. g. by the "Wissenschaftsrat" (a German scientific advisory committee) the safety report was prepared together with the present general contractor SIEMENS/KWU. In February 1993 the TUM and SIEMENS applied for the nuclear license which in the case of the FRM-II will be split into three partial licenses. The first partial license which also contains a provisional positive assessment concerning the reactor was granted by the licensing authority in April 1996, the second partial license (involving the completion of the whole reactor as well as the cold start-up) in October 1997. At present the construction of the technical facilities of the FRM-II is in progress. The structure of the entrance building was finished at the end of 1998 and that of the neutron guide hall one year later. The third partial license is expected to be granted in the second half of 2000; after that the nuclear start-up will follow immediately. The begin of the routine operation and utilization of the FRM-II for scientific research and technical and medical applications is planned for fall 2001.

8. References

[1] **Blombach, J.:** "Sicherheitskonzept des FRM-II"; Proceedings of the *Jahrestagung Kerntechnik 1997*; May 1997.

[2] **Feltes, W.; Strömich, A.:** „Brennstoffqualifikation FRM-II" - B 1100.0002; Report-Nr. A1C-1300334-0; Siemens KWU.

[3] **Nuding, M.:** „FRM-II: Auswertung des Brennstoff-Bestrahlungsexperiments am Reaktor SILOE und Bewertung der Ergebnisse auf mikroskopischer Ebene"; Report-Nr. OPA 218; Technische Universität München, ZBE FRM-II-Bau; 10. Dezember 1998.

[4] **Hofmann, G. L.; Rest, J.; Snelgrove, J. L.:** „Aluminum-U_3Si_2 interdiffusion and its implication for the performance of highly loaded fuel operating at higher temperatures and fission rates (a preliminary assessment)"; Argonne National Laboratory; Oktober 1995.

[5] **Nuding, M.:** "Auswertung der Nachbestrahlungsuntersuchungen an der Testplatte FRM-1501 in den Heißen Zellen LAMA im Rahmen der Brennstoffqualifikation für den FRM-II – Eignungsnachweis des Brennstoffs mit einer Urandichte von 3.0 gU/cm^3 im Brennstoffkern" - 3 B 1100.0010; Report-Nr. OPA 272; Technische Universität München, ZBE FRM-II-Bau; November 19th, 1999.

[6] **Hofmann, G. L.; Rest, J.; Snelgrove, J. L.; Koster van Groos, S.:** „Aluminum-U_3Si_2 interdiffusion and its implication for the performance of highly loaded fuel operating at higher temperatures and fission rates"; RERTR International Meeting, Seoul; October 7th- 10th, 1996.

[7] **Copeland, G.:** „Status of the fuel development"; Presentation; R&D Staff Meeting of the ANS-Project team; January 11th, 1994.