THE NEW GERMAN NEUTRON SOURCE FRM-II

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ABSTRACT

The Technische Universität München (TUM) has built a new high-flux research reactor, the FRM-II. This new reactor will replace the "Forschungsreaktor München" (FRM) which has been operated very successfully for about 43 years.
The FRM-II has been developed with first priority for beam-tube experiments, but it will also provide possibilities for irradiation experiments or isotope production. The reactor was designed to obtain a high and spectrally pure thermal neutron flux is available in a large volume outside of the 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 an unperturbed maximum thermal neutron flux of about 8×10^{14} $cm^{-2}s^{-1}$ will be reached. Because of its "compact-core-concept" the FRM-II will have the best flux-to-power-ratio worldwide:
The fuel element and its highly enriched U_3Si_2-Al-fuel were tested during the licensing procedure of the FRM-II. Within the scope of this "hydraulic test" the stability and the vibration behavior of the fuel plates as well as the long-term behavior of the fuel element were investigated.
The fuel was developed and intensively tested and so could be considered as qualified up to uranium densities of 4.8 gU/cm^3. The TUM irradiated a test-plate containing fuel with 1.5 gU/cm^3 up to very high fission densities. Post Irradiation Examinations (PIE) were performed in order to obtain information about the fine structure of the U_3Si_2-grains.
At present the cold start-up of the technical facilities of the FRM-II has been completed and the reactor is ready for the nuclear start-up. With the operational license granted in May 2003 the start of the routine operation and utilization of the FRM-II for scientific research and technical and medical applications is expected for spring 2004.
During the design and the construction phase as well as during the cold and the nuclear start-up all tasks have been and will be followed very closely by the TÜV. We have checked and approved all values related to the safety of the FRM-II as well as the test program of the hydraulic test and the irradiation tests. Our expert assessments were the basis of the three partial licenses that have been granted by the Bavarian State Ministry for Regional Development and Environmental Affairs.

Introduction

The Technische Universität München (TUM) has finished the construction of a new high-flux research reactor, the FRM-II. This new reactor will replace the "Forschungsreaktor München" (FRM) which has been operated for about 43 years.
The FRM-II has been optimized with first priority for beam-tube experiments, but it will also provide possibilities for irradiation experiments or isotope production.
This paper at first presents the main applications of the FRM-II and its core and plant design. After that a description of the tests performed during the licensing procedure is given. At the end some political topics are discussed.
Up-to-date information can also be found on the FRM-II-homepage: www.frm2.tum.de

The utilization of the FRM-II

As mentioned above the FRM-II has been designed with highest priority for beam-tube experiments. In the field of basic research the investigation of the atomic structure of fluids and solids and the dynamics (vibrations) of their atoms and molecules is most important. Because of the magnetic moment of the neutron it is possible to examine the microscopic origin of the magnetism. One of the instruments will be optimized for experiments in biophysics. In addition the FRM-II will be equipped with an intense positron source and an accelerator for fission products which will be used for research with super-heavy elements. Besides fundamental research the FRM-II will also be used for applied research, in particular for non-destructive material tests using radiography and tomography. Last but not least there will be a dedicated facility (the so-called converter facility) to produce fission neutrons for tumor therapy.
Another field of utilization of the FRM-II is isotope production. The isotopes will be used as tracers e. g. in chemistry or in attrition measurements. Even more important is the production of isotopes that are required to produce radio-pharmaceuticals. The FRM-II will also have irradiation facilities that allow to perform neutron activation analysis on samples taken e. g. from foods or from the environment as well as "neutron transmutation doping" of silicon semiconductors.
In general the TUM plans to use about 30 % of the experimental facilities and installations for industrial and commercial applications (including medicine) and about 70 % for fundamental and applied research.

The concept of the FRM-II compact core.

The FRM-II 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 begin in the thermal neutron field there will be beam-tubes that will provide – with the help of "spectrum shifters" – cold, hot and fast neutrons.
The characteristics of the FRM-II - such as a high maximum thermal neutron flux, a high spectral purity of the energy distribution of the neutrons and a big "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 large heavy water (D_2O) filled moderator tank. Because of the fact that the thermal power should be limited to 20 MW the reactor core was designed as a "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 (HEU, with 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 each). The outer diameter of the active zone of the fuel element is 224 mm (tube 243 mm) and its height is 700 mm. The total height of the fuel element is about 1300 mm. In figure 1 a horizontal cut through fuel element in the region of the active zone is shown.

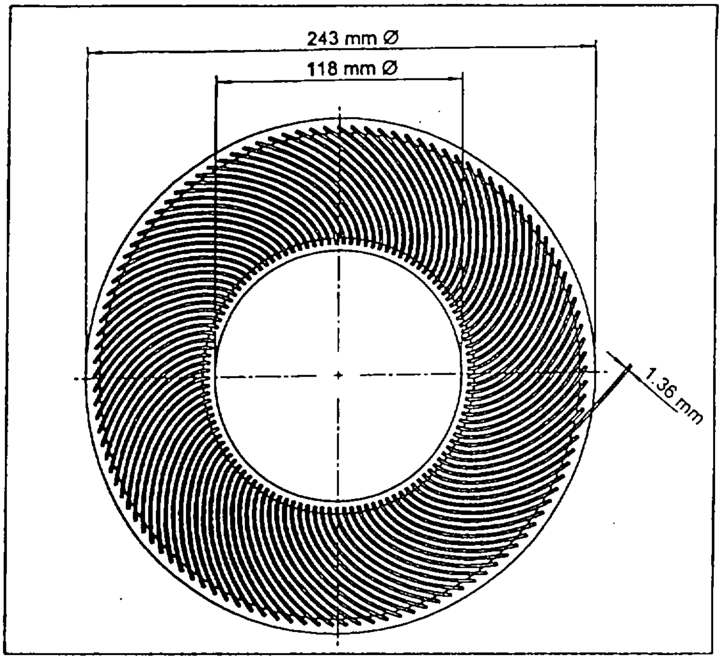

Figure 1: Cross section of the fuel element of the FRM-II in the region of the fuel plates. Each of the 113 fuel plates is 1.36 mm thick and is fabricated by the so-called "picture frame technique". The fuel element contains about 8.1 kg high-enriched uranium. The plates are involutely curved so that the coolant channels between them have a constant width of 2.2 mm. The reactor core of the FRM-II consists of one such fuel element only .

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 give a large 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 by 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 analogous peak at the lower end of the active zone is caused by the reflector-maximum of the thermal neutron flux in the H_2O of the primary circuit and is reduced by a boron-ring in the outer tube of the fuel element (burnable poison). 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. This control rod has a "Beryllium-follower" at its lower end in order to replace the light water of the primary cooling circuit by a high-quality moderator.
Even though the thermal power of the FRM-II was limited to 20 MW an unperturbed maximum neutron flux of about 8×10^{14} $cm^{-2}s^{-1}$ will be reached. That means that the FRM-II will have the highest flux-to-power-ratio worldwide. This is advantageous with regard to the background radiation at the experimental facilities, reactor safety, nuclear waste and costs.

The 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 less effective 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.

The plant design of the FRM-II

Figure 2 shows a schematic vertical cross section through the reactor pool that has a depth of about 14 m and a nearly circular shape in its lower part. On the left upper side one can see the rectangular storage pool ("*Absetzbecken*"), that contains i. a. 50 positions for the interim storage of spent fuel elements. Both pools are made from heavy concrete and are covered on the inside by a watertight stainless steel liner. The thickness of the walls of the pool is more than 1.5 m.
In the center of figure 2 one can see the D_2O moderator tank with the fuel element that is fixed in the central channel ("*Zentralkanal*"). The fuel element is cooled (as already mentioned) by light water with a flow rate of about 300 kgs^{-1}. The water velocity in the fuel region is about 17 ms^{-1}. The pressure at the inlet of the fuel element is about 10 bar and the water temperature rises from about 37 °C to 52 °C.
At shutdown of the reactor three redundant pumps are started to remove the decay heat. Those pumps suck pool water and pump it through three redundant lines ("*Notkühlleitung*") into the primary circuit after the corresponding flaps have opened due to the degreasing pressure of the primary pumps. The water flows back to the reactor pool through the sieve ("*Sieb*") at the bottom of the moderator tank. After 3 hours the pumps can be switched off and – after the pressure is sufficiently low and therefore the two redundant flaps ("*Naturumlaufklappen*") opened just by gravity – the direction of the coolant flow changes from "downward" to "upward" and the residual decay heat is removed by natural convection.
In figure 2 one can also see the central control rod ("*Regelstab*") which is driven from its upper end ("*Regelstab-Antrieb*") and is coupled by a magnetic clutch which can be released if necessary. For this reason the central rod serves as a first fast shutdown system. The second fast shutdown system consists of five shutdown rods that are totally withdrawn during the normal operation of the reactor. Four of the five rods would be sufficient to shutdown the reactor even if the central rod were totally withdrawn, i. e. the Be-follower would be in the core. In figure 2 only one shutdown rod is plotted. The Cold Neutron Source and the beam tubes that are shown schematically in figure 2, too, will be explained later.

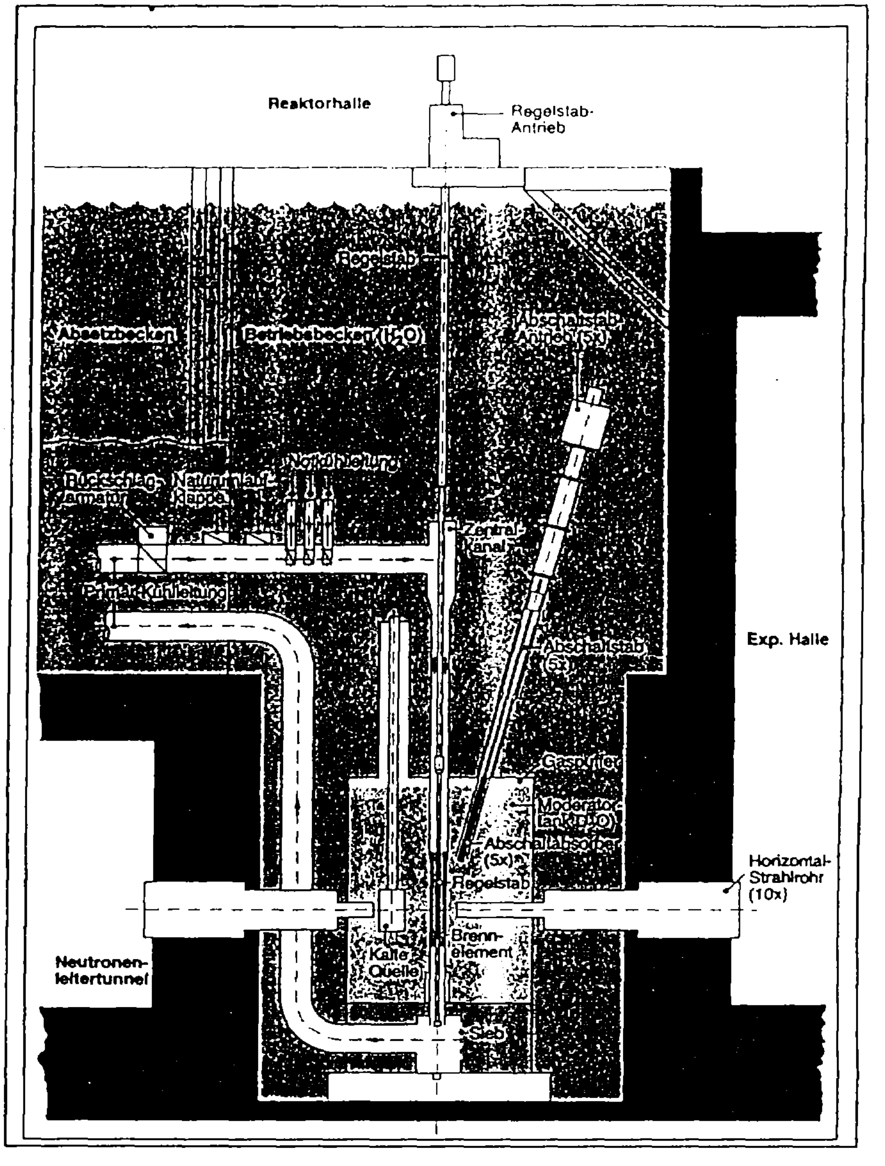

Figure 2: Vertical cross section through the reactor pool. One can see the D_2O-moderator tank, the central channel ("*Zentralkanal*"), the fuel element ("*Brennelement*"), the central control rod ("*Regelstab*") and parts of the primary circuit ("*Primär-Kühlleitung*"). The five shutdown rods ("*Abschaltstab*") – for clarity only one is shown – are fully withdrawn during routine operation. Besides these installations some experimental facilities are shown very schematically: the Cold Neutron Source ("*Kalte Quelle*") and two horizontal beam-tubes ("*Horizontal-Strahlrohr*").

The safety concept of the FRM-II is based on the possibility to shutdown the reactor under all circumstances and – in addition – on the prevention of fission product releases by means of three barriers: fuel matrix and cladding, pool water and reactor building [1]. The pool water is kept under all accident conditions – even in the case of an earthquake or an airplane crash (the latter would be a beyond design basis accident). This aim is met by building the pool out of watertight concrete with an additional steel liner (see above) and by making the walls of the building out of reinforced concrete with a thickness of 1.8 m. Moreover, the ceilings of the 0 m- and 11.7 m-floors of the reactor building are connected to the pool structure with flexible joints in order to keep shockwaves away from it. The beam tubes have two outside barriers for avoiding the loss of pool water. In addition the primary circuit and the primary cell that contains the pumps and the heat exchangers 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.
The safety concept of the FRM-II guarantees that even in the case of a beyond design basis accident – as e. g. a total meltdown of the fuel element – there would be no need for evacuations. Since the pool water does not retain all of the fission products (even though a very high fraction of most elements is retained) the ventilation system of the reactor hall (confinement) is designed to filter and control the very low flow rate of leakage air released through the stack [1].

Building and user facilities

Figure 3 shows a horizontal cut through the reactor pool in the region of the fuel element that is located in the center of the moderator tank (diameter 2.5 m). Ten big horizontal beam-tubes are guiding the neutrons through the wall of the pool into the "experimental hall" or – in case of SR 1 on the left hand side – into the "neutron guide hall". All beam-tubes are arranged tangentially to the core in order to suppress the primary radiation (fast neutrons and γ-radiation) as much as possible. Three beam-tubes begin at the Cold Neutron Source that contains about 2.5 kg of liquid D_2 and is cooled down to about 25 K. Another beam-tube begins at the Hot Neutron Source – an insulated graphite block with a mass of about 14 kg and a temperature of about 2400 °C. In order to produce high-energetic fission neutrons for medical and technical applications an uranium converter facility was installed which allows to move two fuel plates in front of a beam-tube. Besides those installations one can also see some vertical irradiation channels and – in the direct vicinity of the fuel element – the shutdown position of the five shutdown rods.
A horizontal cross section through the whole plant (at about the core midplane level) is given in figure 4. In its lower part the reactor building has the cross section of a square with a length of about 42 m. Here the "experimental hall" with an area of about 1000 m^2 is located. In the upper part the building has the shape of an octagon and contains the "reactor hall"; from there the pool is accessible e. g. for operation maintenance and for handling samples that were irradiated in the vertical channels.
The neutron guides and the scientific instruments are shown in figure 4, too. In the center one can see the neutron guide hall that is about 11 m high, 60 m long and about 45 m wide. This hall shall later be extended into the old FRM which has been permanently shut down in July 2000.

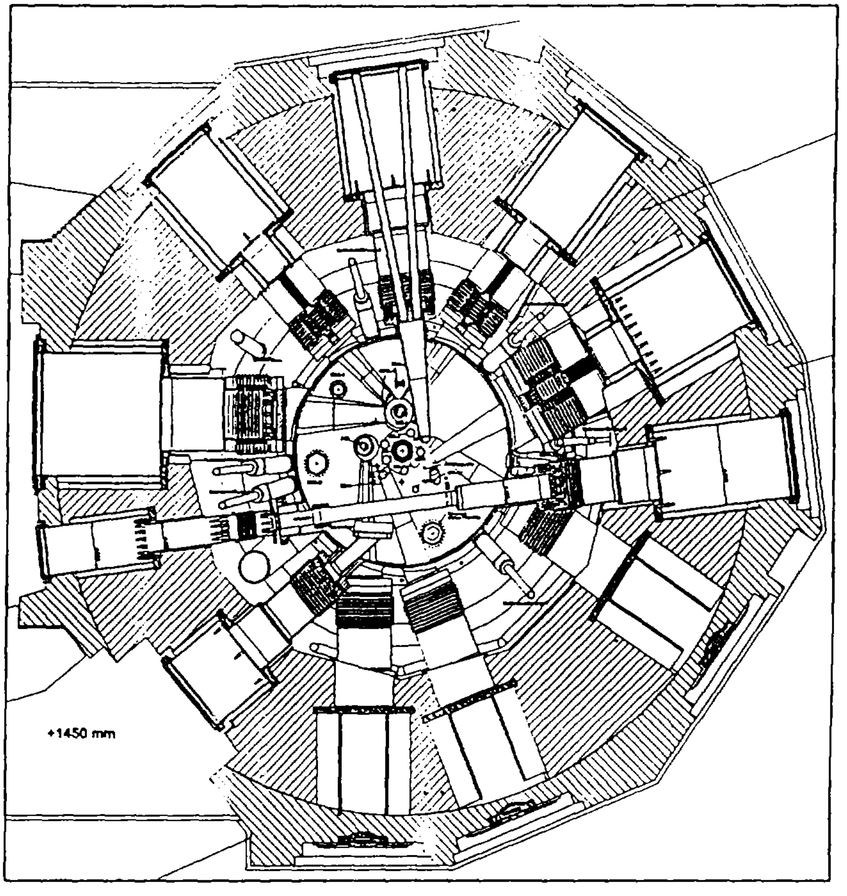

Figure 3: Horizontal cross section through the reactor pool. One can see the cylindrical reactor core in the center of the moderator tank surrounded by the five shutdown rods shown in their shutdown position. Three of the ten horizontal beam tubes begin at the Cold Neutron Source, one at the Hot Neutron 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 and filled with light water.

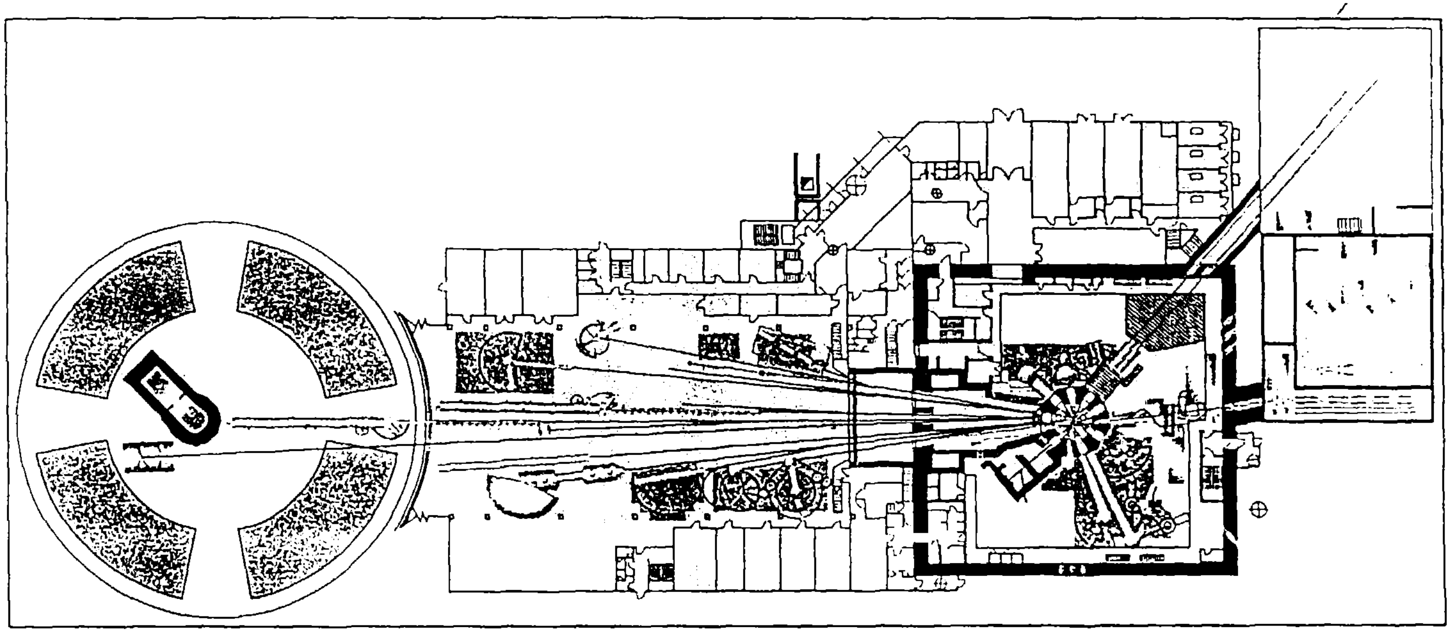

Figure 4: Ground plan of the whole plant with the experimental hall of the FRM-II reactor (on the right), the neutron guide hall (in the center) and the reactor hall of the old FRM (on the left). The entrance building with the main entrance is located at the north-west corner of the FRM-II. The neutron guides and the scientific instruments are indicated in the different areas.

Tests during the licensing procedure

The fuel element and the U_3Si_2-Al-fuel were tested during the licensing procedure of the FRM-II in order to confirm calculations or data taken from the literature.

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 these "hydraulic tests" the stability and the vibration behavior of the fuel plates were investigated. The long-term behavior of the fuel element was tested for 60 days (the designed 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 yield 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 4.8 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 full power 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 high 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, France. 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 5). In contrast to that a sudden strong 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 confirmed by the hydraulic tests and 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 6) 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 [3] 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 [4]. 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 ([5], [6]) and tested against the results of the microscopic

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

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.%. Therefore, both fuels are qualified for the use in the FRM-II.

In addition to these tests the TUM established the "OSIRIS test program" in 1999 in order to gain additional information concerning the irradiation behavior of high-enriched high-density U_3Si_2-Al-fuel. Within the scope of this program it was planned to irradiate two plates until fission densities comparable to or somewhat higher than those at the end of a cycle of the FRM-II [2] were reached. One of the two plates – the so called "Homogeneous Plate" – contained fuel with an uranium density of 3.0 gU/cm^3 and was irradiated until a maximum fission density of about 8 × 10^{21} f/cm^3 was obtained in the fuel-particles. The second plate – the so called "Mixed Plate" – contained fuel in two zones with different uranium densities and was irradiated until maximum fission densities of about 10.4 × 10^{21} f/cm^3 in the 3.0 gU/cm^3-zone and of about 14.3 × 10^{21} f/cm^3 in the 1.5 gU/cm^3-zone were obtained [8].

The irradiation of the Homogeneous Plate (3.0 gU/cm^3) was finished in November 2000 and the results are given in figure 7 where the evolution of the thickness of the plate is shown [8]. As one can see the increase of the thickness is a roughly linear function of the fission density. The results of this part of the OSIRIS program confirm the statement made after the PIE (see section above): U_3Si_2-Al-fuel exhibits a stable swelling behavior up to fission densities of at least 8 × 10^{21} f/cm^3. As we will see later this is even true for much higher fission densities.

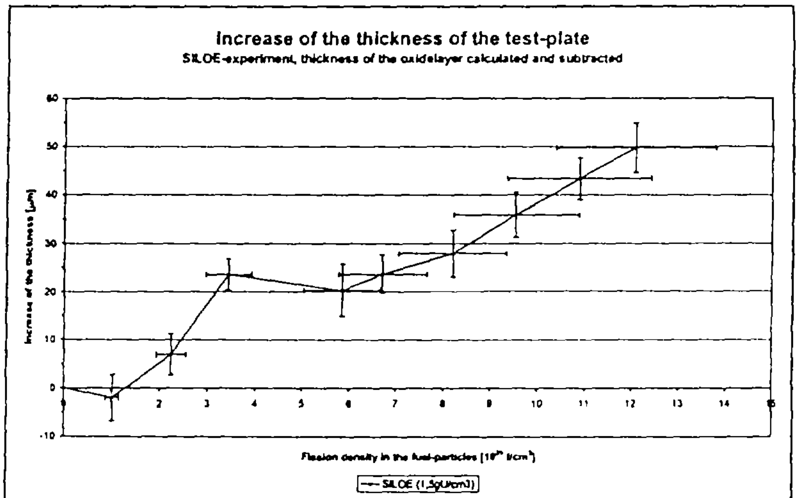

Figure 5: Increase of the thickness of the test-plate with an uranium density of 1.5 gU/cm^3 as a function of the fission density in the fuel-particles. The thickness of the oxidelayer has been subtracted. The error bars for the thickness measurement represent the statistical error obtained from taking 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 [7]. 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 6: Picture of a U_3Si_2 particle in the Al matrix, 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 in the particle 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 [4].

Because of a slightly different irradiation schedule and because the fission densities aimed at were extended to higher values, the Mixed Plate was irradiated until March 2001. The maximum fission density reached in the fuel-particles was 10.4×10^{21} f/cm^3 in the 3.0 gU/cm^3-zone and 14.3×10^{21} f/cm^3 in the 1.5 gU/cm^3-zone. Figure 8 shows the evolution of the thickness of the Mixed Plate measured in the "transversal" direction, i. e. across the border between the zones with the different uranium densities. The difference in the swelling of the two zones is clearly visible and it can be stated that the density grading has no negative impact on the swelling behavior of the fuel [8].

The discussion concerning a reduction of the enrichment

As explained in the first section of this paper the performance of the FRM-II is to a large extent related to the use of high-enriched uranium (HEU). This enables the "compact core concept" yielding a very high neutron flux in conjunction with a low thermal power of the reactor. It goes without saying that the peaceful use of HEU is in agreement with all international laws and in particular with the non-proliferation treaty. International safeguards experts of the IAEA and of Euratom rule out any realistic possibility of diversification or undeclared use of the material.
Nevertheless, the German Federal Government expressed the concern that using HEU in the FRM-II could initiate the danger of proliferation worldwide. In March 2001 the Federal Cabinet fixed the standpoint for its negotiations with the Bavarian State Government: it agreed to put the FRM-II into operation with HEU, but parallel to the routine use a new fuel element with identical geometrical dimensions containing MEU (Medium Enriched Uranium)

should be developed. After designing, qualification and licensing of this fuel element, the FRM-II should be converted to MEU.

In general, such a conversion follows a scheme like this: The reduction of the ^{235}U-enrichment can be compensated by a higher uranium density in the fuel meat so that the ^{235}U-mass remains at least the same.

In case of the FRM-II a conversion according to this scheme is not possible. Because of the high density of the fuel (3.0 gU/cm^3) the margin for an increase of the density is very small. For this reason a conversion to LEU would only be possible with an increase of the core size and would therefore lead to a reduction of the neutron flux by 25 % or more. In addition it would be necessary to re-design and to re-build the whole moderator tank. These impacts on the reactor and on the performance of the reactor are not acceptable. The only compromise would be to reduce the enrichment as far as possible without a change of the outer geometry of the fuel element. In this case the reactor itself can remain unchanged and the penalty concerning the neutron flux would be smaller. The practical values depend on the fuel which can be used: with the qualified U_3Si_2-Al-fuel (uranium density 4.8 gU/cm^3) a penalty of about 4 % may be realistic. If one could use the new UMo-Al-fuels (uranium density up to 8.5 gU/cm^3) that are under development at present a somewhat lower enrichment could be reached. The penalty concerning the neutron flux will then be of the order of 8 %. In any case an extensive development and test program would be necessary in order to qualify the fuel for the use under FRM-II conditions.

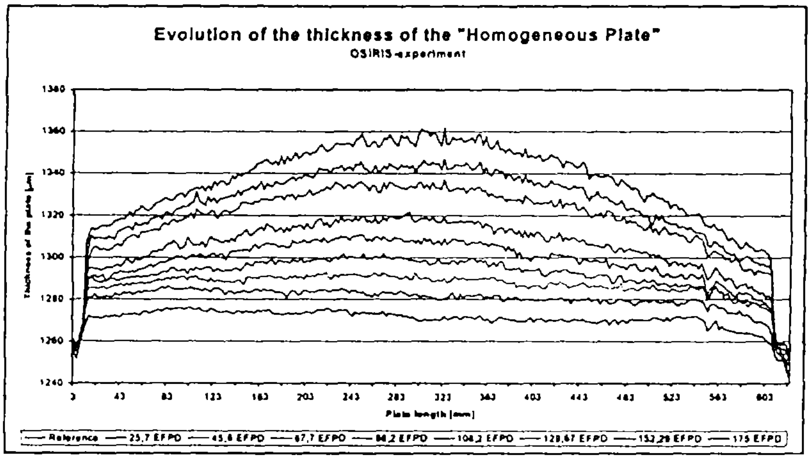

Figure 7: Measurements after each reactor cycle of the thickness of the "Homogeneous Plate" that contained fuel with an uranium density of 3.0 gU/cm^3 in the fuel meat. It is clearly visible that the curves are nearly equidistant, i. e. that the plate is in the stable swelling stage [8].

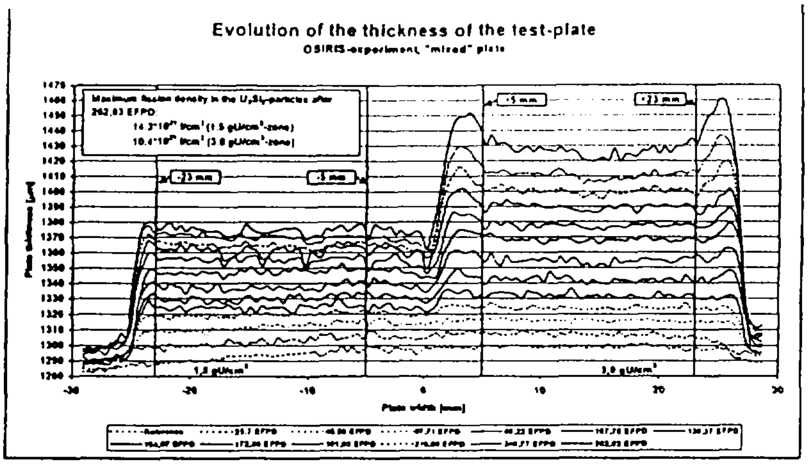

Figure 8: Measurements after each reactor cycle of the thickness of the "Mixed Plate" in the transversal direction, i. e. perpendicular to the border between the areas containing fuel with an uranium density of 1.5 gU/cm^3 and 3.0 gU/cm^3, respectively. The fission densities reached are considerable high (see insert in the figure). Due to the fact that the different curves are nearly equidistant it can be stated that the plate is in a stable swelling stage and that the grading of the uranium density has no impact on the swelling behavior of the fuel plate [8].

Status of the FRM-II project

The first design considerations of the Technische Universität München (TUM) started before the year of 1980. The FRM-II project team of the TUM was established in 1987, after the project had gained the necessary support. After positive statements e. g. by the "Wissenschaftsrat" (a German scientific advisory committee) the safety report was prepared together with the general contractor Siemens/KWU (now Framatome ANP). In February 1993 TUM and Siemens applied for the nuclear license which in the case of the FRM-II was split into three partial licenses. The first partial license which also contained a provisional positive assessment concerning the reactor was granted by the licensing authority (BStMLU) in April 1996, the second partial license (including the completion of the whole reactor facility as well as the cold start-up) in October 1997.

In May 2003 the TUM obtained the third partial license (that includes the operational license). Immediately after the granting of the license the nuclear start-up has started. The whole start-up procedure that includes a test-run of about one reactor cycle will take about three quarters of a year. Afterwards the routine use will start.

Pictures

Figure 9 shows a view of the experimental hall with the structure of the reactor pool, figure 10 a view of the neutron guide hall. In figure 11 one can see the reactor hall and the open surface of the pool. In figure 12 a view of the pool and onto the top part of the moderator tank is shown. Figure 13 shows an overall view of the plant. Finally, in figure 14 one can see the reactor building with the entrance building and the main entrance of the FRM-II.

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[8] **Nuding, M.; Böning, K.**: „Bericht über das Brennstoff-Bestrahlungsexperiment am OSIRIS-Reaktor"; Report-Nr. OPA 297; Technische Universität München, ZBE FRM-II-Bau; April 2002.

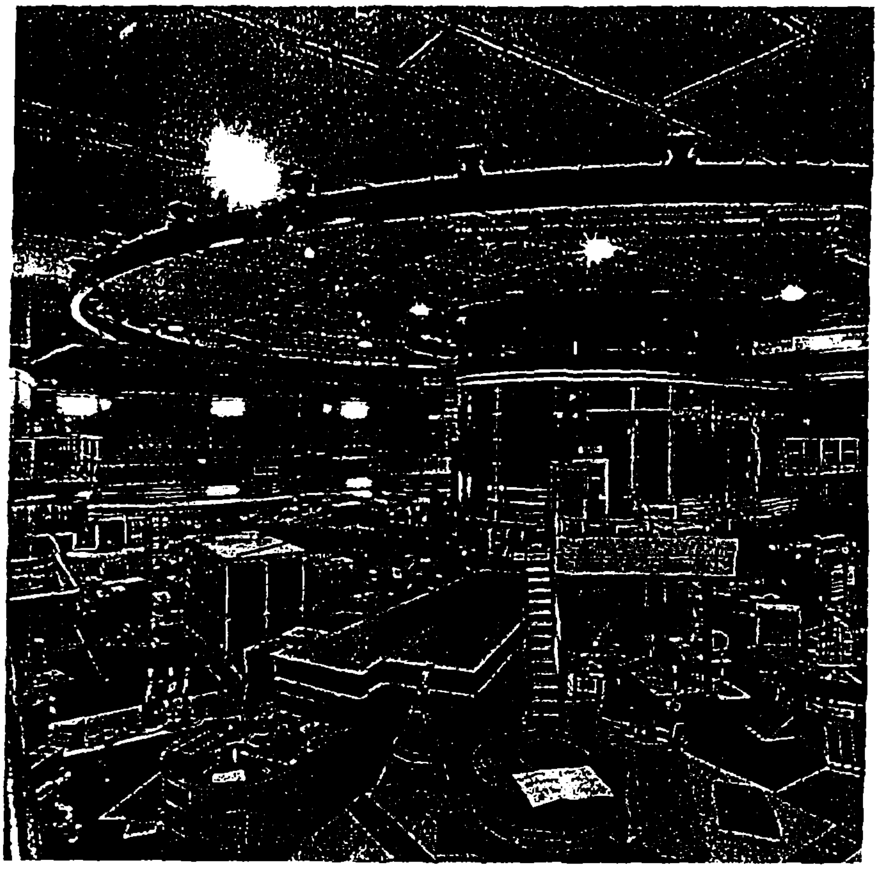

Figure 9: View of the experimental hall of the FRM-II. In the center one can see the react pool and – in the background – the storage pool. The picture was taken in September 2002.

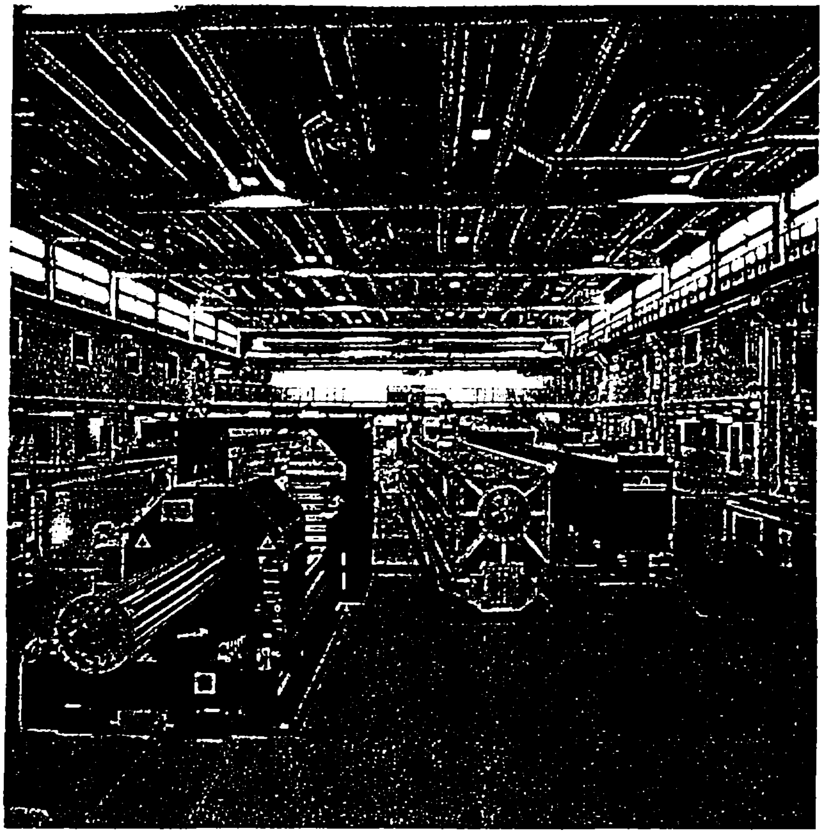

Figure 10: View of the neutron guide hall of the FRM-II. The picture was taken in September 2002.

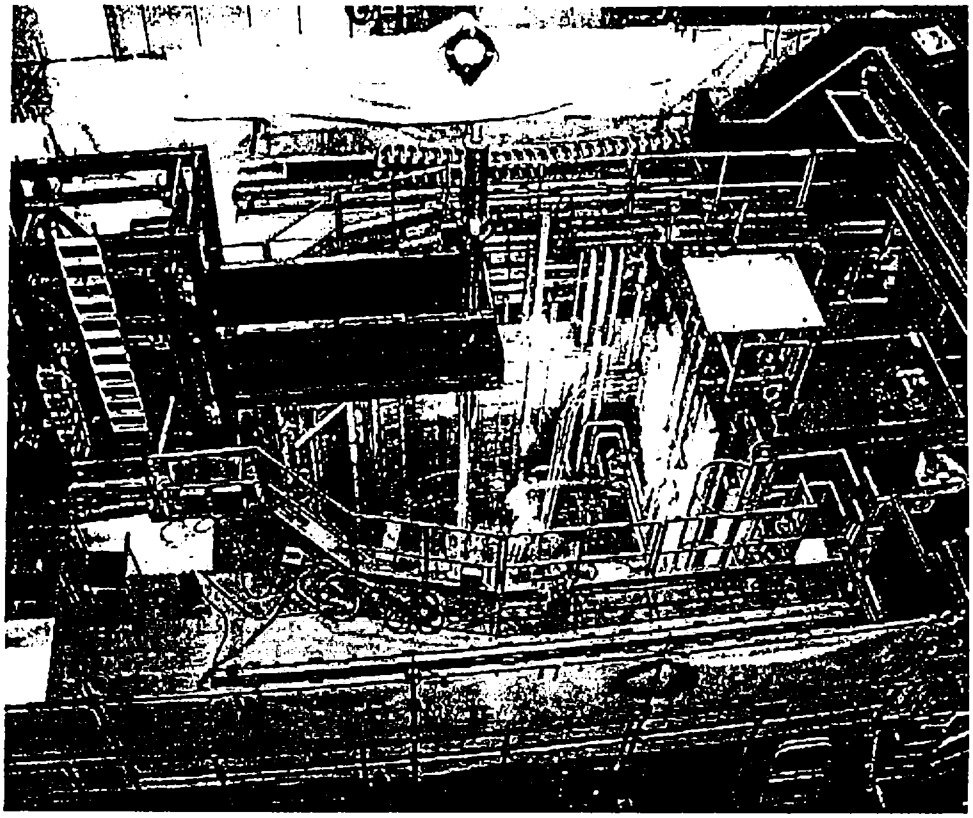

Figure 11: View of the reactor hall. One can see the reactor pool in the center which is not completely filled with water. The storage pool is located on the right and separated by an aluminum door. The picture was taken in March 2001.

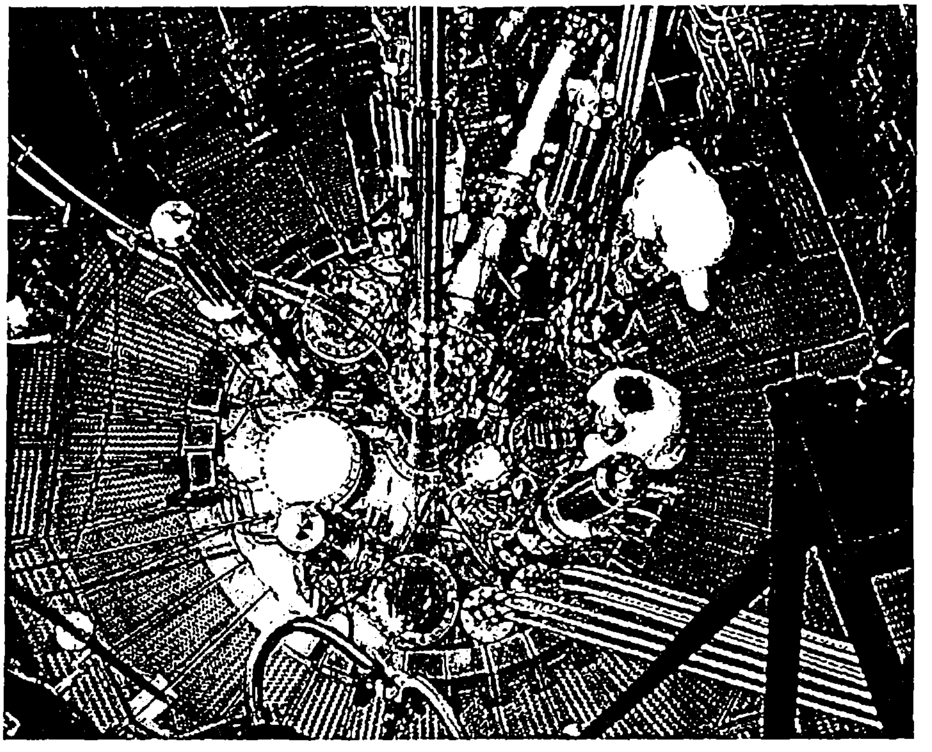

Figure 12: This picture shows a view onto the "support-structure" at the top of the moderator tank. This structure is located about 2 m above the tank itself. In the center of the picture one can see a part of the primary circuit tubes and of the control rod drive. The drives of the five shutdown rods can be identified as well as some external tubes of the irradiation facilities. The picture was taken in February 2001.

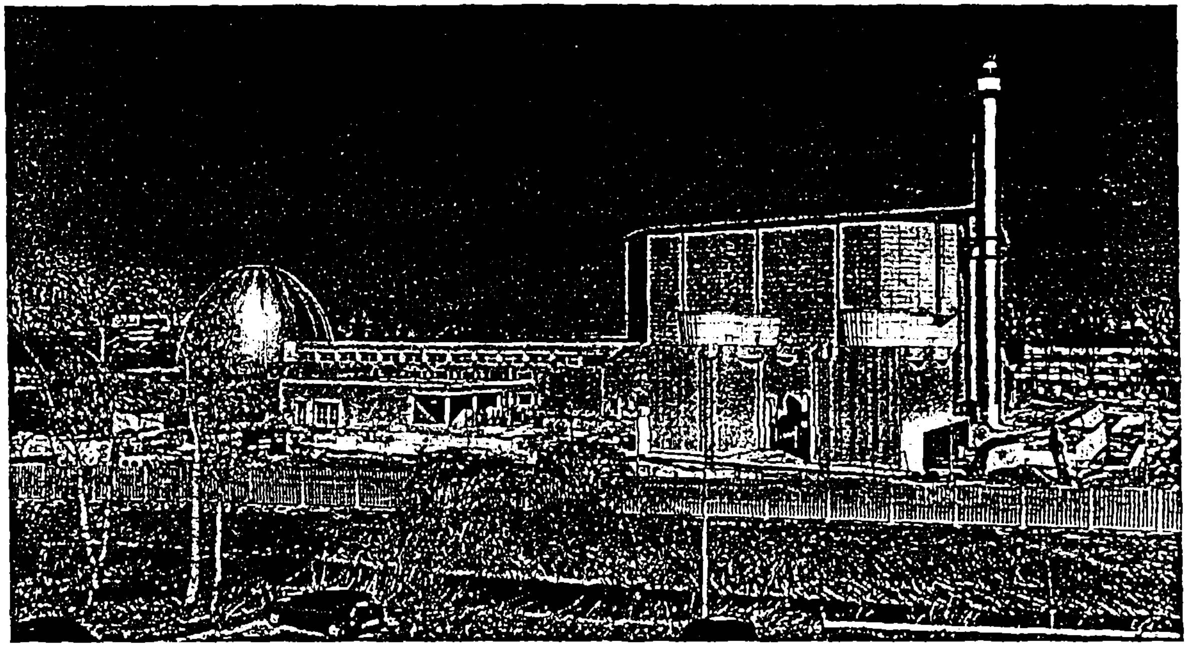

Figure 13: Look at the FRM-II facility. The reactor building (on the right) is 31 m high and has the cross-section of a square in the lower and of an octagon in the upper part. The old, shut-down FRM can be seen on the left hand side and the neutron guide hall in the middle. The picture was taken in March 2001.

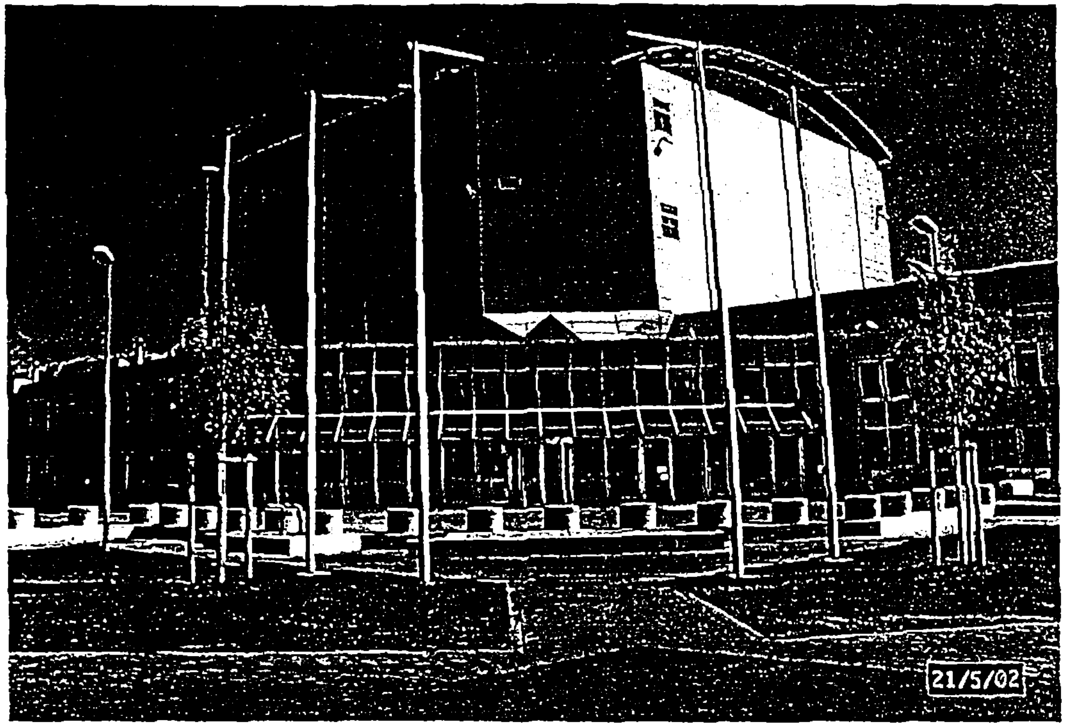

Figure 14: Look at the reactor building and the entrance building of the FRM-II facility. The picture was taken in May 2002.