Improvements to the Primary Circuit of the FRJ-2

by

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Abstract

The primary circuit of the FRJ-2 research reactor was equipped with new main pumps and with a modified flow rate monitoring system in order to regain reliable and scheduled operation of the reactor.

The new pumps are radial canned motor pumps with a horizontal shaft whereas the old ones were axial pumps with a vertical shaft and a motor accommodated in a vertical pipe which was part of the primary pipework. Consequently, the installation of the new pumps required major modification of the pipework and the supporting structure and the replacement of other components like check and diaphragm valves. The characteristic of the pumps was adjusted to the pressure loss of the primary circuit so that the flow rate of the primary circuit with all three pumps in operation is nearly the same as with the old pumps. This was one prerequisite to get the installation approved by the supervisory authority (no license required pursuant to the German Atomic Energy Act).

The flow of the primary circuit is measured by a Dall tube in each of the four so-called downcomer pipes leading the water from the reactor tank onto the suction side of the primary pumps. The original flow monitoring system consisted of one differential pressure transmitter connected to all four Dall tubes via two small vessels - one for the high and one for the low pressure side of the Dall tubes. In 1998 the one transmitter was replaced by three in order to form a 2oo3 system. Subsequently, it was discovered by the peculiar response of the monitoring system to a shutdown of pumps that gas accumulates in the vessel of the low pressure side due to the permanent small water flow across the Dall tubes. Therefore, a modification of the system was required by the supervisory authority and its technical expert. The new system has four transmitters each connected to one Dall tube. Three of them are used to form the 2oo3 monitoring signal for the plant protection system. The fourth transmitter is only used for the measurement of the flow rate by adding up the signals of all four transmitters.

For the implementation of the improvements a reactor outage time of 7 ½ months was necessary, starting at the beginning of February 1999. At the beginning of September, the primary circuit was put into operation and reactor operation will be resumed at the end of September.

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1. Introduction

The FRJ-2 research reactor of Research Center Jülich is a D_2O-cooled and moderated reactor with a power of 23 MW. It is mainly used for neutron scattering experiments and for radioisotope production for medical applications and research.

In 1998, the reactor suffered three failures of a primary main pump. Each event caused a reactor trip, which in Germany must be reported to the supervisory authority, and in total a loss of operating time of 35 days. Against the background of these events it was decided to replace the primary main pumps by new pumps of a different type in order to regain reliable and scheduled operation of the reactor. The outage time of the reactor was also used to modify the flow monitoring system of the primary system. This became necessary when it was discovered that gas accumulated in the differential pressure system influencing the dynamic behavior of the system.

2. Installation of the New Primary Main Pumps

2.1 Description of the Primary Circuit

Due to the cost of heavy water, the primary circuit of the FRJ-2 has a very compact design, as is shown in Fig. 1. The circuit is accommodated beneath the reactor block in the so-called D_2O plant room. Three main pumps in parallel circulate the coolant through the circuit. They receive the coolant from the reactor tank via four so-called downcomer pipes and the upper manifold and pump it back via the lower manifold and three heat exchangers in parallel to the lower plenum beneath the grid plate. From there it passes through the core to the tank. The two shutdown pumps, of which one is automatically demanded after switch-off of the main pumps, are also connected to the two manifolds.

The general arrangement of the primary circuit, shown in Fig. 1 for the old main pumps, was not changed by the replacement of the main pumps. However, since the old and new pumps are of a different type the pump loops had to be adapted. Instead of the old diaphragm valves new flap valves were installed for the isolation of each individual pump loop because of their shorter design. The check valves which hinder a return flow via the loop in the case of pump failure were also replaced by new ones of a different design.

The failure of one main pump does not impair the cooling of the core to such an extent that an immediate shutdown of the reactor is required. But this is the case if more than one pump fails. Due to the rapid decrease of flow in such an event, the reactor must be scrammed very quickly. Measurements with a turbine meter have shown, for instance for the old primary main pumps, that 0.3 s after the loss of all main pumps the flow rate drops below the value at which under steady-state conditions flow instability might occur. The same is true with the new pumps as will be shown later. Because of the confined space, the seismic hazard and the tritium content of the heavy water it was not possible to improve the inertia of the pumps by fly wheels.

The main pumps are powered by the main grid. If this fails the pumps also fail. In such an event, the reactor scram is initiated first by opening the motor contactors, whereby the opening of one out of the three contactors will already shut the reactor down. The second shutdown criterion is the low primary coolant flow rate controlled by the flow rate monitoring system. However, a transient thermodynamic analysis is necessary to show that the system responds in time.

2.2 Comparison of the Old and New Pumps

The old pumps were axial pumps with a vertical shaft and motor accommodated in a vertical pipe which was part of the primary circuit pipework (Fig. 2). The canned motor was located in the upper part of the pipe forming an annular gap with the pipe through which the main water stream flowed. A bypass stream passed the motor cooling the stator coil and providing the water for the hydrodynamic journal and thrust bearings. The pump itself was located at the bottom part of the unit. It had a spiral impeller and a row of guide blades up- and downstream of the impeller. One weak point of the old pumps was that the stator lamination sheets were not very well fixed in the motor housing so that they could rattle thus cutting into the insulation of the cables. Another weak point was the water-lubricated bearings and the small gap between the rotor and stator laminations causing damage to the lamination in the case of a failure of a journal bearing. Not least, there were difficulties in procuring spare parts for the pumps.

The new pumps are completely different. They are canned motor pumps with a horizontal shaft and a radial impeller (Fig. 3). The rotor of the motor runs in the coolant whereas the stator coil is separated from the coolant by two so-called gap tubes with a gas-filled gap between the two tubes. This reduces the electrical efficiency of the motor so that the electrical power is about 40 % higher than for the old pumps. The motor is flanged to the spiral housing of the pump, which is integrated into the primary circuit pipework. This has the advantage, compared to the old pumps, that in the case of motor or bearing damage only the motor with the pump impeller need be disassembled and replaced by a spare unit.

2.3 Hydraulic Parameters of the Modified Primary Circuit

The installation of the new pumps was approved by the supervisory authority as an unessential modification. This was done on condition that the hydraulic parameters of the primary circuit with all three pumps in operation do not vary too much between the old and the new pumps. The problem in fulfilling this prerequisite was that the installation of the new pumps required an adaptation of the pump loops so that the flow resistance of the primary circuit was changed, too. Therefore, it was not sufficient to adjust only the characteristic of the new pumps to the characteristic of the old pumps in the corresponding range of flow rate. The change of the flow resistance characteristic of the primary circuit also had to be taken into account. However, this change could not be measured in advance.

In order to keep the uncertainties as low as possible at least the flow resistance characteristic of the new pump loop was measured. The comparison of the results with the calculated values revealed that the calculation underestimated the flow resistance by about 10 %. It was assumed that the same degree of underestimation could be applied to the calculated flow resistance of the old pump loops. The change of the flow resistance characteristic of the modified primary circuit was determined by this combined method of measurement and calculation. Fig. 4 shows the flow resistance characteristic curve of the old circuit together with the expected curve of the modified circuit.

The pump characteristic was then adjusted to the flow resistance characteristic of the modified primary circuit so that the two curves would probably intersect at a flow rate between 3 % and 5 % larger than the flow rate of the old operational point. The margin of 4 % average in flow rate was considered to be sufficient to cover all remaining uncertainties in a way that a drop of the real flow rate below the value of the old circuit could be excluded having in mind that a larger positive deviation from the old value could easily be coped with by throttling of valves.

For the adjustment, the new pumps were installed in a test circuit together with the new pipe section, since the measurement of the flow resistance of the new pump loop was combined with the adjustment of the pump characteristic. The pump characteristic was adjusted by reducing the diameter of the impeller. Fig. 4 shows the characteristic curve of the new pumps. The new operational point, also shown in Fig. 4, reveals that the flow rate prediction was rather accurate. The adjustment of the characteristic of the new pumps to the flow resistance characteristic of the modified circuit was so good that no fine tuning of the flow rate by throttling of valves proved to be necessary. The flow rate is 6 % larger than the flow rate of the old circuit.

As mentioned in the introduction, another important parameter from the safety point of view is the decrease of the flow rate versus time in the case of a failure of more than one pump. As an example, Fig. 5 shows this parameter for the switch-off of all three pumps. As can be seen, the modified circuit is only marginally better than the old circuit. In this respect, the new pumps and pump loops represent no real improvement, which was not expected from the design of the pumps.

3. Improvement to the Primary Flow Rate Monitoring System

3.1 Arrangement and Behavior of the Old System

The flow of the primary circuit is measured by a Dall tube in each of the four so-called downcomer pipes, which lead the water from the reactor tank to the upper manifold on the suction side of the primary pumps. The original flow monitoring system consisted of one differential pressure transmitter connected to all four Dall tubes via two small vessels - one for the high and one for the low pressure side of the Dall tubes. When last year the one transmitter was replaced by three in order to form a 2-out-of-3 (3oo3) system it was discovered that the response of the system to a shutdown of pumps changed during reactor operation. A detailed investigation revealed that gas accumulated in the vessel of the low pressure side due to the permanent small water flow across the Dall tubes. 98.9 % of the accumulated gas consisted of helium from the cover gas of the reactor tank and 1.1 % of heavy hydrogen from radiolysis of the coolant.

Fig. 6 shows the arrangement of the old differential pressure system with three transmitters. The two connecting vessels stood upright and the four differential pressure pipes were connected to the individual vessel at different heights leaving a wake space of 50 ml at the top of the vessel, where the gas was collected on the low pressure side. The fact that this happened only on the low pressure side is attributed to the subatmospheric pressure (-0.32 bar) on this side causing a degassing of gas dissolved in the coolant. The flow between the Dall tubes via the differential pressure pipes and the connecting vessel swept the gas into the vessel. Measurements have shown that the flow rate between the four downcomer pipes varies between 113.8 Kg/s and 129.7 kg/s causing an average difference of the differential pressure between the corresponding Dall tubes of 148 mbar, of which the largest share arises on the low pressure side. This difference was balanced by an equivalent flow between the corresponding Dall tubes.

The way in which the gas in the low pressure vessel influenced the response of the system to the switch-off of two operating pumps can be seen from Fig. 7. When the system was solid the flow signal decreased shortly after the start of the rundown of the pumps whereas with gas in the system the flow signal first increased before it decreased. Although the decrease was steeper than for the solid system there was a delay in the initiation of the low flow trip of 40 ms. The reduction of flow means that the pressure on both sides of the differential pressure system increases with the highest increase, of course, on the low pressure side. If gas is present there in the connecting vessel, it must first be compressed before the higher pressure is transferred to the transmitter. The compression requires the acceleration of the water column in the pipes so that the low pressure side could not respond instantly as the solid high pressure side did.

Sometimes under steady-state conditions the measured flow of the primary circuit increased by up to 10 % for a few seconds. This behavior can also be attributed to gas in the low pressure system, particularly in the pipes reducing the hydrostatic pressure imposed on the connecting vessel by the fluid. It is interesting to realize that the replacement of the water in a pipe by pure gas reduced the hydrostatic pressure by 143 mbar, which corresponds to an increase of the measured flow by 12 %. It was presumed that the gas was either collected in the Dall tubes or in the connecting vessel and was swept out into the pipes from time to time by pressure fluctuations.

3.2 Modifications to the System

There were two solutions for the improvement of the differential pressure system. The one was the utilization of connecting vessels with the connection of the four differential pressure pipes at the vessel head and the location of the vessels just below the height of the Dall tubes. The advantage would have been that the hydraulic formation of the mean flow value, which greatly reduced the fluctuation of the flow signal, was maintained. However, this solution was rejected by the TÜV expert because it did not conform to the corresponding DIN standard.

Therefore the second solution had to be applied, consisting of four transmitters each connected to one of the four Dall tubes. The average flow value is formed electrically. Three transmitters are used to form the 2oo3 signal for the plant protection system. This means that the flow of only three of the four downcomer pipes is automatically controlled. Since there is no possibility of a blockage of such a pipe this is acceptable from the safety point of view. The higher fluctuation of the individual signal during normal operation, however, required the reduction and the adjustment of individual low flow thresholds for the reactor trip. The reduction of thresholds compared with the threshold of the old system means a later trip of the reactor after the occurrence of an event resulting in a reduction of the primary flow rate and requiring a reactor trip by the flow monitoring system.

3.3 Behavior of the New System and Implication for Reactor Safety

The low flow thresholds for the individual Dall tubes were determined on the basis of a 24 hour test run at zero reactor power and different water temperatures. The warning threshold was set at 5 % and the trip threshold 10 % below the lowest individual flow rate measured. Of course, it was observed that the trip threshold should always be high enough to guaranty the safe operation of the core under steady-state conditions.

Fig. 5 shows the response of the new flow rate measuring system to the simultaneous switch-off of all three new main primary pumps. As expected, there is no overshoot of the flow signal any longer. The trip of the reactor by the flow monitoring system is initiated at the latest 580 ms after the start of the rundown of the pumps. At this time, the flow rate has already decreased to 55 % of the normal flow rate. Under steady-state conditions, flow instability may occur in the hot channel if the flow rate reaches 75 % of the normal flow rate. Thus, a transient thermohydraulic analysis had to be carried out to prove that the initiation of the reactor trip by the new flow monitoring system is still adequate to protect the reactor from being damaged if the first reactor trip signal by the contactors of the pumps were to fail in the event of a switch-off of all pumps.

For this analysis, the thermohydraulic CATHENA code developed by AECL was used. The modeling of the core and primary system as well as the boundary conditions were taken from a previous analysis described in /1/ with the exception of the rundown curve of the pumps, which, of course, was adjusted to the new pumps. Fig. 8 shows the maximum fuel temperature of the hot channel versus the time calculated by CATHENA. The temperature does not exceed 137 °C. The DNB-point is not reached. As soon as the reactor power is reduced by the drop of the coarse control arms the fuel temperature decreases. The shutdown of the reactor is initiated in time to avoid a blockage of the hot channel. Since the rundown curve of the new pumps does not differ very much from that of the old pumps one can conclude from the previous analysis /1/ that the situation becomes critical when the reactor is not tripped within about one second.

4. Time Schedule

The replacement of the primary main pumps had been prepared for a long time in advance. Therefore, all components were already at the site when work started on the reactor. Also, the approval of the supervisory authority had been received.

On February 5, 1999, the reactor was shutdown. At first, the fuel elements and the so-called coarse control arms were unloaded from the reactor. Then, the upper manifold was fixed in position. The old pumps were disconnected from the circuit, drained, dried and dismantled. Subsequently, the diaphragm valves of the pump loops were replaced by flap valves. For this purpose, the upper and lower manifold had to be drained. This was a crucial situation, since the drainage of the upper manifold means that the four down comer pipes are drained, too, so that there is no shielding between the reactor tank and the primary circuit plant room directly beneath these pipes. All this work was carried out by our reactor maintenance staff and was finished at the end of April.

The new pumps with the supporting structure and the new pipe sections were installed by Babcock. For reasons of safety in case of earthquakes, the pumps stand on spring/damping elements. When the first pump was placed on these elements it was discovered that the weight is 50 % greater than stated by the manufacturer. The consequence was that the spring/damping elements had to be replaced and the static analysis for the supporting structure and the dynamic analysis for the circuit to prove its resistance to the design earthquake had to be repeated. These additional measures caused a delay of about 4 weeks. All the mechanical work in the framework of the installation of the new pumps was finished at the end of July.

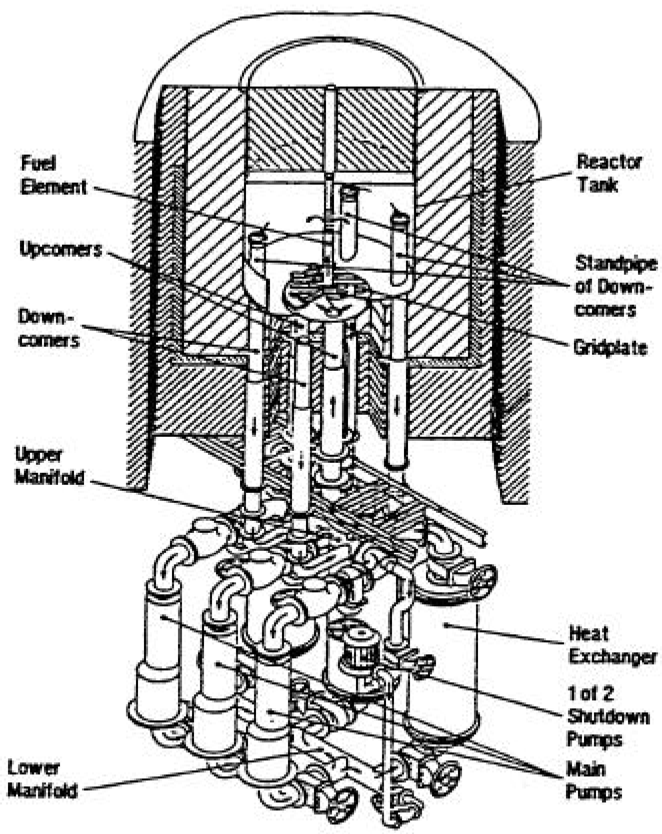
Subsequently, the pumps were electrically connected to the control board, which had already been installed outside the reactor hall. This took an additional two weeks so that the new pumps were ready for the start-up test at the end of July. However, additional work inside the primary plant room postponed until this shutdown period and the installation of the new differential pressure system of the flow rate monitoring system delayed the test until the beginning of September. On September 9, the pumps were put into operation for the first time. A 24-h test was carried out over the following weekend and at the beginning of the next week all the other tests were performed. Since all the test results proved to be satisfactory the reactor will be restarted with the new pumps and the modified differential pressure system of the flow rate monitoring system on September 27, 1999.

5. Conclusion

Despite the thorough preparation, the replacement of the primary main pumps and the modification of the primary flow rate monitoring system at the FRJ-2 research reactor took about 71/2 months. This is only two weeks more than scheduled. In addition, the shutdown period was used for a lot of other maintenance work and improvements deliberately postponed until this long shutdown period. Thus, the whole period was not solely devoted to the improvement of the primary system. Nevertheless, we are sure that the improvement justifies the long outage of the reactor. The new pumps run very smoothly and provide a little bit larger flow rate of the primary circuit. The higher power of 40 % will hopefully be compensated by better reliability of the new pumps, which was the main purpose of the replacement. The modified differential pressure system of the primary flow rate monitoring system avoids gas entrainment into the system so that the response of the system to a sudden flow rate reduction now corresponds to the expected behavior. The lower warning and trip thresholds required by a larger fluctuation of the individual flow rate signals compared with the old system do not impair the safety of the reactor in the case of failure of the primary coolant pumps.

6. References

/1/ R. Nabbi, J. Wolters
Loss of Main Pumps at the Research Reactor FRJ-2 with Delayed or without Scram
The American Society of Mechanical Engineers, HTD-Vol. 192, Thermohydraulics of Severe Accidents
Editors: R. M. Singer, and M. S. El-Genk, B00k No. H00750-192



F . 1: Perspective View of the Arrangement of the Reactor and the Primary Circuit of FRJ-2

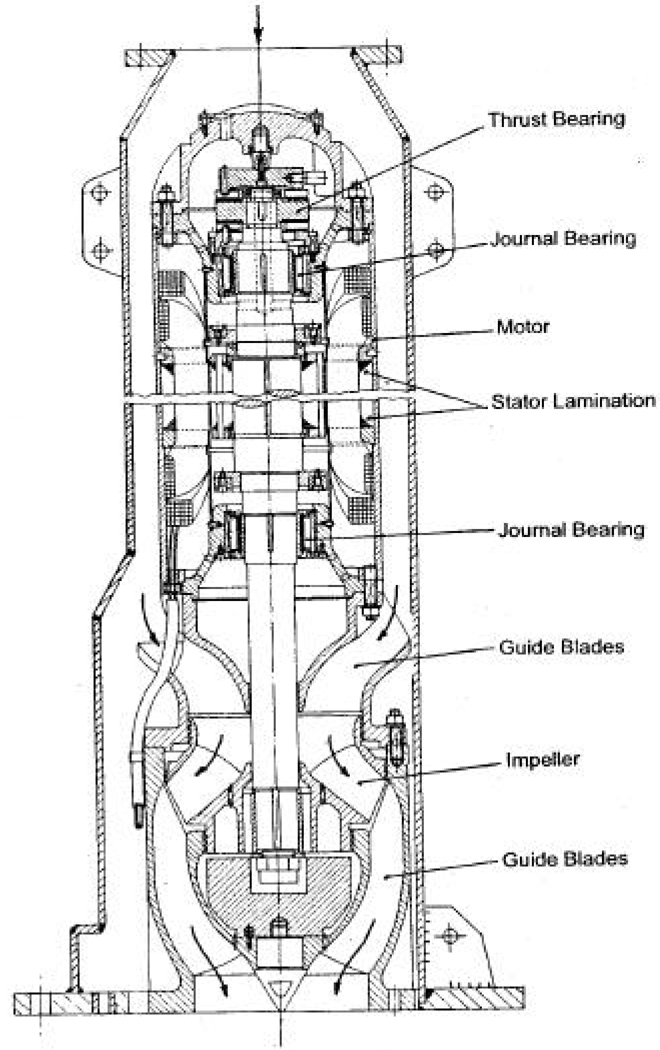


Fig. 2: Section through the Old Primary Main Pump

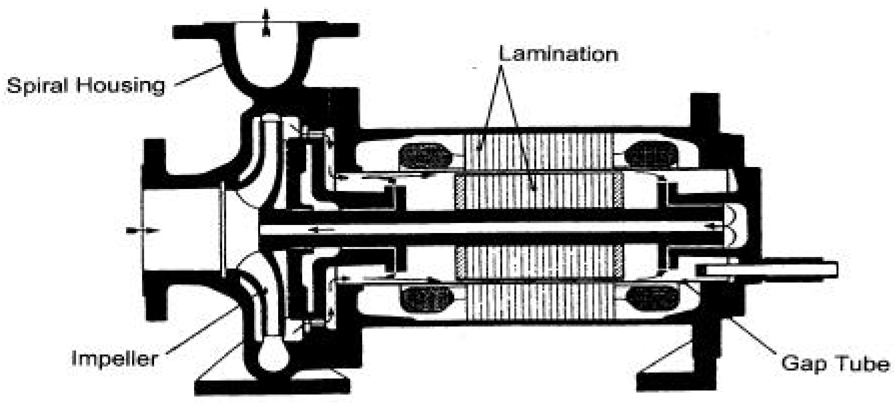


Fig. 3: Section through the New Primary Main Pump

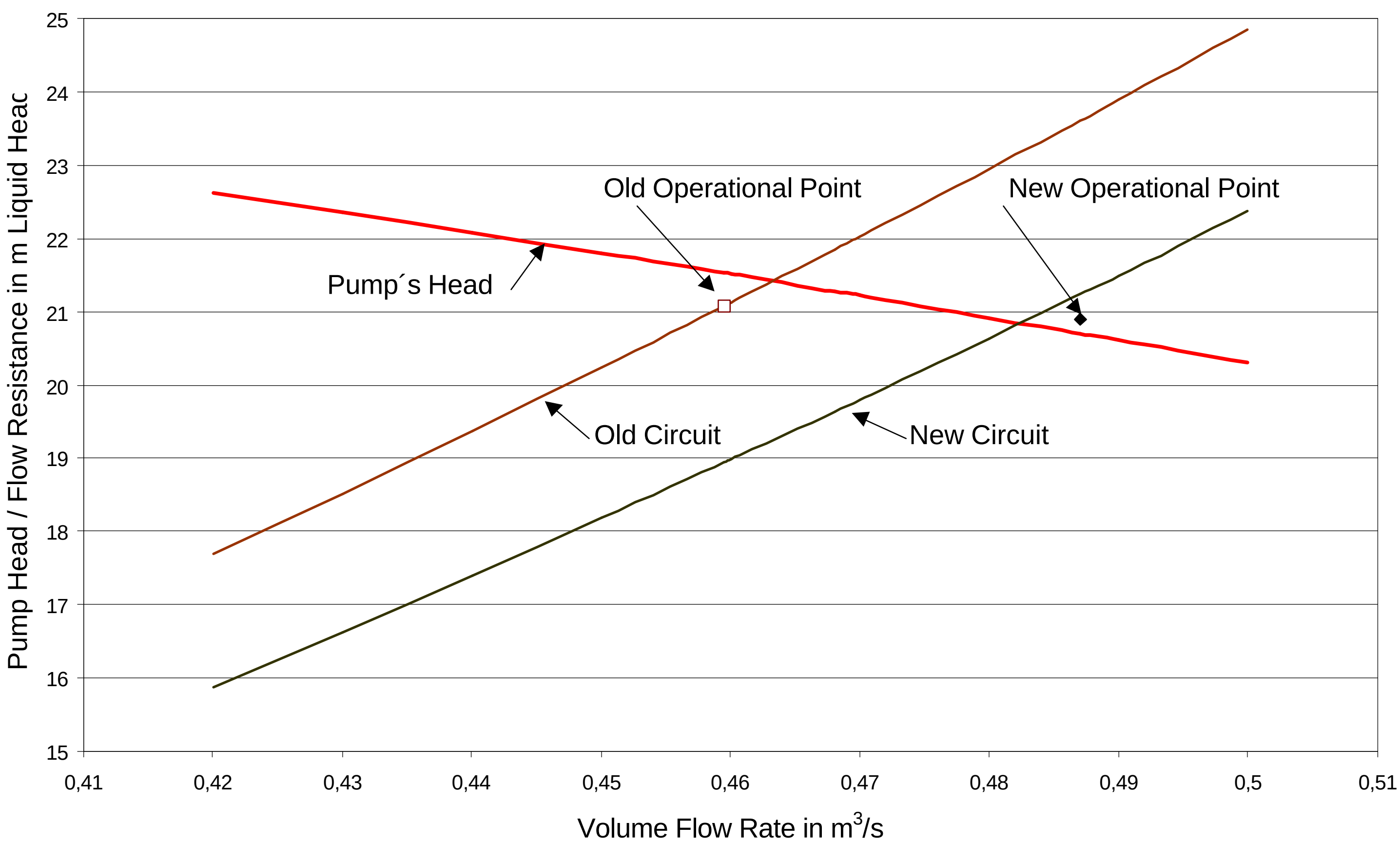


Fig. 4: Characteristic of the New Pumps and the New and Old Circuit

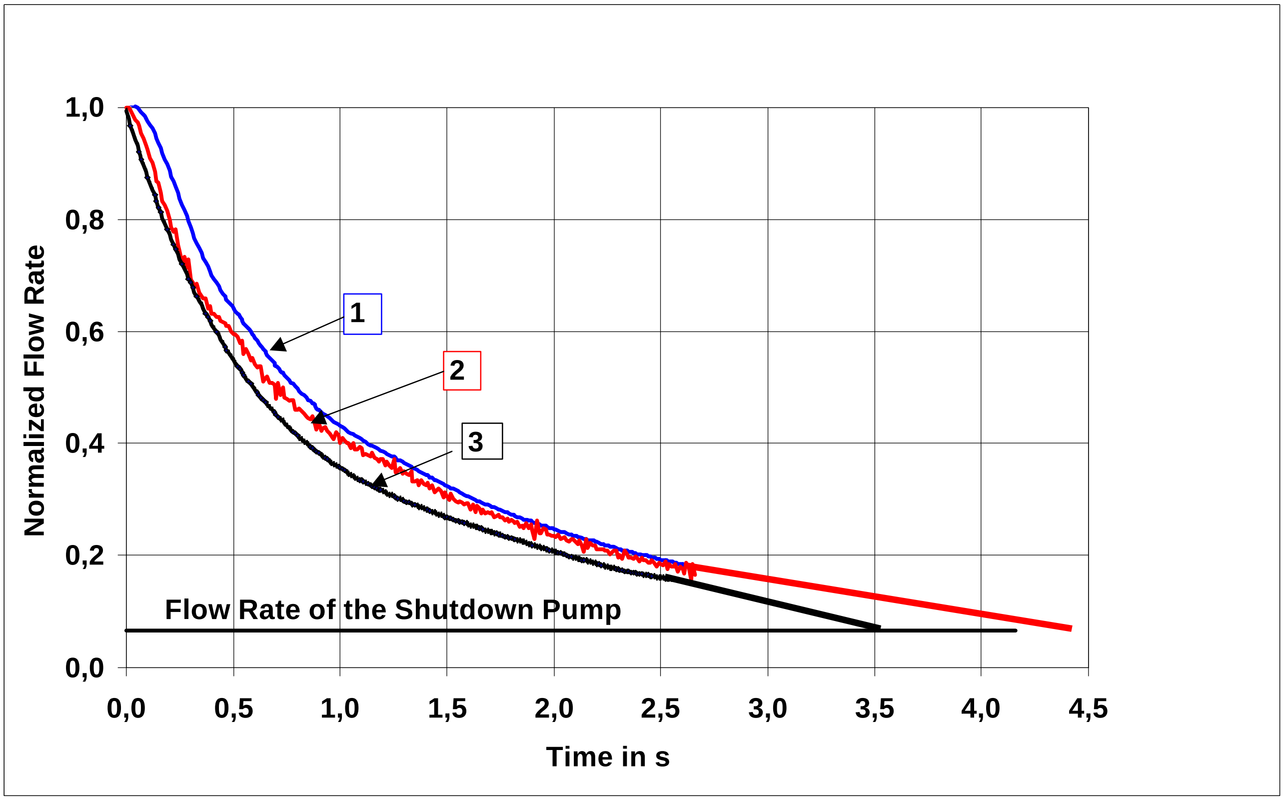


Fig. 5: Measured and Relief Flow Rate of the Primary Circuit after Switch-Off of All Three Main Pumps

1: Response of New Flow Rate Monitoring System
2: Real, Derived from Curve 1
3: Measured for the Old Pumps with a Tubine Meter

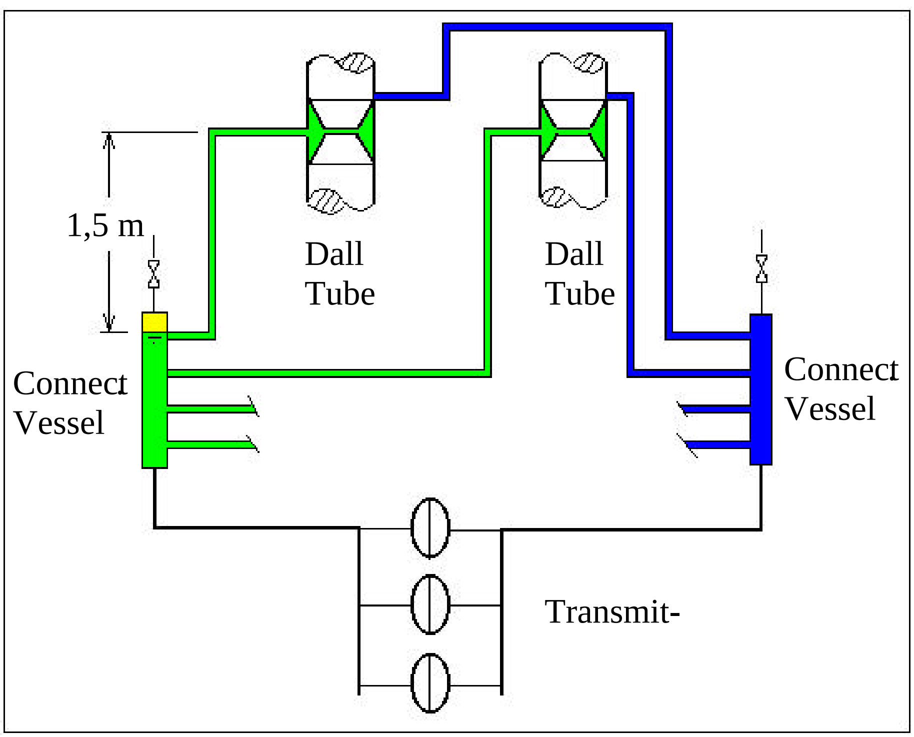


Fig.6:Arrangement of the Former Differential Pressure System for the Flow Rate Measurement

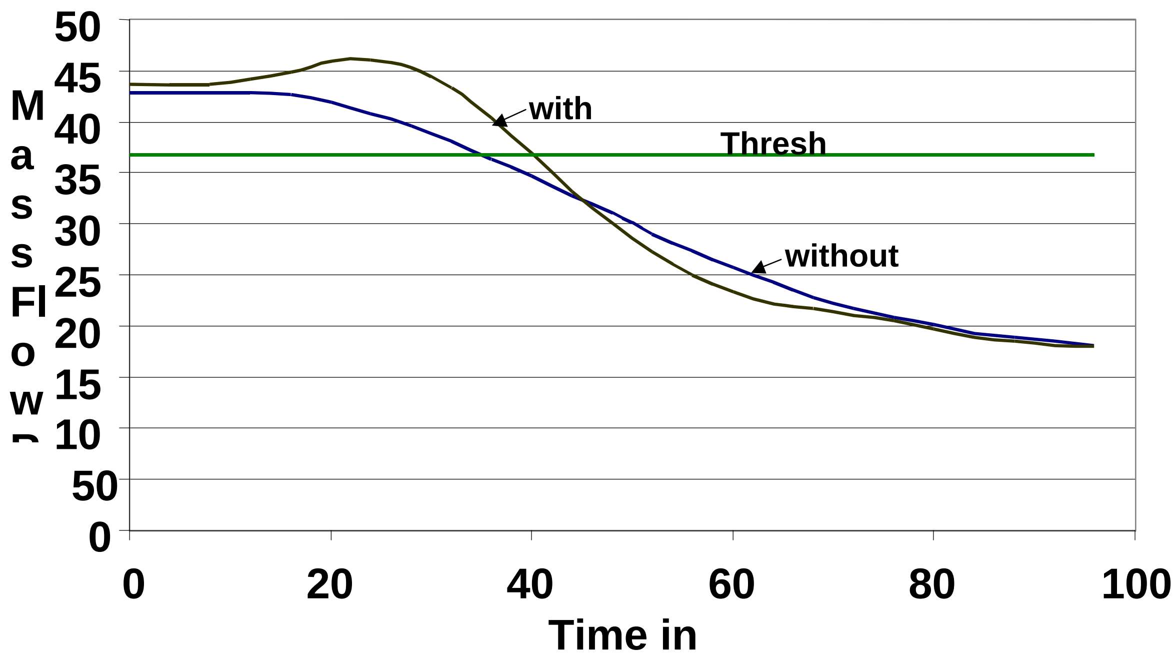


Fig. 7: Flow Signal versus Time after Switch-Off of Two Main Pumps with and without Gas in the Differential Pressure System

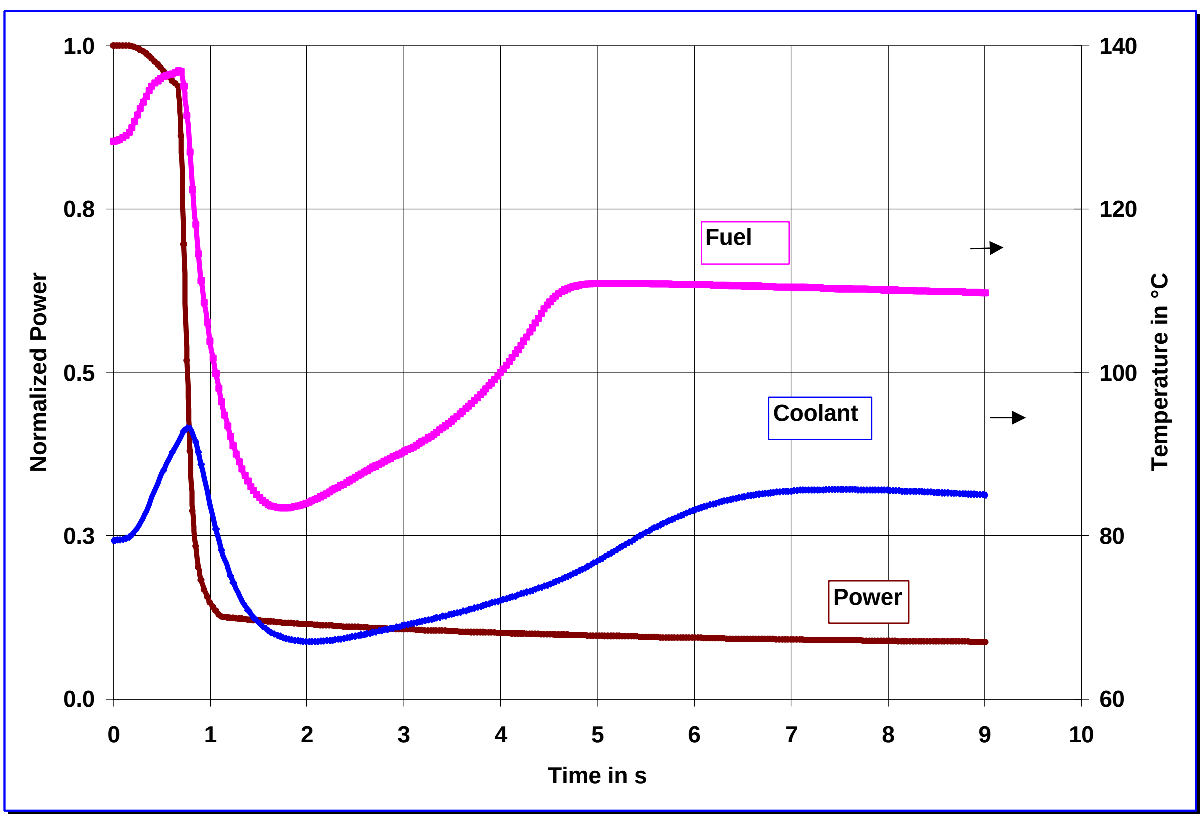


Fig. 8: Maximum Fuel and Coolant Temperature and Reactor Power after Loss of all Main Pumps and a Delayed Reactor Scram by the New Flow Monitoring System