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FRM-II: A new Reactor also for Isotope Production

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SUMMARY. The "Forschungsreaktor München II" (FRM-II) is a multipurpose research reactor which is being built by the Technical University of Munich and which will be available in 2001. Its single fuel element reactor core being operated at 20 MW thermal power will be installed within a heavy water moderator tank. Besides the well thermalized neutron spectrum this design provides the particular advantage that the maximum of the flux density ($\Phi_{th} \approx 8\times10^{14}$ $cm^{-2}s^{-1}$) will be located outside of the core volume and thus be available for experimental purposes. The FRM-II will mainly be used for beamtube experiments; in addition, however, it will be equipped with various irradiation facilities among these a pneumatic dispatch system and an automatically operated fast pneumatic dispatch setup for the investigation of short-lived isotopes. A hydraulic dispatch system will offer the possibility of high dose irradiations. Finally the FRM-II will be equipped with a silicon doping facility to be operated on an industrial scale. Optionally the corresponding irradiation channels will also be available for the insertion of a rotating sample holder or the irradiation of voluminous specimens.

1. INTRODUCTION

Since almost 40 years the Technical University of Munich (TUM) is operating the "Forschungsreaktor München" (FRM), a light water moderated 4 MW swimming pool reactor of the MTR-type. Among other purposes like the education of students or systematic investigations in the field of neutron scattering the conduction of irradiation experiments for the benefit of basic research and industrial applications is an important task of the FRM. This statement is supported by the number of more than 53,000 irradiations which have been conducted at the FRM so far.

With respect to today's requirements regarding the neutron flux density and the neutron spectrum, however, the FRM is under certain aspects not competitive any more. Therefore the Technical University of Munich has designed a new reactor - the "Forschungsreaktor München II" (FRM-II) - which is being built presently in close vicinity to the FRM. The main purpose of the FRM-II is the supply of neutrons for beamtube experiments. On the other hand, however, it will be equipped with various irradiation facilities which will cover a broad band of potential irradiation requirements.

The FRM-II is under construction since summer 1996. According to the present schedule it will be available for first experiments in 2001.

2. GENERAL DESIGN OF THE FRM-II

The central component of the FRM-II is a very compact single fuel element core containing approximately 8.1 kg of high density uranium silicide fuel contained in an aluminum dispersion. The U-235 enrichment is 93%. The reactor will generate a thermal power of 20 MW.

Geometrically the core is designed in form of two concentric cylinders with inner and outer diameters of 113 mm and 243 mm, respectively, and an active height of 700 mm. A total of 113 identical fuel plates being curved to involute shape are welded between the concentric cylinders thus providing cooling channels of a constant width of 2.2 mm. In order to limit the power density in the vicinity of the outer periphery of the core the fuel density within each plate is reduced steplike at a radius of 105.6 mm from 3 g/cm^3 in the inner region to 1.5 g/cm^3. For the same purpose the bottom part of the fuel element is equipped with a boron ring acting as a burnable poison.

The fuel element of the FRM-II is designed to be placed in a vertical core channel tube which separates the light water cooling circuit from the heavy water moderator tank surrounding the core. The cooling water will be taken from the light water reactor pool and pumped downwards through the core at a flow rate of approximately 1000 m^3/h. The corresponding temperature increase of the coolant is estimated to be about 15 K.

The FRM-II reactor will be controlled by a single hafnium control rod which will be moved within the inner tube of the fuel element. The lower part of the control rod is connected to a beryllium follower. The Hf-rod can be decoupled from the control rod drive mechanism to fall down and act as a fast shutdown system. A diverse and redundant fast shutdown system is provided by five hafnium rods which are fully withdrawn during reactor operation. Four of the five hafnium shut down rods suffice to shut down the reactor even in the hypothetical case that the control rod would totally move out of a fresh fuel element. In addition the compact core design offers pronounced inherent safety features which would make the reactor subcritical under all postulated severe accident conditions.

As mentiond above the FRM-II reactor core is embedded within a large heavy water moderator tank which is cylindrical in shape with equal height and diameter of 2.5 m. After generation more than 70% of the fast fission neutrons are leaking into the moderator tank where they are thermalized. Consequently, the maximum of the thermal neutron flux density is located outside the reactor core. Thus it is in a position which is available for experimental purposes. Its numerical value has been calculated for undisturbed conditions, i.e. neglecting the influence of the beamtubes and other moderator tank installations, to be about 8×10^{14} cm^{-2}s^{-1}. It is noteworthy that the corresponding flux density of fast neutrons (E>0.1 MeV) is lower by a factor of roughly 1000. A sketch of the thermal neutron flux profile is given in Figure 1. The FRM-II will be operated in fuel cycles of approximately 50 days at full reactor power. It is scheduled to offer 5 cycles per year after each of which the fuel element will have to be changed.

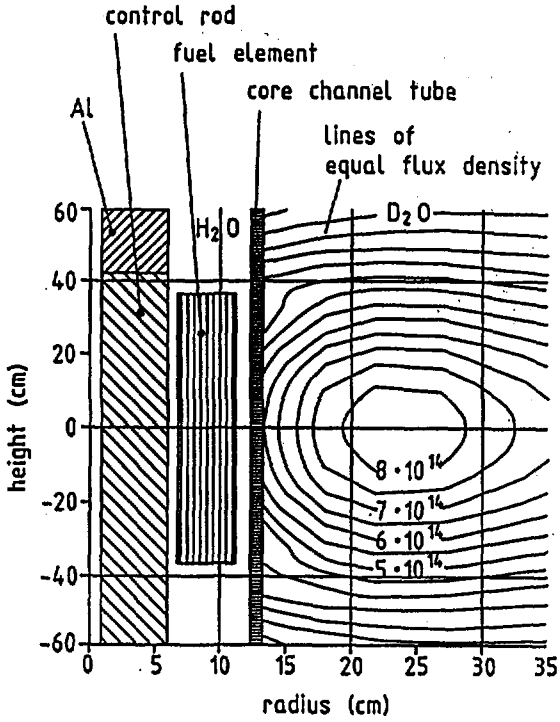

Figure 1. Lines of equal thermal neutron flux density (given in cm^{-2}s^{-1}) in the vicinity of the FRM-II reactor core. Note that the maximum flux density is located outside the core volume within the moderator tank.

The concept of the FRM-II and its compact core is described in more detail in (1,2,3,4).

3. IRRADIATION FACILITIES

The FRM-II will be equipped with a variety of irradiation facilities offering very flexible irradiation conditions. In particular important parameters like the neutron flux density, the integrated neutron fluence or the size of specimens can be varied in a wide range. All of the irradiation positions offer an almost pure thermal neutron spectrum characterized in addition by a low γ-heating. In addition to the setups for material irradiation the FRM-II will be equipped with a facility for the cancer therapy by fast neutron irradiation.

The irradiation service of the FRM-II will be open for interested parties from universities, research institutes and industry as well. In particular the silicon doping and eventually the isotope production for applications in medicine and technique is scheduled to be carried out on a commercial base.

In the following sections some of the various irradiation setups will be presented in more detail.

3.1 Pneumatic dispatch facility

The pneumatic dispatch facility is assigned to the short term irradiation of small specimens. One of its major tasks will be to provide samples for neutron activation analysis or tracer experiments. Since the neighbouring institute for radiochemistry of the TUM is one of the most important users in these fields of science it will be connected to the unloading station of the irradiation facility by means of an underground transportation tube allowing the fast and easy delivery of specimens. The corresponding data will be sent simultaneously via a computer network.

The facility will consist of six independent irradiation channels being arranged in two bundles. The corresponding irradiation positions are located within the heavy water moderator tank in a distance of 550 mm (1. bundle) and 700 mm (2. bundle) from the central axis of the cylindrical reactor core. According to their different height coordinates the six irradiation channels will offer thermal neutron flux densities between 5×10^{12} $cm^{-2}s^{-1}$ and 2×10^{14} $cm^{-2}s^{-1}$. All of the near core installations will be manufactured from AlMg3, a low activation and easy machinable material. The facility will be suited for specimens with a maximum volume of 13 cm^3 which will be contained in polyimide capsules (diameter $\approx$ 24 mm, length $\approx$110 mm) during irradiation. This material offers the particular advantage of negligible activitation and temperature stability up to more than 100°C whereas according to finite element calculations even under saturation conditions the empty capsule is heated by about 5 K only due to ß- and γ-radiation. On the other hand because of radiolysis the maximum applicable dose is limited by the capsule material to approximately 10^{18} cm^{-2}.

A separate control and handling room for the pneumatic dispatch facility will be available in the reactor building. It will contain the two central components of the facility, namely the control computer and the pneumatic system. The latter will consist of the gas supply, a blowing machine, the connecting tubes between the handling room and the irradiation positions and two glove boxes containing the setups for loading and unloading. High purity CO_2 gas was choosen for the operation of the entire pneumatic system because of its low activation properties and its chemical inertia. In order to avoid to load the system accidentally with an inacceptable excess presssure the necessary volume of gas for each transportation process will be supplied from two pressure vessels of 2 l (insertion of the capsule) and 8 l (extraction), respectively, both of which will be kept at 2.5 bars. The expansion of these pressure vessels will produce a pressure peak which will accelerate the capsule on its first meters to a velocity of about 10 m/s. For the remaining distance the capsule will be slided with constant velocity by the gas stream produced by the blowing machine. The loading and unloading devices for each irradiation channel will be arranged in a lead shielded glove box which will be a part of the pneumatic system. According to this design the entire handling of the specimens will be done in a controlled CO_2 atmosphere. Consequently the danger of a parasitic Ar-41 production due to the unintended irradiation of air being contained in the capsules is minimized. In addition due to the installation of the unloading device within a glove box any possible contamination by e.g. rupture of a capsule will be restricted to the irradiation facility alone. Finally a permanent contamination control is foreseen by means of an aerosol monitoring system being installed within the off-gas of the pneumatic dispatch facility.

In order to guarantee a proper function of the entire pneumatic dispatch facility a permanent computer control will be available. Besides the detection of general malfunctions like e.g. a loss of pressure or the input of humiditity into the pneumatic system a complete supervision of each irradiation specimen will be realized. For this purpose any movement of a capsule with respect to the loading and unloading device, the irradiation position or the decay position contained in each of the irradiation channels will be registered by means of a light barrier. A peculiarity of the control unit is the use of an acoustic sensor being mounted onto the irradiation tube outside the pool water which will register the strike of the specimen upon arrival at the irradiation position. The corresponding signal will indicate the begin of the exposure time. After accumulation of the desired neutron fluence the control computer will automatically initiate the return of the specimen from the irradiation position into the decay position or the unloading device.

The future demand for irradiations at the pneumatic dispatch facility was estimated by means of an analysis carried out at the present FRM to be about 500 irradiations per year. It is however supposed that the demand will increase after the FRM-II will be in routine operation. Therefore the facility was designed to allow a throughput of up to 5000 irradiations per year.

3.2 Hydraulic dispatch facility

In many respects the hydraulic dispatch facility is a complementary setup to the pneumatic system described above. It is, however, assigned to the long term irradiation of small and medium sized specimens ($V < 30$ cm^3). Like for all the facilities presented in this paper its irradiation position will be located within the heavy water moderator tank offering a thermal neutron flux density of about 4.5×10^{14} cm^{-2}s^{-1}. The corresponding γ-dose rate was calculated to be about 4×10^5 Sv/h. Two identical facilities will be used in parallel.

The general design of the hydraulic irradiation facility is schematically shown in Figure 2. The facility will be operated using light water from the storage pool of the FRM-II as transportation medium. The water will be circulated in an open circuit which will be driven from an instrumentation box containing a rotary pump, a regulation valve, a flowmeter and a bidirectional valve which allows to change the flow direction. This unit will be installed within a water-tight container to be mounted within the storage pool. The container will also be equipped with the inflow and outflow of the circulating water.

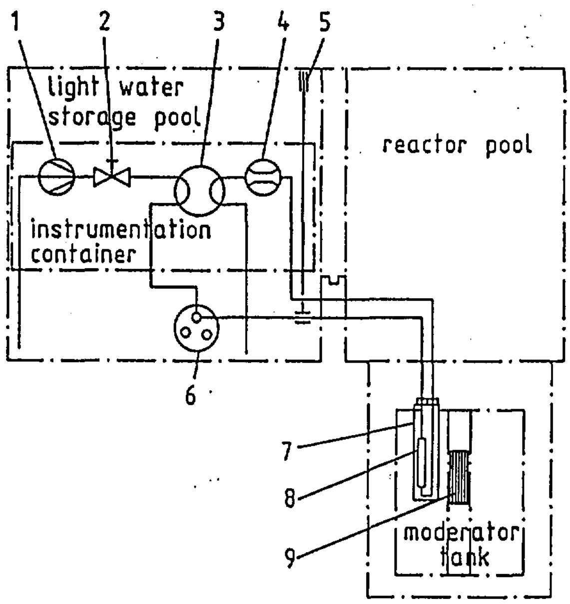

Figure 2. Operation scheme of the hydraulic dispatch facilty. The numbers indicate:
1: rotary pump, 2: regulation valve, 3: bidirectional valve, 4: flowmeter, 5: acoustic sensor, 6: loading and unloading device, 7: irradiation insert, 8: irradiation position, 9: reactor core

Samples will be manipulated from a handling platform being located at the rim of the storage pool. The loading and unloading device will have the form of a rotating cylinder offering three positions for insertion of specimens, transportation into the irradiation channel and extraction from the facility. For radiation protection reasons it will be located in a depth of about 2.5 m below the surface level of the pool. The loading capacity will allow the simultaneous irradiation of up to 5 specimens per channel. During exposure the samples will be contained in standard Al-capsules which are suitable for multiple use. Outside of the moderator tank two separate tubes will be available for the transportation of the capsules and the backflow of the circulating water. In contrast, within the heavy water tank both of the above tubes are combined to a single insert and the circulation is maintained in form of a concentric arrangement.

The control instrumentation of the hydraulic dispatch facility will be similar to the one for the pneumatic setup. Light barriers will be available in the loading and unlaoding device in order to register outgoing and incoming irradiation capsules and an acoustic sensor will be used for the proper registration of the irradiation start.

3.3 High flux pneumatic dispatch facility

The FRM-II will be equipped with a high flux irradiation facility being designed as a "medium-fast" pneumatic dispatch system. It will primarily be used for the neutron activation analysis of short-lived radioisotopes exhibiting decay times in the order of few seconds. Under standard conditions these isotopes will be activated up to saturation. Consequently the sensitivity of the measurement is directly correlated to the neutron flux density. Therefore the irradiation position of the facility will provide the highest available flux density, namely $\Phi \approx 6\times10^{14}$ $cm^{-2}s^{-1}$. Alternatively the same setup will be used for the high sensitivity detection of fission materials via delaied neutrons.

The main requirement for the facility is to guarantee a rapid delivery of the activated specimen to the measuring device. Consequently all handling will take place in the reactor building thus keeping the transportation lengths short and the delivery times below 2 s. In order to fulfil this request a capsule design of an outer transport capsule exhibiting a lateral slit and an inner sample holder containing the specimen has been developed. Upon arrival at the measuring position the route of the transportation tubes is curved in a way that will lead to the automatic separation of both capsules by means of the centrifugal force. Finally the sample holder containing the specimen will be slowed down dynamically by transformation of transversal into rotational kinetic energy, and it will be stopped softly at the measuring position which of course will be lead shielded in order to minimize the background radiation. Simultaneously a light barrier will start the measurement.

For the construction and operation of the high flux facility mostly the same materials will be used as for the standard setup, i.e. the irradiation insert will be manufactured from AlMg3 and CO_2 will be used for the transportation. The irradiation insert within the moderator tank, however, will be constructed in form of a thimble. Thus light water from the pool will be used as coolant. The transport capsules will be made from polyimide. They will, however, be rectangular in shape in order to guarantee a fixed geometry for the separation of the inner sample holder. In addition this design guarantees the abrasion from the capsule to be small even in case of high velocities.

3.4 Silicon doping facility

The neutron transmutation doping (NTD) of silicon [$\text{Si-30 (n,}\gamma\text{) Si-31} \xrightarrow{\beta} \text{P-31}$] is an application of the FRM-II which will be carried out on an industrial scale. The reactor will offer two irradiation channels for the NTD of Si crystals with diameters of up to 4" and up to 8", respectively. All of the crystals are supposed to be 500 mm in height. The total doping capacity of both channels is scheduled to be approximately 10 t/year.

Each of the irradiation channels will be installed in a vertical tube. In order to achieve the required high homogeneity of the doping profile the crystals will be moved twice through the irradiation channel while they will be rotated with respect to their central axis. The lead of the resulting helical motion will be matched to the vertical gradient of the neutron flux density. The desired doping concentration can be controlled in a wide range via the velocity of the vertical motion: The minimum exposure time is about 3 minutes corresponding to a P-doping of 7×10^{13} cm^{-3}. On the other hand there is no upper limit for the exposure time from the engineering point of view.

The axial distance of the irradiation channels from the fuel element will be approximately 1 m. In this distance even the introduction or extraction of large Si crystals is estimated to change the reactivity of the reactor by 0.05% only. Moreover the change in reactivity will be slow enough that it can be compensated by the reactor control. In addition the crystals will be subject to a heat load the maximum value of which will be approximately 6.7 kW for an 8" specimen contained in an AlMg3 transportation cask. This heating power will be dissipated to the light water from the reactor storage pool to be used as coolant. The corresponding power density at the crystal surface is calculated to be about 1 W/cm^2. Thus at a constant flow rate of 0.2 l/s the cooling water will be heated by 8 K only.

It is evident that the loading and unloading of the Si doping facility will be possible at full reactor power. The entire handling of crystals to be doped will be done remotely by means of handling tools which will be installed on a movable bridge spanning over the reactor pool.

Finally it has to be noted that the silicon doping facility can be used for other purposes too. Alternatively a rotating sample holder suitable for the irradiation of a large number of small specimens under identical conditions can be inserted into its irradiation channels. A further application will be to provide an irradiation position for large volume specimens or in particular for liquids.

4. STATUS OF THE PROJECT

The project group FRM-II of the Technical University of Munich is working since 1987. The application for a nuclear license was submitted in 1993 after the general concept of the reactor and the safety analysis report had been worked out in collaboration with the company Siemens/KWU (the former Interatom) which was appointed general contractor for the construction of the FRM-II in 1994. In 1996 the first partial nuclear license was granted covering the acceptance of the safety concept, site development and construction of the reactor building.

Right now the project group FRM-II and Siemens/KWU are working out the detailed design documents for the installation of all components of the reactor facility. It is expected that based on these documents the second step of nuclear licensing will be awarded by the German authorities still in 1997.

The third and final partial nuclear license will cover the full reactor operation and is estimated to be obtained in 2001. The nuclear start up will be followed by a 50 days test run at full power and finally by routine operation.

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