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Thermohydraulic and Mechanical Analysis of the Research Reactor Munich II Compact-Core

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Abstract

The new research reactor Munich II (Forschungsreaktor München II, FRM-II), which is under construction at the Technical University of Munich, Germany, contains a compact reactor core consisting of one single fuel element, assembled by two concentric tubes between which 113 involutely bent fuel plates are located rotationally symmetric.

In order to perform the hydraulic and mechanical testing of the FRM-II fuel element, two test facilities have been built at the Department for Nuclear and New Energy Systems of the Ruhr University Bochum.

The first mocks up the central region of the reactor coolant system of the FRM-II in a 1:1 scale with emphasis on the fuel element and the inflow and discharge section in order to enable the analysis of the FRM-II core.

In the course of the testing the vibration behaviour and the flow resistance of the core were investigated. Likewise start-up and shut down tests of the main pump unit were simulated and the flow profile at the outlet of the element as well as the flow division inside the core were determined. Furthermore an endurance test lasting 60 days (equivalent to 1.2 operating cycles) was performed, too.

Tests including blockages of parts of the reactor cooling system cross section at the core entrance sieve proved the efficiency of the cooling capacity. No major resonances occured during operation and an endurance test neither showed any incidents nor irregularities.

In order to investigate the concept of the decay heat removal in the FRM-II a second test facility was built. This facility simulates the thermohydraulic conditions in one cooling channel of the FRM-II by means of an electrically heated test section, which enables different operating conditions of the decay heat removal system as well as enhanced safety investigations.

In the FRM-II the decay heat, which is produced after a shutdown, is removed by means of decay heat removal pumps, which maintain a downward flow in the fuel element for at least three hours. After the coast down of the decay heat removal pumps, the remaining part of the decay heat can be given off to the water in the reactor pool by means of an upwards directed natural convection flow.

Results gained so far have proved the feasibility to cool the fuel element by natural convection both at normal operation of the active decay heat removal system and in case of a complete loss of the decay heat removal pumps. This experimental sequence is expected to be finished by August of 1998.

1 The Concept of the FRM-II

At the Technical University of Munich (TUM) an efficient high flux neutron source, the research reactor Munich II (Forschungsreaktor München II, FRM-II), is built. In order to provide a maximum neutron flux density of $8{\cdot}10^{14}$ n/(cm^2·s) at a thermal power of 20 MW a new compact reactor core was designed, consisting of a single fuel element which is cooled by light water and surrounded by a heavy water moderator. Figure 1 shows a sectional view of the FRM-II reactor building.

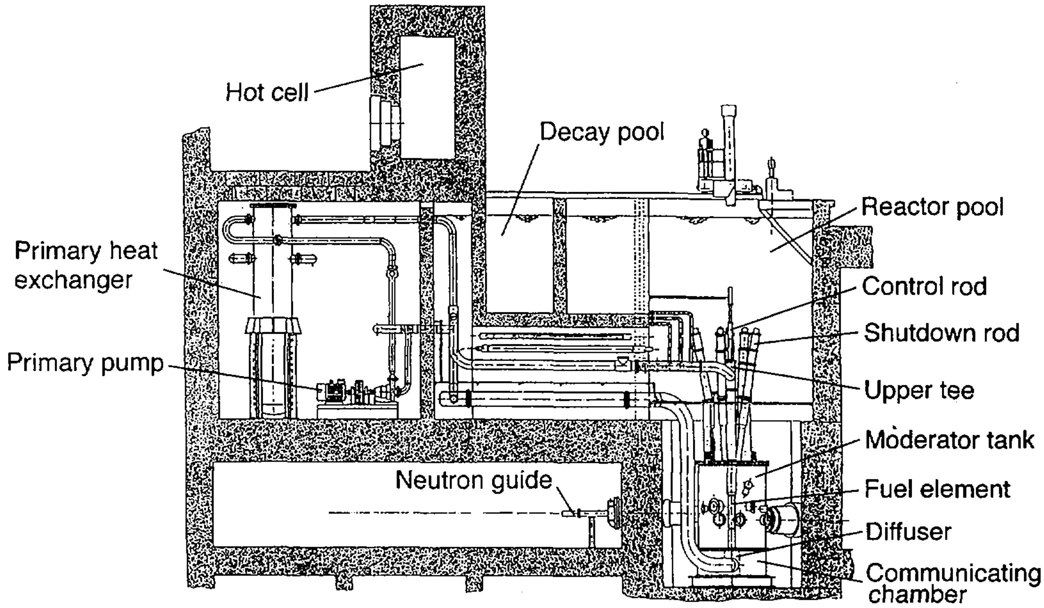

Fig. 1: Sectional view of the FRM-II reactor building (Source: Siemens KWU)

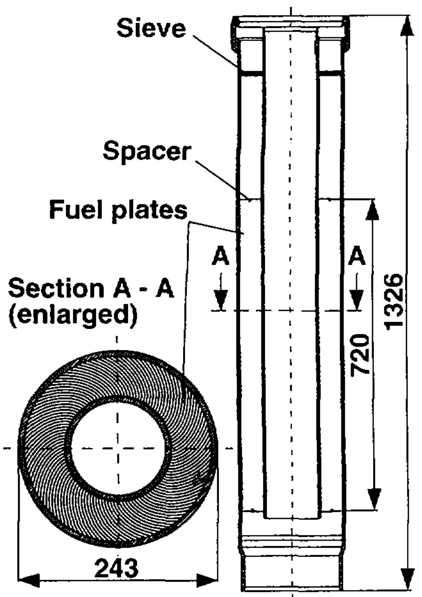

Fig. 2: *Longitudinal and cross section of the fuel element*

Figure 2 shows a longitudinal and a cross section of the fuel element. The fuel element itself consists of two concentric tubes between which 113 involutely bent fuel plates are situated rotationally symmetric. Each plate has a thickness of 1.36 mm and a length of 720 mm. Between the plates, cooling channels with a width of 2.2 mm are formed. At the ends of the fuel plates two annular spacers are situated, which reinforce the inlet and the outlet of the plate zone.

During normal reactor operation the thermal power is removed by a volumetric cooling water flow rate of 300 l/s, which flows downwards through the cooling channels of the fuel element. The velocity of the light water in the cooling channels during this mode of operation is 17.4 m/s. After a shut down of the reactor cooling pumps are started by the reactor safety system, which provide a volumetric cooling water flow rate of 60 l/s, reducing the velocity in the cooling channels to 3.2 m/s. In order to remove the main part of the decay heat the cooling pumps run for at least three hours. After the coast down of the cooling pumps the flow in the reactor cooling system stops and so called "natural convection flaps" are opened by their own weight, providing a connection to the reactor pool. Through this flow path the remaining part of the decay heat can be given off to the water in the reactor pool by means of an upwards directed natural convection flow.

2 Analysis of the Fuel Element

A water test facility was built at the Ruhr-University of Bochum, at the Department for Nuclear and New Energy Systems, which mocks up the central region of the reactor coolant system of the FRM-II. The objectives of the tests performed are the verification of the hydraulic design of the FRM-II compact core, the proof of the feasibility of the core cooling in case of a partly obstructed fuel element sieve and the verification of the fatigue strength of the fuel element by means of an endurance test.

The vibration behaviour and the flow resistance of the fuel element are investigated. Start-up and shut down tests of the primary pumps are simulated and the flow profile at the outlet of the element is measured also. Furthermore the flow division between the fuel element and the central control rod respectively the surrounding central channel tube is analysed. An endurance test and hydraulic and mechanical calculations complete the test program.

2.1 The FRM-II Fuel Element Test Facility

The FRM-II fuel element test facility mocks up the reactor cooling system between the upper tee above the fuel element and the diffuser in the lower communicating chamber. The mock up of the fuel element itself differs from the original just in the use of depleted instead of enriched uranium. The inflow and discharge section, the central control rod as well as the hydraulic circumstances match exactly those of the research reactor, therefore the results gained with the test facility can be applied directly to the environment conditions of the FRM-II.

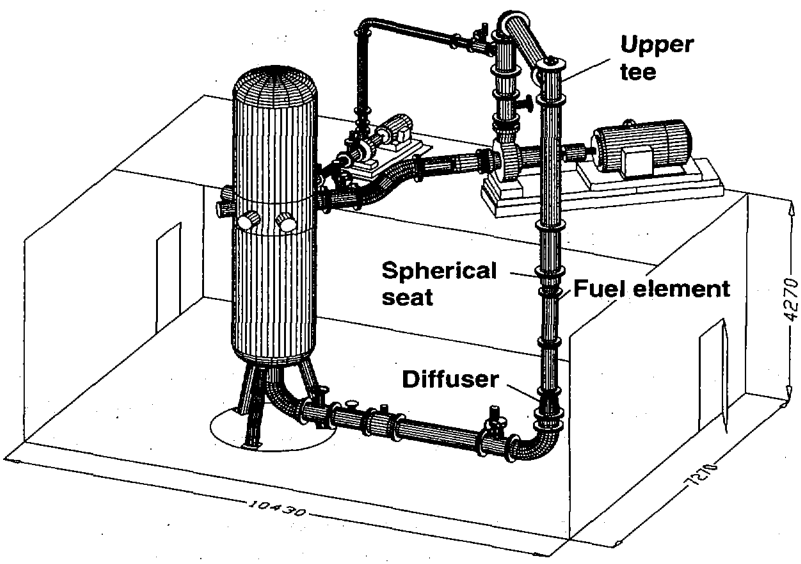

Fig. 3: Test facility for the hydraulic and mechanical analysis of the FRM-II fuel element

Under operation the FRM-II fuel element is driven at a nominal cooling water flow rate of 300 l/s. Despites the realisation of all running conditions of the FRM-II, the test facility enables flow rates up to 425 l/s which coincides with an increase of the flow rate by a factor of sqrt(2) and therefore double the hydraulic load.

Figure 3 shows an overview of the test facility. Beginning at a storage tank with a volume of 10 m^3, two pump units lead parallel to the test section. The flow through the test section ist directed downwards from the upper tee to the diffuser in the lower communicating chamber. The fuel element is situated in a spherical seat, corresponding to the situation in the FRM-II.

The two alternative pump units used enable flow rates up to 60 l/s corresponding to the decay heat removal respectively up to 425 l/s. After leaving the test section the water is led back horizontally into the storage tank.

2.2 Tests Performed and Results

The vibration measurements in operating conditions are performed with two accelerometers, one placed in the upper region of the fuel element at the spherical seat and the other at the lower edge of the element on the outside of the central channel tube. The tests are carried out at flow rates up to 360 l/s. Due to the lack of space it is impossible to place accelerometers inside the fuel element. By the use of preliminary experimental modal analysis the possibility to measure the vibrations of the fuel element at the outside of the central channel tube was proved.

As an example, Figure 4 shows the acceleration level depending on the frequency for different flow rates measured at the spherical seat. It increases with increasing flow rates while the qualitative vibration behaviour in relation to the frequency is maintained. No local maxima of a heigth sufficient to indicate resonances could be recognized. During tests investigating the main pump run-up and shut down no major resonance regions could be measured either.

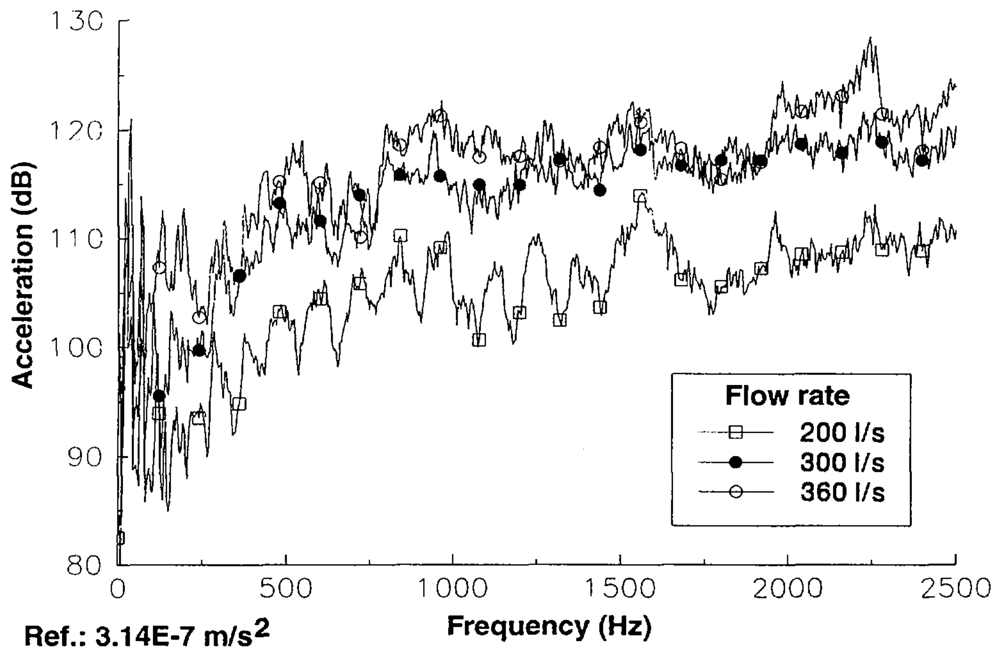

Fig. 4: Acceleration at the spherical seat

In order to investigate the pressure course inside the fuel element the static pressure was measured by the use of 12 pressure transducers located along the longitudinal axis of the fuel element. Figure 5 shows the pressure course measured at different flow rates varied from 200 to 360 l/s.

The pressure loss increases with increasing flow rates whereas the main pressure loss can be recognized at the sieve and at the inlet into the plate region respectively in the plate region itself.

The measurements concerning the flow division inside the element and the flow profile at the outlet of the fuel plates proved the feasibility of the core cooling. As an example, Figure 6 shows the total pressure measured at the outlet of the plate zone in case of a free sieve for a volumetric flow through the plate zone of 287 l/s.

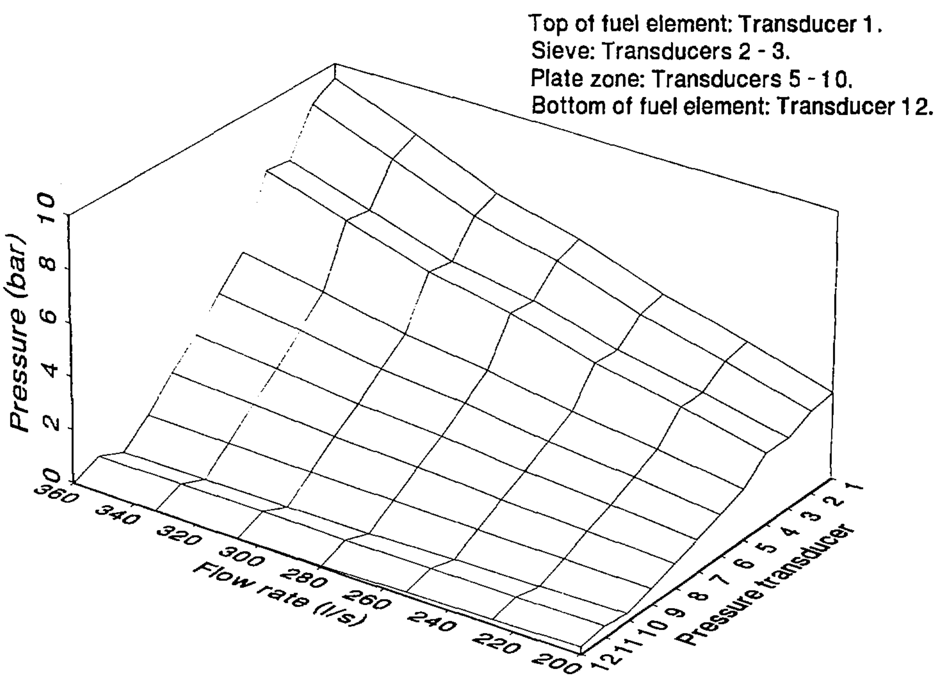

Fig. 5: Pressure course inside the fuel element

A pitot tube was conveyed below the plates in a straight line starting at the inner tube, so that each cooling channel was intersected at right angles. The exact position of the pitot tube can be determined by means of the radius and the angle displaced. In the region of the spacer, which is situated at half length of the channels, the pitot tube had to be removed from the plates slightly, therefore the measurements in this part do not show the exact total pressure. These measurements were performed at 113 straight lines both in case of free and of 90°-obstructed sieve.

All cooling channels are cooled equaly which is the same in case of free and of 90°-obstructed sieve. In the latter case the flow balances in the space between the sieve and the inlet into the plate zone so that the flow division in the plate zone remains nearly the same as in case of free sieve.

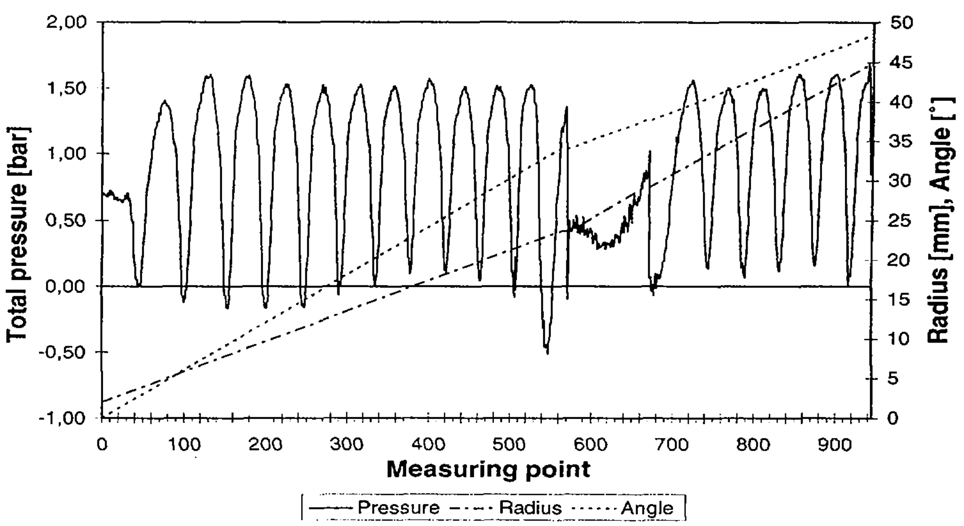

Fig. 6: Total pressure at the outlet of the plate zone

The endurance test was performed at a flow rate of 350 l/s for a period of 60 days whereas a nominal operating cycle of the FRM-II lasts 52 days. In the course of this tests no changes of the vibration behaviour could be investigated.

3 Analysis of the Decay Heat Removal

3.1 The FRM-II Decay Heat Removal Test Facility

In order to investigate the increase of the wall and the water temperatures as well as the appearance of pressure pulsations during the transition from forced to natural convection in the FRM-II-core, a test facility, which is shown in Figure 7, was built at the Department for Nuclear and New Energy Systems. The facility, operated with demineralized water, simulates the thermohydraulics of the FRM-II. It provides a pool water temperature of about 40°C and a pressure of about 2 bar at the lower end of the core. The core itself is represented by a test section, which simulates just one cooling channel of the FRM-II-fuel element. The test section, which has a sectional area of 2.2 mm x 35 mm, is located between two vessels, representing the amounts of water above and below the original fuel element. The difference in the hydraulic diameter of the test section compared with a FRM-II cooling channel is just 3%.

Two different flow circuits are to be realized in the test facility in order to simulate the downwards directed forced convection flow in the FRM-II-core on the one hand and the upwards directed natural convection flow on the other hand, which develops after the coast down of the cooling pumps. The decay heat, which is produced after a shut down of the FRM-II, is represented by heating the walls of the test section electrically, while the velocity of the forced flow is adjusted by means of a throttle valve in one pipe of the test facility. The processes during the coast down of the cooling pumps are simulated by opening a large by-pass to the throttle valve which causes an immediate breakdown of the driving pressure difference at the test section and a stop of the forced downward flow. Because of the heated channel walls in the test section, an upwards directed natural convection flow develops.

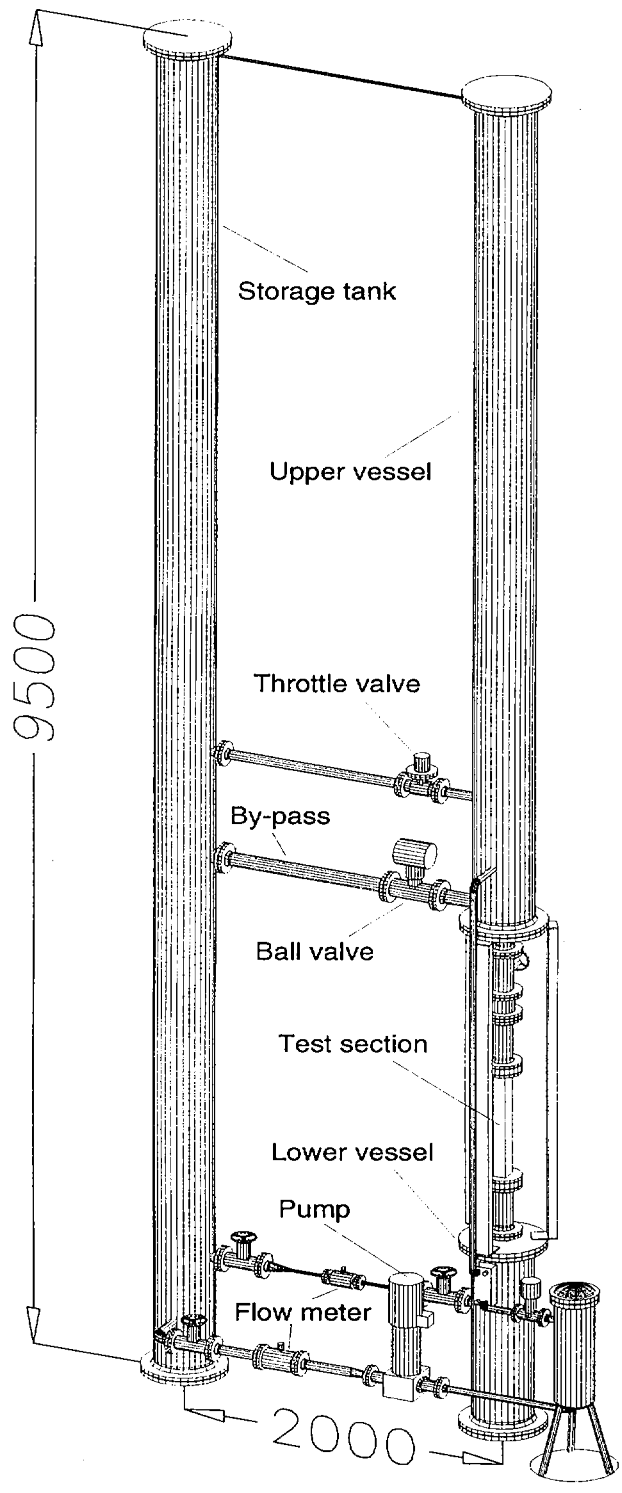

Fig. 7: Facility to investigate the decay heat removal in the FRM-II

During the test runs, the temperatures of the channel walls are registered at 12 different places by means of NiCr-Ni-thermocouples, while the water temperatures are detected at the upper and the lower end of the cooling channel by two Fe-CuNi-thermocouples. The amplitudes of the pressure pulsations in the cooling channel are measured by three pressure transducers, which are able to record pressure frequencies up to about 100 kHz. The membranes of the pressure transducers are situated in the plane of one cooling channel wall in order to detect the pressure pulsations immediately. The velocity and the direction of the flow inside the test section are registered by means of an inductive flow meter, while the heat flux in the channel walls is adjusted by a controllable transformer, which provides a direct current of up to 800 A.

3.2 Tests Performed and Results

Up to now experiments were performed, which simulated the transition from forced to natural convection in the core of the FRM-II both at normal operation of the cooling system and at a complete loss of this security device. The transition from forced to natural convection during the test runs is initiated 10 s after the data recording was started. In case of normal operation of the cooling system the cooling pumps run for at least three hours, so that the maximum axially averaged heat flux density, which has to be removed by natural convection after the coast down of the pumps, is 2.6 W/cm^2.
As shown in Figure 8, the flow in the test section remains single phased after the transition from forced to natural convetion in case of normal operation of the cooling system. No boiling processes, especially no pressure pulsations, appear at the given pressure, because the wall temperatures do not exceed 120°C.

If a complete loss of the cooling system occurs, none of the three cooling pumps will start working after a shut down of the reactor. In this case the entire decay heat has to be removed by natural convection, which means that the heat flux in the channel walls during the development of the natural convection flow is 10.6 W/cm^2. The test results displayed in Figure 8 and 9 show an increase of the wall temperatures up to about 150°C while in the middle of the test section maximum pressure pulsations with an amplitude of 0.2 bar at a frequency of about 15 Hz are registered.

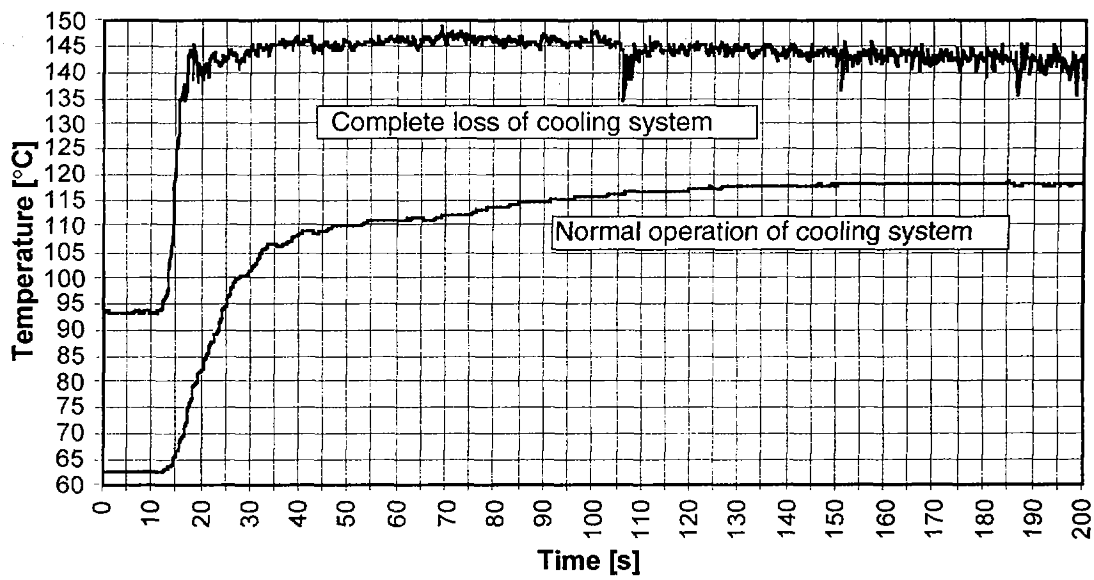

Fig. 8: Wall temperatures at the upper part of the heated zone during the transition from forced to natural convection

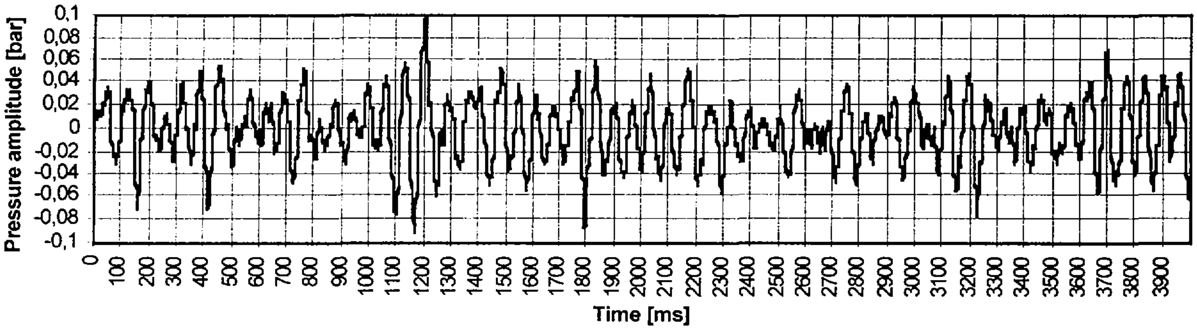

Fig. 9: Maximum amplitudes of pressure pulsations after the transition from forced to natural convection at a dead loss of the cooling system

These results proof the possibility to remove even the entire decay heat of the FRM-II by natural convection, because the detected thermal and mechanical loads of the channel walls represent no danger for the structure of the fuel element. Above that, the measured wall temperatures in the test section are higher than in the original cooling channels, because in contrast to the test section the edges of the FRM-II cooling channels are not heated.

4 Summary

In order to perform the hydraulic and mechanical testing of the FRM-II compact core, a water test facilitiy was built at the Ruhr-University of Bochum. During the course of the tests the feasibility of the core cooling in case of free and of a partly obstructed sieve could be proved. No major resonance regions could be investigated during operation and the endurance test showed neither any incidents nor irregularities.

Concerning the removal of the decay heat in the FRM-II, a second test facility has been built. The main attention of the experiments focusses on the thermohydraulic processes in one cooling channel of the FRM-II-fuel element during the transition from forced to natural convection, which takes place after the coast down of the cooling pumps. The possibilty to remove the decay heat by natural convection even in case of a complete loss of the cooling system pumps could be proofed by results of the tests.