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Abstract

Overpower tests of well characterized fuel pins at burn-up of 10.000 - 30.000 MWD/te UO_2 are being performed at the Reactor DR3 at Risø as an important part of the Danish fuel test programme.

The test are made in high pressure rigs, in which BWR or PWR conditions are simulated. The rigs are connected to a shielded out-of-pile control circuit by means of which the pressure and water quality are controlled and regulated. The heat load of the fuel pins is determined by the calorimetric method.

This paper gives a description of the present experimental equipment, the planned developments and selected results from the test programme.

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1. Introduction

In the high pressure rig system at the DR3 reactor at Risø, Denmark, various tests with LWR fuel pins have been performed since 1968.

The equipment in which these tests are carried out, is designed for testing at various heat rating levels such as overpower tests, power cycling tests and tests for investigating the interaction between fuel and cladding at high heat rating.

The rig system is also well suited for irradiation of fuel pins to high burn-up over periods of several years.

The out-of-pile parts of the equipment are shielded in order to allow operation with fuel pins developing small leaks, while failed pins releasing big amounts of fission products to the primary system, may necessitate the removal of the rig from the reactor before scheduled reactor shut down. Equipment has been constructed for fast removal of the rigs from the reactor if necessary, such that dismantling and clean up of the rig and out-of-pile system can be done without significant interference with normal reactor operation.

The rigs are designed such that the fuel pin can be taken out for inspection or exchanged.

The rigs are, compared with loops, very cheap to manufacture and require a minium of control circuits and instrumentation, for example up to 4 rigs can be operated by a single out-of-pile circuit.

2. Description of the facilities

The equipment is simulating BWR or PWR conditions during the tests.

The equipment is installed in the DR3 reactor, a 10 MW heavy-water moderated and cooled research reactor (Pluto type).

The maximum unpertubed thermal and fast neutron fluxes in the irradiation zone are 1.5×10^{14} and 4.5×10^{13} n/cm^2 sec., respectively. The normal operation period for the reactor is 23 ½ days followed by a shut down of 4 ½ days for maintenance, exchange of fuel and experiments.

Cooling of the rigs is performed by conduction either to a special light water experiment cooling system or to the reactor primary heavy water coolant circuit.

Active gases from rigs are collected in a common fission gas storage system from which release can be performed in a controlled manner.

The two rig types developed are named HP1 and HP2. The HP1 was originally designed based on a German proposal, ref. 1, with radial heat transfer from the fuel pin to the primary pressure vessel, guided by a disc arrangement. In the HP2 rig, the fuel pin is cooled by natural convection of the primary water guided by a riser tube. Later in the development a riser tube was used instead of the disc section in a new version of the HP1 rig with Zr-2 pressure vessel.

The two types of rigs use nearly the same out-of-pile control circuit and instrumentation, shown on fig.2, the only difference being that the HP1 rig has a secondary coolant system.

The out-of-pile circuits are used for control, pressurizing and cleaning of the primary water system.

2.1 The HP1 irradiation rig

The HP1 rig is designed for operation in the hollow fuel elements in the DR3, where the unpertubed thermal neutron flux is between 0.8 and 1.5 x 10^{14} n/cm^2 sec. The fast neutron flux is estimated to be in the range 2 - 6 x 10^{13} n/cm^2 sec.,including contribution from the fission neutrons in the fuel pin.

The rig in its first versions (MKI and II) consist of an aluminium (ALMg3) pressure vessel (fig.1) cooled on the outside by a secondary coolant flow. In the pressure vessel the fuel pin is surrounded by a special disc arrangement made from zircaloy, acting as a flow guide for the pressurized water circulating between the fuel pin and the pressure vessel wall. The heat developed in the fuel pin is tranferred from the cladding surface to the pressurized water by subcooled boiling.

The main objection against this design is that only the fuelled section of the fuel pin, where subcooled boiling occur, will operate under the thermal conditions existing in a power reactor, whereas the plenum chamber and the end plugs have lower temperatures. This condition arise from the zircaloy guide discs, which confines the circulation of the subcooled water to discrete sections along the pin.

This disadvantage is largely overcome in the MK III version of the rig, where a riser tube is used instead of the disc section. The subcooled water then circulates along the fuel pin driven by natural convection and guided by the riser tube. The flow is reversed in the annulus outside the riser tube where the heat is transferred through the pressure vessel wall to the secondary coolant flow. The pressure vessel of the MK III version, made from zircaloy-2, can be used for operation up to 150 bars, whereas the operating pressure for the aluminium vessel was limited to 80 bars.

The temperature of the subcooled water in the pressure vessel is measured by thermocouples.

The height of the reactor core limits the irradiation zone of the rig to 600 mm. Fuel pins of a diameter up to 15 mm can be irradiated in the rig.

2.2 The HP2 irradiation rig

This rig is designed for an irradiation facility in the pool water just outside the reactor core, where the unperturbed thermal neutron flux is about 6×10^{13} n/cm^2/sec. The fast neutron flux is estimated to about 1×10^{13} n/cm^2/sec.,including contribution from the fission neutrons in the fuel pin. The fuel pin, fig.1, is placed in a stainless steel pressure vessel in which the primary pressurized water (up to 80 bars) circulates along the fuel pin by natural convection, guided by a zircaloy riser tube,with subcooled boiling on the surface of the fuel pin.

The flow is reversed in the annulus outside the riser tube, where the heat is transferred to the reactor pool water through the pressure vessel wall and an aluminium thimble, separated by a gas barrier. By changing the gas mixture in the gas barrier the subcooling of the water may be varied. The temperature of the subcooled water is measured by thermocouples.

The diameter of the fuel pin can be varied even more than in the HP1 rig due to a larger diameter of the pressure vessel, while, owing to space limitations from other facilities, the lenght of the irradiation zone of the rig is 400 mm.

In a special version of the HP2 rig it is possible to power cycle the fuel pin between zero and full power by moving the pin in and out of the irradiation zone by means of a hydraulic driven piston placed in the lifting rod of the fuel pin.

In another version of the HP2 rig power cycling of the fuel pin between full power and partial power can be achieved by means of a moveable absorber screen made from canned silver, placed inside the pressure vessel. The screen is also moved in and out of the irradiation zone by a hydraulic driven piston. In both versions the differential pressure driving the piston is delivered by the primary system pump. The direction of the movement is reversed by a special arrangement of magnetic valves.

2.3 Out-of-pile circuit

Both rig types are connected to out-of-pile control, pressurizing and cleaning circuits. The primary circuits are identical for the two rig types, but the HPl-rig is further connected to an out-of-pile low pressure secondary cooling system.

A diagram of the out-of-pile circuit is shown in fig.2. A small flow, 1 cm^3/sec., is circulated in the closed circuit by a pump. Water returned from the rig is cleaned in a mixed bed ion exchanger and then passed through the off gas vessel before returning to the pump. The circuit has a warning for low flow, and radioactivity in the water is controlled by a radiation detector. The purity of the water is measured by a conductivity meter placed after the ion exchanger. Sampling valves makes it possible to take out water samples for analysis. Filling of the circuit is done from the filling vessel and the circuit can be drained to a dump vessel.

The circuit is pressurized from a helium bottle connected to the off gas vessel through a gas lock. The off gas vessel has a free water surface and is also acting as expansion vessel to absorb volume change of the water caused by variation of temperature. The water level in the off gas vessel is measured by a level indicator. The gas pressure in the circuit is monitored by pressure switches which first give a warning and then reactor trip either if the pressure decreases below a preset value in order to protect the fuel pin against burn-out or if the pressure increases above a preset value in order to protect the system against high pressure. The pressure switches are connected in a 2 out of 3 system to the trip guard lines of the reactor.

The circuit is connected to an active gas storage unit through a gas lock. The gases discharged from the system are stored in this unit. A relief valve is protecting the circuit against high pressure. Discharge from the relief valve is also stored in the active gas unit. The valves used in the system are either manually operated valves or magnetic valves. All components and tubes are made from stainless steel.

It is possible to operate continuously with a fuel pin developing a small leak, but the circuit is shielded to take activities from a failed fuel pin. With a failed fuel pin the reactor is shut down and the rig with fue[illegible] the hot cells. After unloading of the failed pin, the rig is easily cleaned before further irradiation.

In order to avoid operator faults causing loss of system pressure followed by reactor trip, rutine operations such as adjustment of the system pressure and the water level in the off gas vessel is made by means of locks consisting of two magnetic valves. The magnetic valves in the locks are operated by a turnable multi-switch allowing only one of the valves in a lock to be open at a time.

2.4 Secondary coolant circuit

Each of the HP1-type rigs is connected to a separate secondary cooling circuit for removal of the heat from the rig during irradiation. The flow through each of the secondary circuits is monitored by 3 differential pressure transducers, which are connected to the trip guard lines of the reactor in a 2 out of 3 system in order to protect the rig and fuel pin against overheating in case of secondary flow failure.

2.5 Safety aspects

Heat transfer experiments have been performed in out-of-pile rigs with electrically heated rods closely simulating the conditions in the real in-pile rig. By means of these experiments burn-out limits have been determined for fuel pins in the different rig designs as a function of the operating pressure in the primary system. The obtained burn-out limits are shown in fig.3.

Out-of-pile experiments have also been performed in order to examine the consequences of a possible loss of pressure in the system on the safe operation of the rigs and the reactor. In such an experiment the response time was determined for a safety instrumentation based on pressure switches and thermocouples. From the results shown in fig.4, it is seen that a safety instrumentation based on pressure switches acts sufficiently fast to prevent burn-out of the fuel pin in case of depressurization. During almost 8 years of operation there has only been one case of loss of pressure in the primary circuits; this was due to the failure of a conductivity meter, and the pressure switches tripped the reactor as planned and no damage of the fuel pin was observed.

2.6 Test conditions

Heat load

The heat output from the HP1 rig is determined by means of the measured flow and temperature difference between inlet and outlet of the secondary coolant system.

The heat output from the HP2 rig is calculated from the difference between the mean temperature of the water in the annulus outside the riser tube and the temperature of the heavy water in the reactor pool.

The heat load of the fuel pin is found by correcting the rig power for γ-heat.

Temperatures

For both rig types the subcooled boiling is beginning at a surface heat flux of about 50 W/cm^2.
The surface temperature of the cladding at subcooled boiling may be determined by adding the wall superheat given by Jens and Lottes equation (ref.2) to the saturation temperature of the primary water at the given system pressure.
In the heat transfer experiment with electrically heated rods (see section 2.5), the inside surface temperature of the heated rod was measured. Calculations of the outside surface temperature based on the measured inside temperature gave a lower value than the method using the saturation temperature and Jens and Lottes equation (5°C lower at a pressure of 70 bars). This lower surface tempearture is assumed to be caused by suppression of the saturation temperature of the water due to dissolved gases mainly originating from the gas in the off-gas vessel used for pressurizing the system.

The heat transfer experiment was pressurized by nitrogen, while the in-pile rig system is pressurized by helium. The solubilities of nitrogen and helium as a function of pressure and temperature are only slightly different.

Water chemistry

The electrical conductivity of the ion exchanged water is measured continuously. Water samples, as well as samples of the cover gas in the off-gas vessel, are taken for routine check.

For BWR irradiations, the only conditioning of the primary water is by means of the ion exchanger, which is a 1:1 mixed-bed. In PWR-type experiments, the pH is increased by addition of a N_2+H_2 mixture to the helium cover gas in the off-gas vessel, and thereby adjusting the equilibrium $N_2+3H_2 \rightleftarrows 2NH_3$ in the primary coolant. In this case, the ion exchanger is also a 1:1 mixed-bed type, but with the cat-ion on ammonium form.

Typical results from water and gas samples are as follows:

Irradiation type			BWR	PWR
Water samples	Conductivity	(μ S/cm)	0.5	12
	pH		5.8	10
	Solids	(ppm)	<1	< 1
Gas samples	He	(%)	99.8	96
	H_2	(%)	0.1	2
	N_2	(%)	0.01	2
	Ar + O_2	(%)	0.01	0.02

New rigs and out-of-pile circuits are cleaned up by operation with a "clean-up fuel pin" for one reactor period before an experiment is started. Corrosion products from the rig system are deposited on the "clean-up pin". After such a clean-up period only very thin surface deposit are observed on the cladding surface of fuel pins irradiated in the rig even for irradiations lasting a couple of years.

2.7 Future development

Power cycling and power ramps in HP1 rigs

A new facility using a BF_3 absorber gas to change the neutron flux level of a HP1 rig during full reactor power is planned. The facility will replace a fuel element in the core but it will still have a central hole for insertion of a normal HP1 rig. The new facility will improve the possibities for making power cycling and power ramps of fuel pins.

Failure detection

In our present equipment it takes about 6 minutes for released fission products to reach the radiation detector. In ramp test experiments it is important to know the failure time more accurate. In planned fuel pin experiments a small bellows pressure detector placed in the plenum of the fuel pin will be used for detection of the pressure increase caused by a failure. The pressure detector will also measure the pressure during the test.

Cladding deformation

Fuel pins will be instrumented with weldable strain-gauges for in-pile measurements of local cladding strain.

3. Overpower tests

Rapid power increases in UO_2-Zr fuel pins may lead to cladding failure, especially after high burn-up at a steady or decreasing power level.

A number of well characterized fuel pins of both BWR and PWR type have been subjected to power ramps in the HP-system after pre-ramp irradiation to a burn-up in the range 10000 - 35000 MWD/tUO_2.

Pre-ramp irradiation

The pre-ramp irradiation is performed in a HP-rig at a decreasing heat load due to burn-up of the fissile material. A typical plot of the irradiation history is shown in fig.5. (ref.3). After completed pre-ramp irradiation, the HP-rig containing the fuel pin is taken to the hot cells for nondestructive characterization such as profilometry, eddy current testing and gamma scan and to the DR1 reactor for neutron radiography.

Power ramp

The power ramp test is made during a normal reactor start-up with short holds at lower reactor power levels for routine calibrations.

The power increase for tests made in HP1 rigs is obtained by moving the rig to a position in the center of the reactor core with a higher thermal flux. Power increase of up to 75% can be achieved by this method.

The power increase for tests made in HP2 rigs is obtained by replacing the H_2O in the primary system with D_2O before reactor start-up. By this method a power increase of 20% is possible.

At the reactor start-up the reactor power is first increased to a level which gives about the same heat load of the fuel pin as the latest pre-ramp heat load.

After a hold at this level the reactor power is raised to full power at a rate corresponding to the desired ramp-rate. If the fuel pins fails during the ramp test, the reactor is tripped, and shortly after the rig is isolated from the out-of-pile system by remotely operated equipment. Finally the rig with fuel pin is transferred to the hot cells for examination.

A typical profilometry plot (fig.6) shows the effect of a overpower test (ref.3).

The rig is returned to the reactor after removal of the pin in the hot cell. The rig and the out-of-pile system are ready for use to a new pin test after clean-up lasting about one week.

Further results from the overpower test programme carried out in this equipment are reported in ref.3 - 6.

4. Tests at high heat load

Two BWR type UO_2-Zr fuel pins have been tested at a heat load of about 900 W/cm for investigation of the effect of partial melting on the interaction between UO_2 and cladding.

One of the tests developed at its first start-up a big failure with molten UO_2 running out in the aluminium pressure vessel of the HP1 rig used. The reactor was tripped immediately by the instrumentation due to over pressure in the system. The rig with the failed fuel pin was handled without problems.

The other test was irradiated as planned for one reactor period without failure.

5. Operation experience

Since 1968 a total of 4 out-of-pile systems, 12 HP1 rigs and 4 HP2 rigs have been manufactured. The out-of-pile circuits have been used almost continuously since that time. Only the first two HP1 rigs have been scrapped, one of them because of the molten UO_2 descriped in section 4, while the rest of the rigs still are in use.

At present about 85 fuel pin tests have been carried out in the equipment with very few operating problems. It is possible to run 4 HP rigs in series operation on the same out-of-pile system which improves our irradiation capacity. The 4-series operation are especially used for long term tests. In the beginning diaphragm pumps were used in the out-of-pile system, but due to frequent diaphragm failures one of the diaphragm pumps in each system was replaced by an electromagnetic pump of our own design. The other diaphragm pump is still used as stand-by pump and for moving the fuel pin or the absorber skirt in the HP2 rig.

Several of the aluminium and zircaloy pressure vessels have been inspected inside and no essential corrosion has been found. One of the Zr-2 pressure vessels have recently been taken to hot cells for destructive testing after an accumulated operating time of 2 years.

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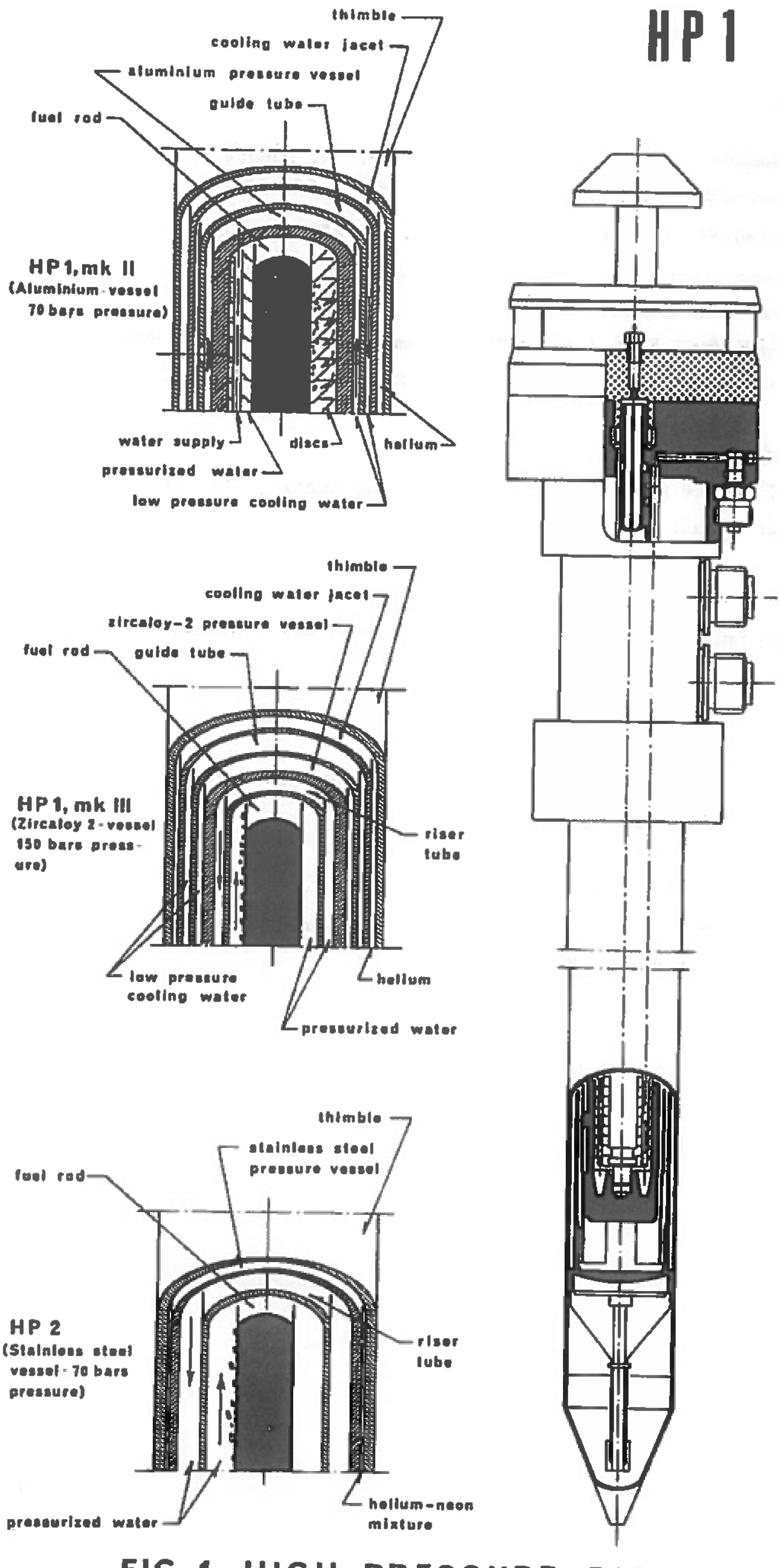

FIG 1. HIGH-PRESSURE RIGS

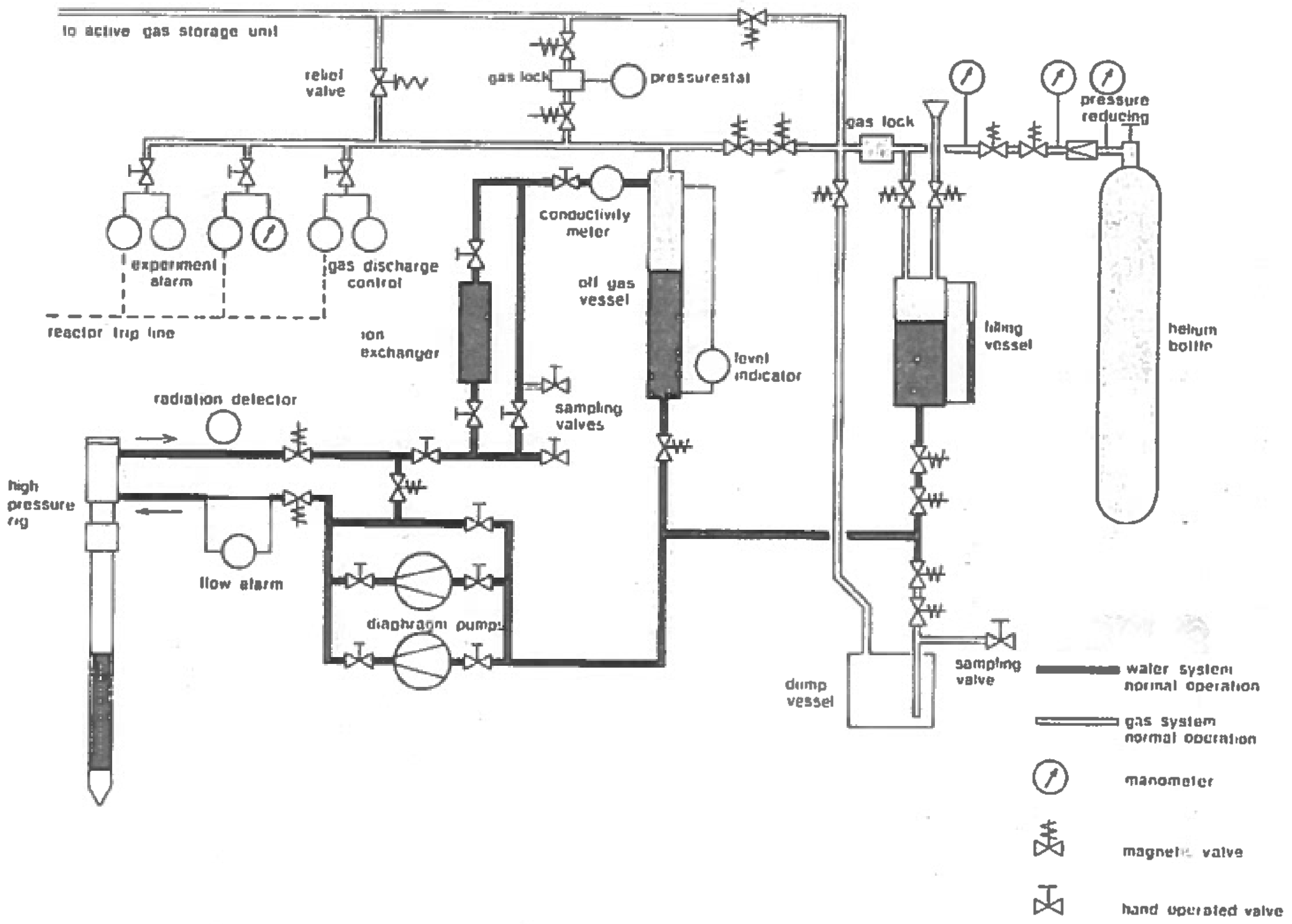

Fig. 2.

High Pressure Circuit for HP1 and HP2 Rigs

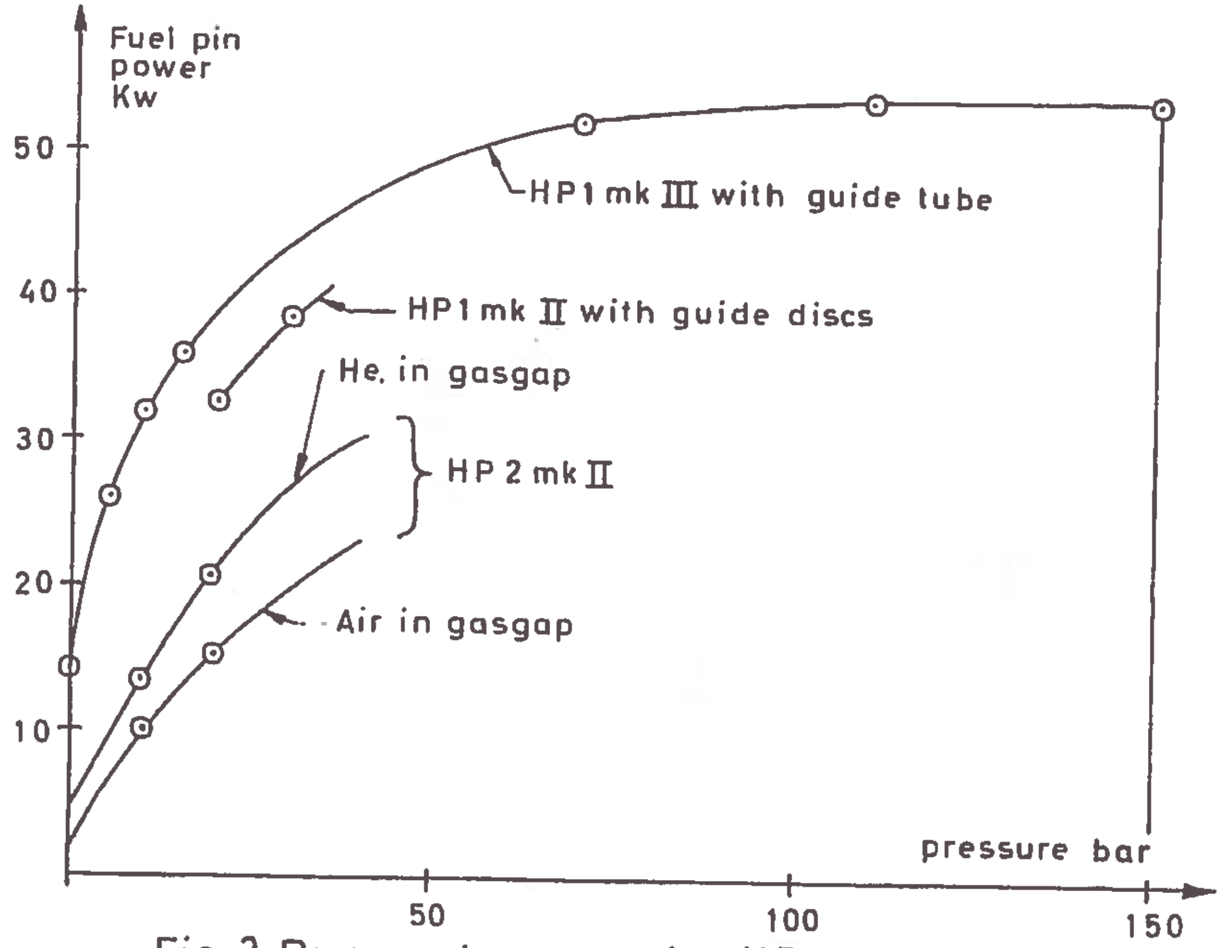

Fig. 3. Burn-out curves for HP1 and HP2 rigs

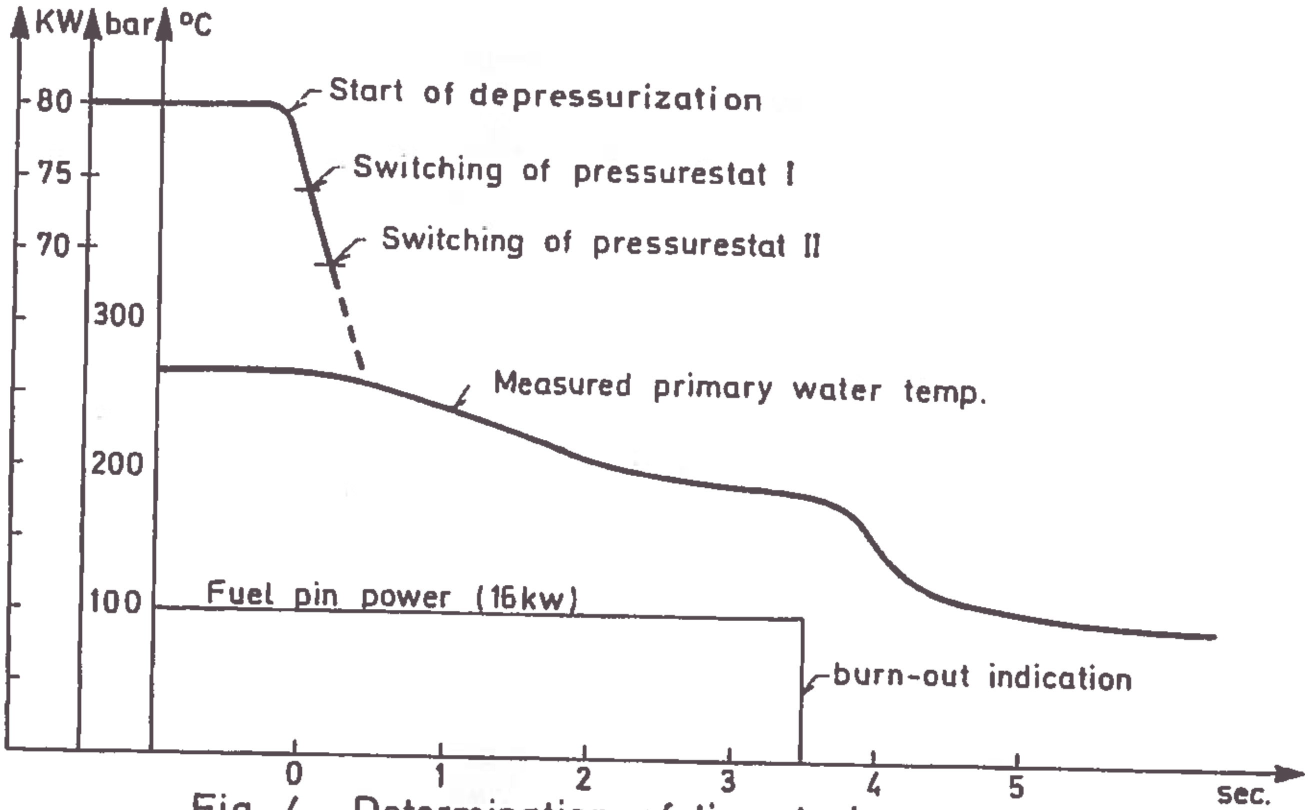

Fig. 4. Determination of time to burn-out following a depressurization accident and the response times for pressurestats and thermocouples (HP 1 rig)

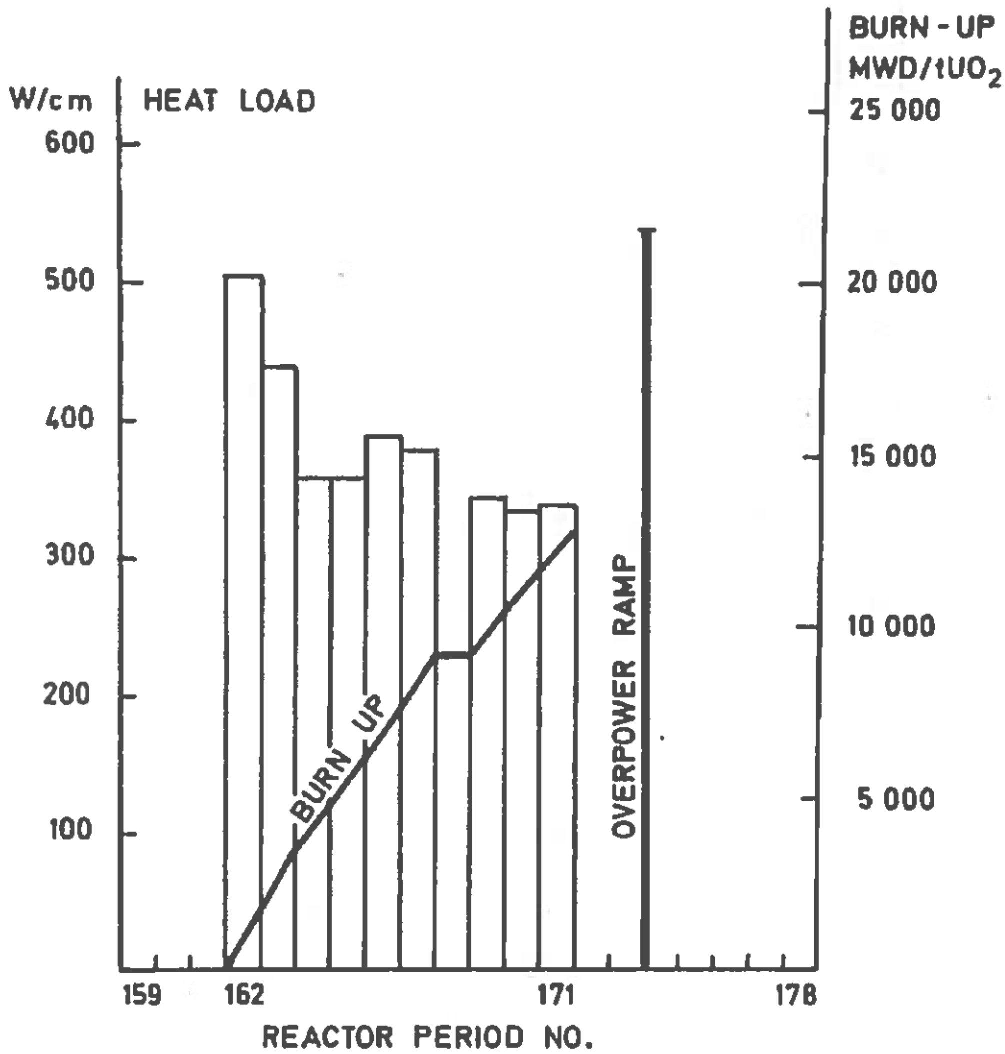

Fig. 5. Irradiation History (ref.3)

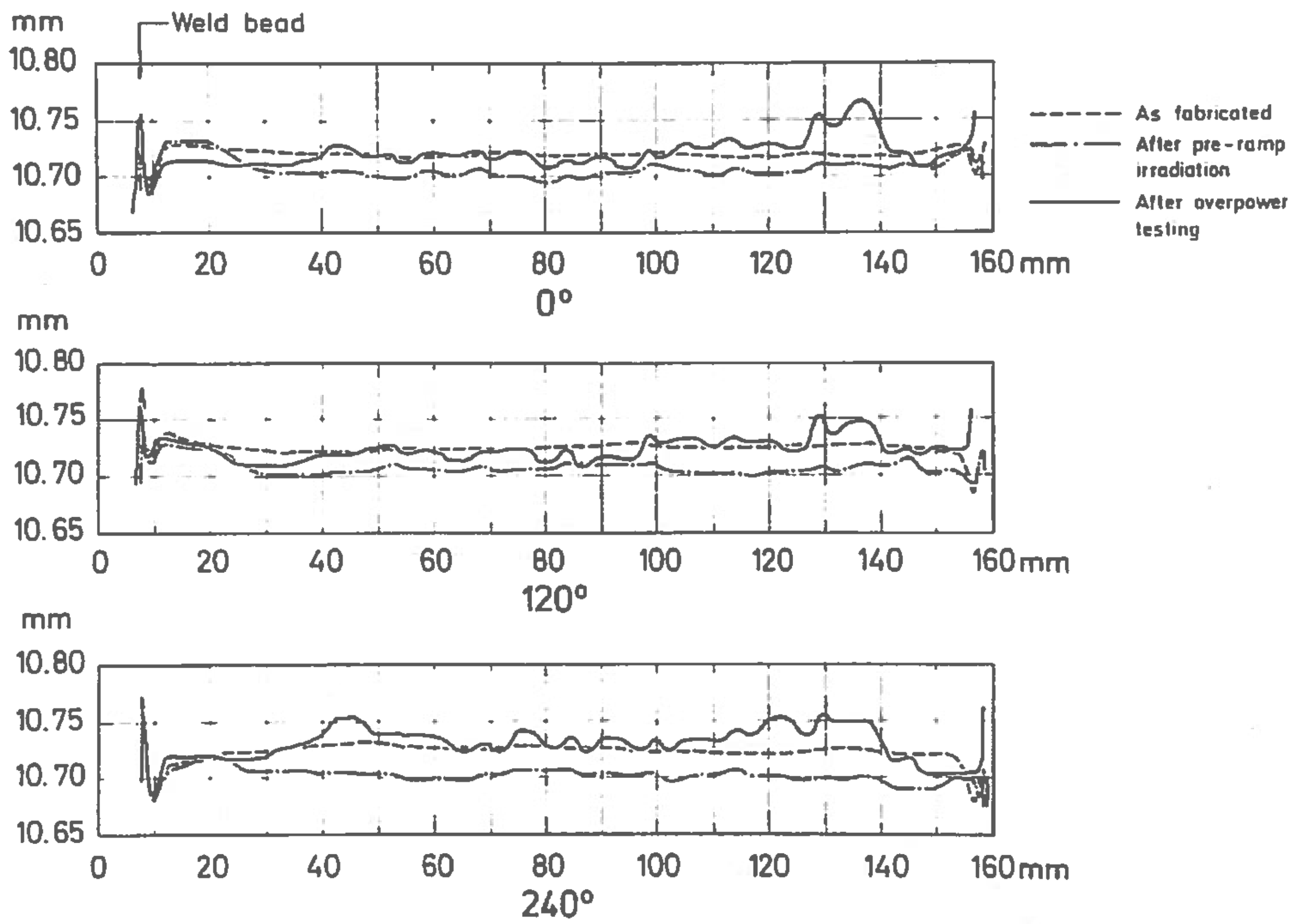

Fig. ?. Profilometry (ref.3)