RESEARCH AND DEVELOPMENT OF IN-CORE TRANSDUCERS AT THE CIAE

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Abstract

In this paper, R & D of in–core transducers at the CIAE are briefly summarized. With the construction and commissioning of PWR nuclear power plant in China, fuel rod behavior needs to be studied carefully. As conventional transducers can not meet the requirements of in–core applications, R & D of in–core transducers are developed. Since 1980's, several kinds of in–core transducers have been successfully fabricated and tested under the conditions simulating PWR. At present, in–pile tests of the transducers combining with the studies of individual behavior of PWR fuel rod are being planned at the CIAE.

1 Introduction

The objective of developing in–core transducers at the CIAE is to create powerful tools for studying the behavior and changes in the properties of PWR fuel rods. Many in–core transducers have proved to be reliable for in–core applications (ref. 1–11). In general, conventional transducers can not provide the required data with sufficient accuracy, that makes it necessary to design special transducers for in–core applications. At the present time, emphasis is placed on some transducers which can be used to measure the main parameters of PWR fuel rods under normal operating conditions, such as fuel temperature, fission gas release, fuel rod cladding elongation, fuel densification etc.

The design and fabrication of in–core transducers are much more complicated than those of conventional transducers. It is required that the effects of radiation on the performance of in–core transducers should be estimated. Therefore, choice of structural materials and insulating materials and seal techniques should be considered carefully.

Up to now, five kinds of in–core transducers have been fabricated and out–of–pile tests of transducers for calibration, sensitivity, temperature effect, pressure effect, stability, durability studies have been successfully conducted under the conditions simulating PWR.

The transducers are:

– Tungsten–Rhenium (W3%Re / W25%Re) thermocouple assemblies used for measuring centreline temperature of fuel pellets up to 1800℃.
– Pressure gauge (membrane type) used for measuring fission gas pressure inside fuel rod.
– Linear variable differential transformers (LVDTs) used for measuring fuel rod cladding elongation, fuel densification and fuel stack height.
– Turbine flowmeter with throat 32 mm in diameter used for measuring fuel channel flow rate.
– Gamma thermometers used for measuring gamma heating and relative power distribution of fuel rod.

At present, in–pile tests of the transducers including the development of Instrumented Fuel Rods (IFRs) are being planned at the CIAE and are reported here.

2 R & D of in–core transducers

2–1 High temperature thermocouple assembly

Two types of Tungsten–Rhenium (W3%Re / W25%Re) thermocouple assemblies of 1.64 mm OD and 1.0 mm OD have been developed for measuring fuel centreline temperature (ref. 1,2,3,4,5,7). Fig. 1 is the configuration of W / Re thermocouple assembly of 1.64 mm OD which is same as that of 1.0 mm OD. For fuel centreline temperature measurement, the fuel pellets with central hole are required for the installation of W / Re thermocouple.

Thermocouple assembly consists of the W3%Re / W25%Re wires with beryllia insulation and tantalum sheath, transition tube and lead wire cable with mineral insulation and stainless steel sheath of 1.0 mm in diameter. The transition tube (Fig. 1), which is located inside the gas plenum of fuel rod and forms a thermocouple junction, is designed, aiming at realizing a very reliable connection between the sheath of leadwire and the end of fuel rod. In order to prevent the diffusion of fission gases into the cable insulation, seal–welding is applied to connect the transition tube with tantalum sheath and leadwire cable. Obviously, as two connecting points of the W / Re thermocouple wires and the leadwires are positioned inside the transition tube, the possibility of introducing measurement errors is increased. For this reason, a high temperature furnace with two heating sections is equipped for calibrating thermocouple assemblies. The maximum temperature of one heating section is 2000℃ for the top of W / Re thermocouples and the other is 800℃ for the transition tube. The distance between two heating sections can be adjusted according to the length of the thermocouple assembly.

Eight thermocouple assemblies (five thermocouple assemblies of 1.64 mm in diameter and three of 1.0 mm in diameter) have been calibrated in the furnace. At the range of 1000℃ to 1800℃ their measuring precision is close to-2.5%. For eight thermocouple assemblies tested, no open–circuit has been found after fifteen times of thermal shock in which the average rate of temperature rise is 44℃ / sec from 300℃ up to 1800℃ and the average rate of temperature drop 6.3℃ / sec from 1800℃ down to 300℃, as shown in Fig. 2.

2–2 Pressure gauge

A thin membrane forms the boundary between the fission gas pressure to be measured and an external gas system where the pressure can be adjusted to balance the measured pressure. The membrane rests against an electric contact, which signals when the unbalanced pressure causes the membrane to move (ref. 1,6). The configuration of pressure gauge is shown in Fig. 3. This type of pressure gauge is especially suitable to measure the fission gas pressure in fuel rod under normal operating conditions because the build–up of pressure inside a fuel rod proceeds slowly. In order to connect the pressure gauge to the upper end of fuel rod, the Zircaloy / stainless steel connectors of 10 mm OD for PWR fuel cladding have been also made successfully at the CIAE.

In our experience, the membrane made of constant elastic alloy has the advantages of higher sensitivity and shorter response time than that of Platinum and stainless steel ones. Electro–beam welding is employed to avoid the deformation of membrane. The insulating materials are ceramics. This choice of design techniques is aimed at enhancing the reliability of pressure gauges under PWR operating conditions.

Out–of–pile tests including sensitivity, temperature effect, durability and iodine corrosion studies have been successfully conducted under the conditions simulating realistic PWR. The membranes are forced to oscillate 2×10^4 times at the null position by means of a balancing pressure system, no failure of membranes was observed.

A force–balance system to detect displacement of a membrane has been developed. It mainly consists of four electromagnetic valves (EV1,EV2,EV3,EV4), fast response pressure sensor (P1), remote– controlled pressure gauge (P2), buffer tank, balancing tank, beta detecting station and He–bottle, as shown in Fig. 4. For the measurement of fission gas pressure inside fuel rod, valves adjust automatically the balancing pressure (P′) equal to the fission gas pressure (P), simultaneously the balancing pressure is recorded by system, as shown in Fig. 5.

2–3 Linear variable differential transformer (LVDT)

Type SH5 linear variable differential transformer (LVDT) consists of coaxial primary and two secondary coils with a movable ferritic core in the center, as shown in Fig. 6. The position of the movable core determines the relative magnitude of the voltage induced in the two secondary coils by an alternating current in the primary coil (ref. 1,5,6,7,8,9,10,11).

To meet the in–core conditions the materials employed are limited to metals and ceramics. Coils are wound with ceramic insulated wire on a bobbin which is flamesprayed with ceramics. By means of electro–beam welding and argon arc welding the LVDT is tightly sealed, aiming at enhancing the reliability of LVDT under PWR operating conditions.

Readout instrument called DISPLACEMENT METER SH005 is designed, in which a constant current generator is used to reduce the influence of the long cable connections (more than 100 m) between LVDT and readout instrument.

The main performance of LVDTs including relationship between output voltage and displacement, temperature effect, zero shift and stability have been studied carefully under the conditions simulating PWR. The calibration curves at different temperature level are shown in Fig. 7. The temperature effect is found to be approximately 5% increase of signal for 100℃ temperature increase. This effect can be explained as a decrease in the eddy current losses in the stainless steel coil assembly due to the increase in the specific electrical resistance of the surrounding metal parts.

2–4 Turbine flowmeter

Type TFM–II turbine flowmeter is applied to measure the flow rate of coolant which together with the reading of temperature rise of the coolant determines the power of fuel rods loaded in a irradiation rig. The flow rate is obtained by measuring electric pulse induced in the pick–up coil with the permanent chrome steel (ref. 1,4,6,7).

As shown in Fig. 8, the turbine flowmeter consists of the rotor, shaft, bearing, pick–up coil, signal cable and housing. The pick– up coil for commercial turbine flowmeters designed for installation in pipes is usually unsuitable for in–core applications because the pick–up coil protrudes 20 mm or more from the housing and are not sealed. In this design, a small pick–up coil is inserted into the flowmeter housing without increasing the overall diameter of a irradiation rig. The same coil material and techniques as used in LVDT are employed in the manufacturing of the pick–up coil. The bearing material is graphite. All of the non–moving parts are connected together by argon arc welding or laser spot welding except the rotor and bearing, which makes the flowmeter more reliable.

The type TFM–II flowmeter has been successfully tested to 2500 hrs at 320℃ and 15.5 MPa in a out–of–pile high temperature and high pressure loop. No rotor stop is discovered, as shown in Fig. 9. When the rotor is forced to stop, the maximum pressure drop is less than 0.01 MPa. Table 4 gives its main specifications.

2–5 Gamma thermometer

The configuration of type GT–I gamma thermometer is shown in Fig. 10. As gamma flux is absorbed in a steel cylinder mounted in argon atmosphere in a pressure container, the resulting temperature rise is measured by means of Chromel–Alumel thermocouples. It is used for measuring the relative power distribution of fuel rod (ref. 1,6,7,11).

In this design, the inside surface of gas filled casing and gamma absorber are well polished to reduce radiation heat losses. The casing is filled with argon gas which has low thermal conductivity. A Chromel–Alumel thermocouple is inserted into the gamma absorber at a sufficient distance to minimize the influence of thermal contact resistance between the measuring junction and the absorber. Its main advantages come from its simplicity and longer lifetime in a high radiation field, and the disadvantages are larger size and longer time response.

A type GT–I gamma thermometer was irradiated in a Swimming Pool Reactor in 1980, the integrated thermal neutron flux reached 5.3×10^{19} n / cm^2 . GT–I provided repeatable signal for a certain level of reactor power. Fig. 11 shows the relationship between temperature difference and reactor power.

3 Irradiation programme

In–pile tests of transducers will be performed at the CIAE, combining with the studies of behavior of PWR fuel rod. The programme includes the irradiation tests of three Instrumented Fuel Rods (IFR), as listed in Table 4, in a Swimming Pool Reactor at the CIAE, aiming at improving the performance of in–core transducers in nuclear radiation field, developing irradiation rig and experimental techniques and studying the behavior of PWR fuel rods under normal operating conditions.

The first Instrumented Fuel Rod named IFR–26–01 has been designed and the irradiation test for IFR–26–02 and IFR–26–03 is being planned. IFR–26–01 is aimed at the study of performance of W / Re thermocouple assembly and turbine flowmeter in nuclear radiation field. If possible, the fuel centreline temperature will also be measured. As shown in Fig. 12, a single fuel rod with a length of 400 mm and double stainless steel claddings is designed. Fuel pellets are the same as used in Qinshan nuclear power plant. A W / Re thermocouple assembly of 1.64 mm OD is inserted into the central hole of fuel pellets. Aluminium alloy pieces are mounted between double stainless steel claddings for simulating PWR fuel temperature and removing the heat generated in the fuel rod. Chromel–Alumel thermocouples and a turbine flowmeter are employed for measuring coolant outlet / inlet temperature and flow rate, respectivily.

For IFR–26–02 and IFA–26–03, emphasis is placed on in–pile tests of pressure gauges (membrane type) and LVDTs and the measurements of the fission gas pressure inside fuel rod and fuel cladding elongation, respectively.

4 Conclusions

This report is only a brief summary which presents the activities in connection with in–core transducer and the current IFR irradiation programme at the CIAE.

Five transducers have been fully tested under the conditions simulating realistic PWR. Their main performances have attained the design's goal.

With the construction and commisioning of PWR nuclear power plant in China, it becomes obvious that the fuel rod behavior needs to be studied thoroughly. On the basis of the current IFR irradiation test programme at the CIAE the further imformation on the performance of in–core transducers in nuclear radiation field can be obtained early, and continuous improvements of in–core transducers, irradiation rig design and experimental techniques make it possible to observe fuel rod behavior under realistic PWR operational conditions.

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Table I Main specifications of pressure gauge

Dimension	ϕ15 x 57 mm
Sensitivity	0.03 MPa
Max. operating temperature	350℃
Measuring range	0–4.5 Mpa

Table II Main specifications of LVDT

Type	SH5
Dimension	ϕ11.5x 70 mm
Linear range	0–5 mm
Sensitivity	30 mv / mm
Max. service temperature	350℃
Exciting frequency	400 Hz
Accuracy	1 % (out–of–pile)

Table III Main specification of turbine flowmeter

Type	TFM–II
Inside diameter	32 mm
Measuring range	5–14 m3 / hr
Max. pressure drop	0.01 MPa
Operatinging pressure	15.5 MPa
Operating temperature	320℃

Table IV In-pile test programe

IFR name	Purpose	Characteristcs	Transducers to be installed
IFR-26-01	· W/Re thermocouple assembly testing · Turbine flowmeter testing · Fuel rod centreline temperature measuring	· Single fuel rod · UO_2 with center hollow · Stainless steel cladding	· W3%Re/W25%Re thermocouple assembly · Turbine flowmeter · Chromel-Alumel thermocouples
IFR-26-02	· Pressure gauge testing · Force-balance system testing · Fission gas pressure measurements	· Single fuel rod · UO_2 · Stainless steel cladding	· Pressure gauge (membrane type) · Chromel-Alumel thermocouples
IFR-26-03	· LVDTs testing · Cladding elongation or fuel densification measurements	· Single fuel rod · UO_2 · Zircaloy cladding	· LVDTs · Chromel-Alumel thermocouples

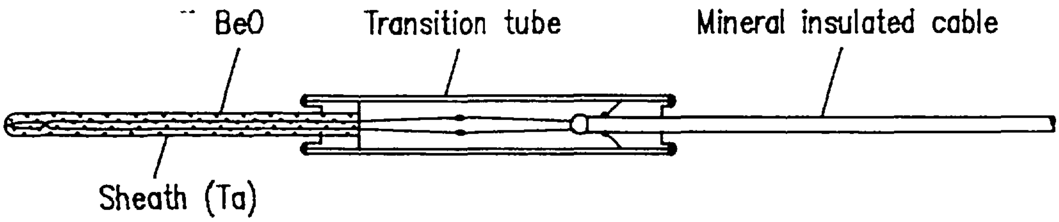


Fig. 1 Configuration of W3%Re/W25%Re thermocouple assembly

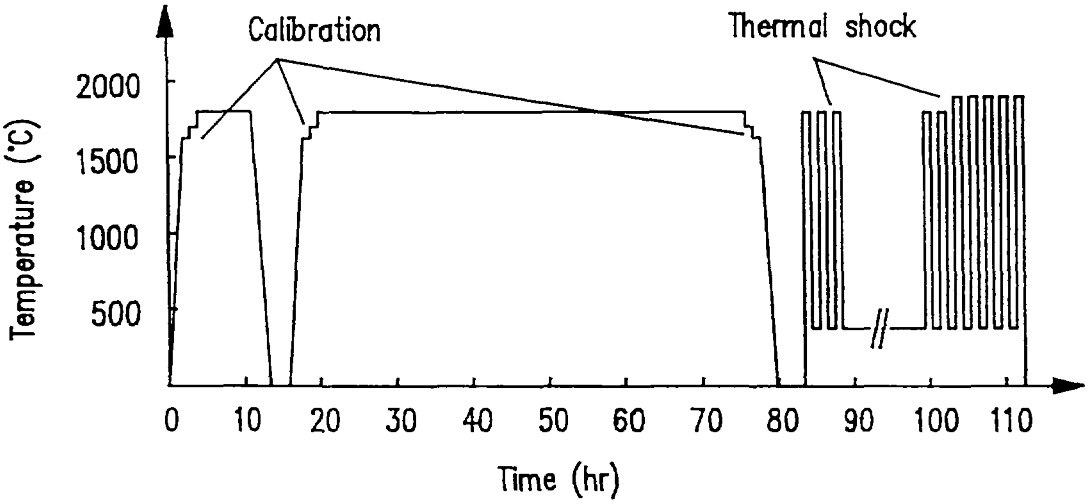


Fig. 2 Calibration and thermal shock of W/Re thermocouple assembly

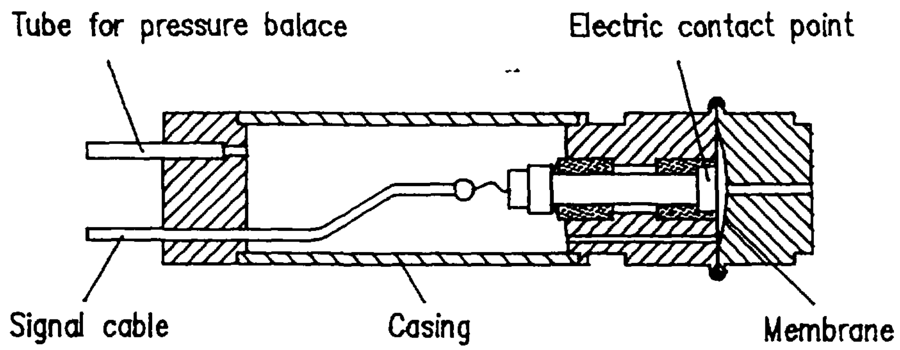
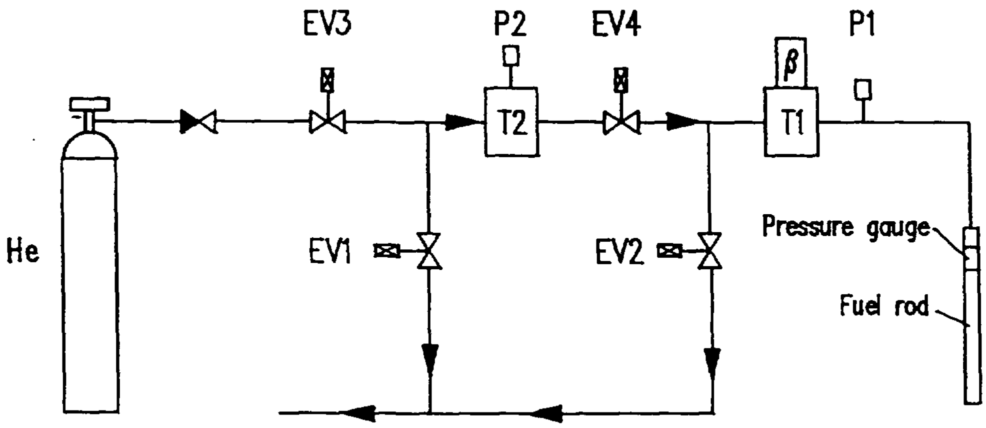


Fig. 3 Pressure gauge (Membrane type)



P – Pressure sensor
EV – Electromagnetic valve
β – β detecting station
T1 – Buffer tank
T2 – Balancing tank

Fig.4 Pressure measuring system

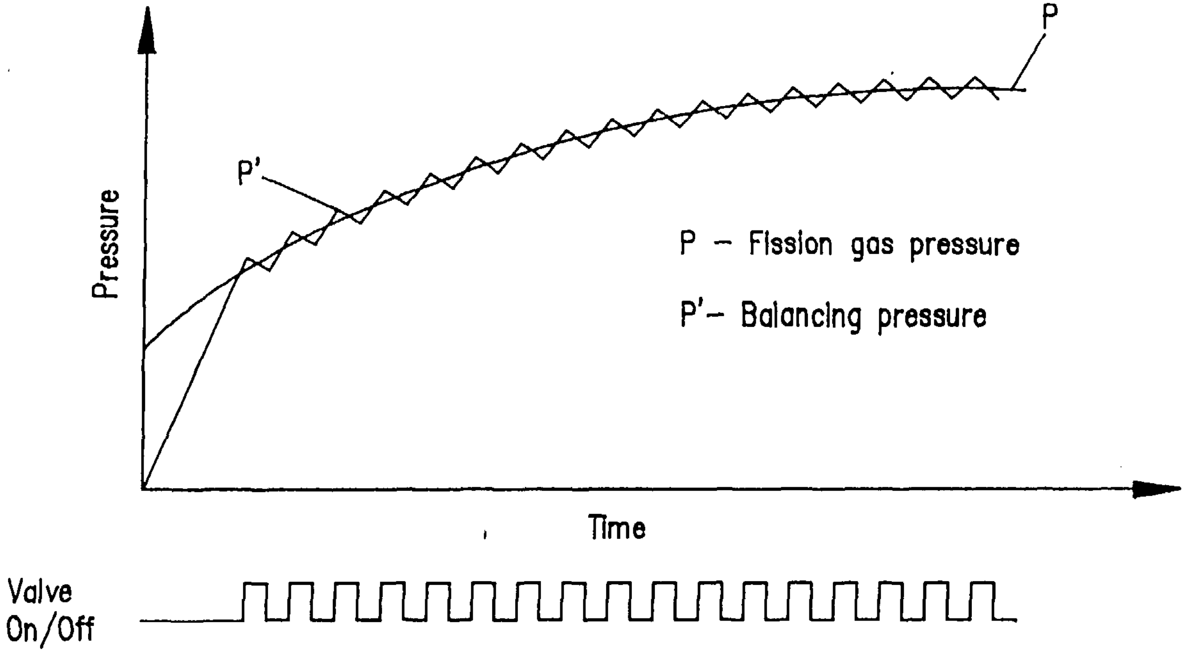


Fig.5 Pressure measurement

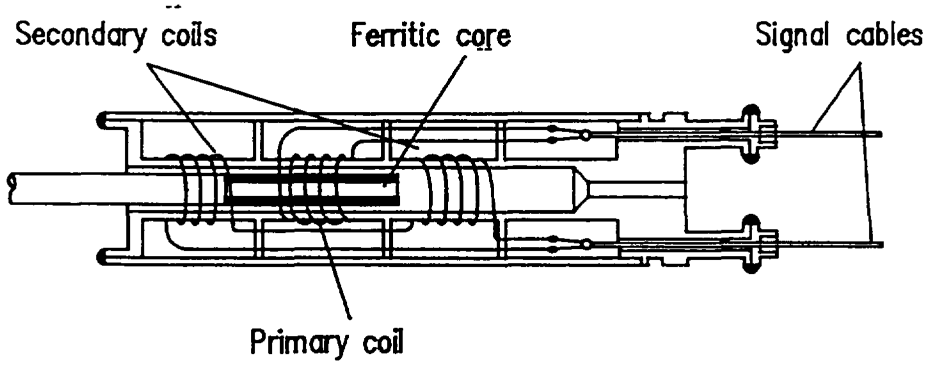


Fig. 6 Type SH5 linear variable differential transformer

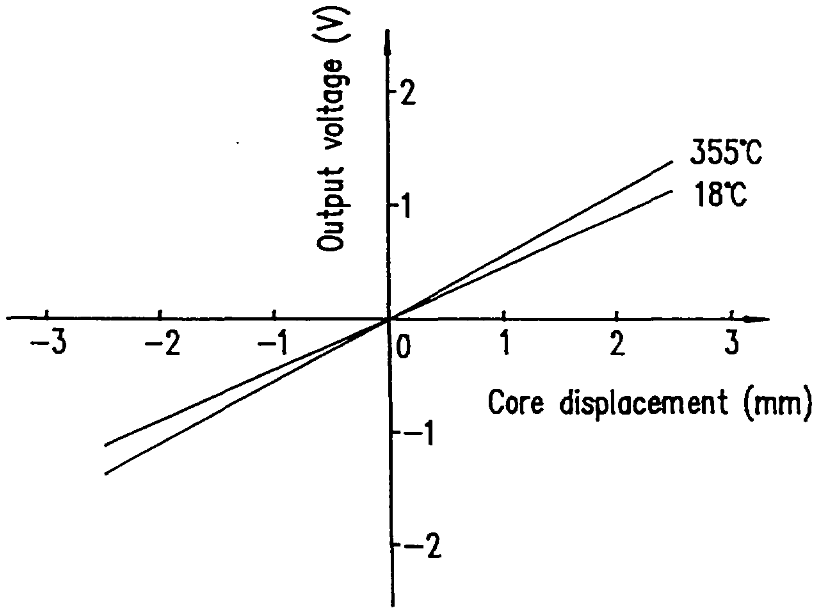


Fig. 7 Calibration curves of SH5 LVDT

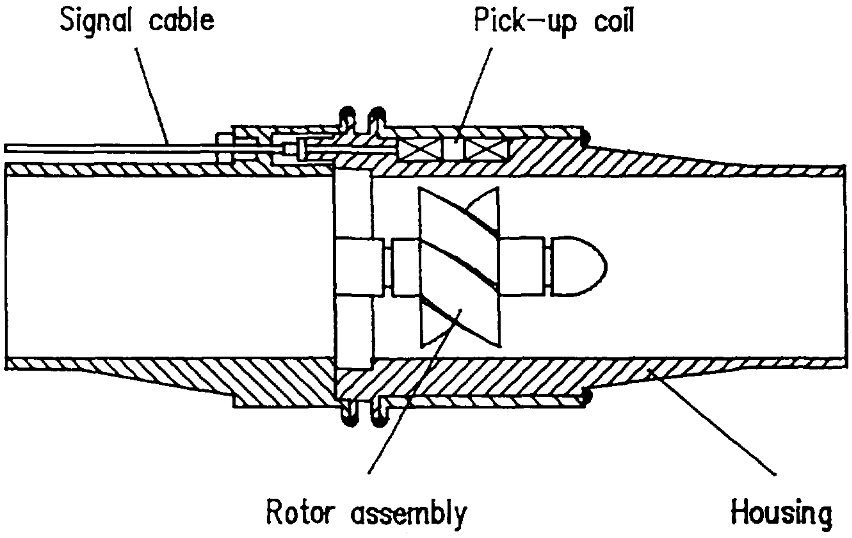


Fig.8 TFM–II turbine flowmeter

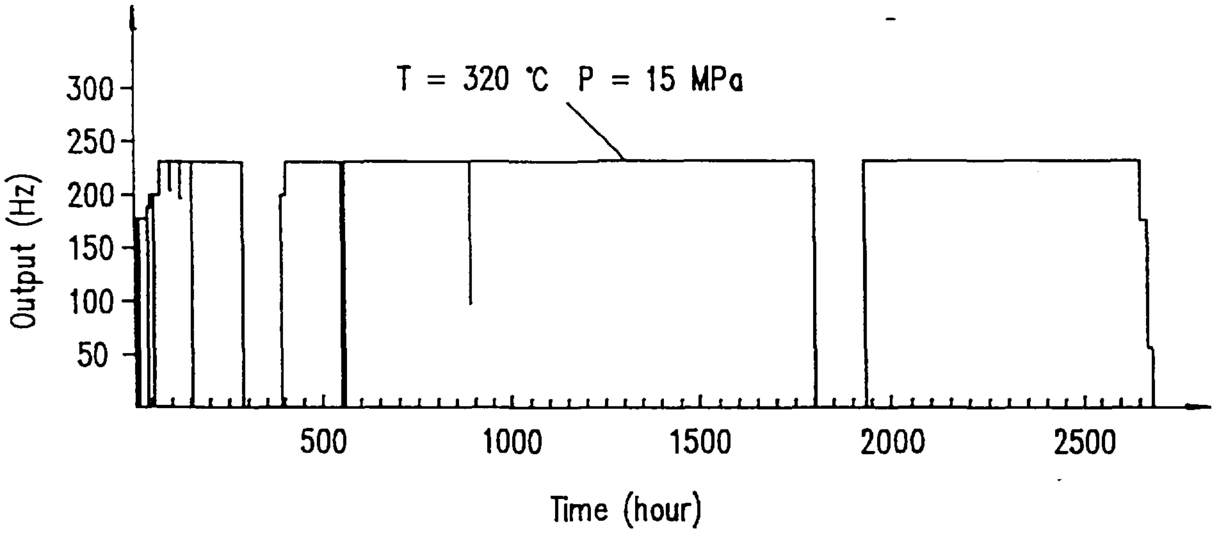


Fig.9 Operating history of TFM–II flowmeter

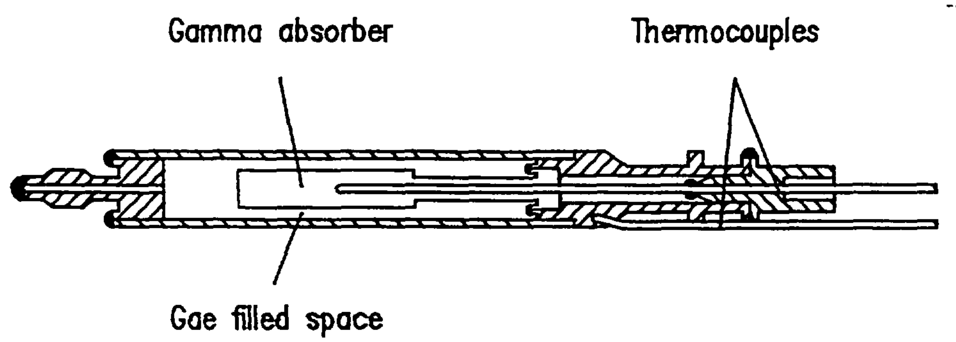


Fig. 10 Type GT—1 gamma thermometer

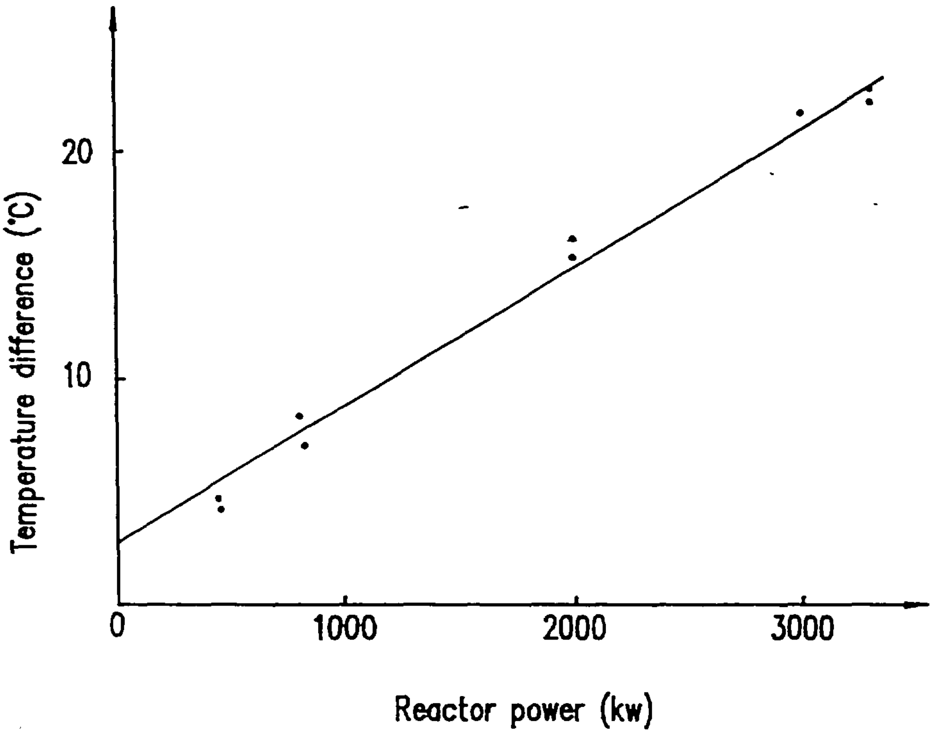


Fig. 11 Relationship between temperature difference and reactor power

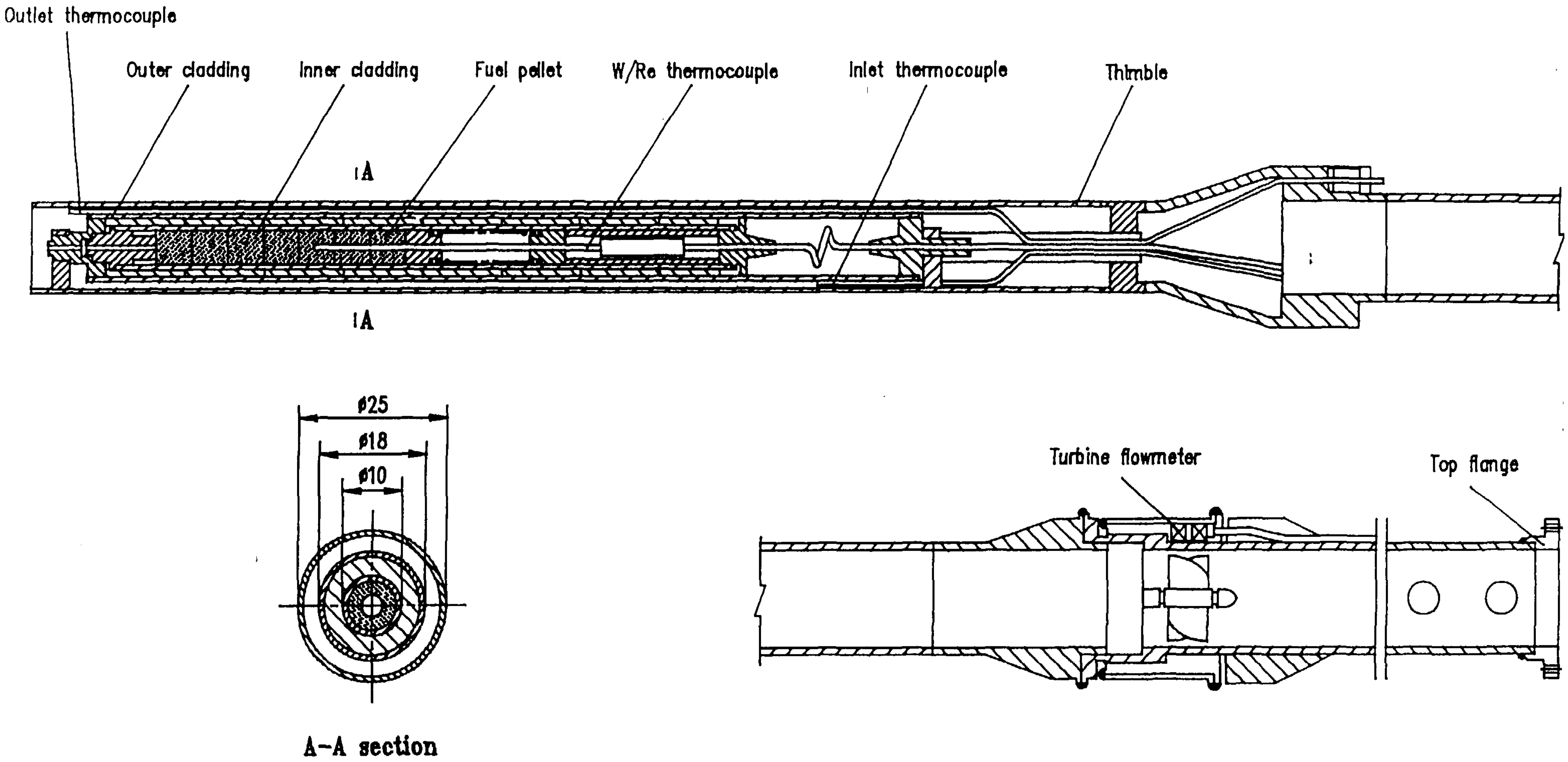


Fig. 12 Diagram of IFR-26-01 irradiation rig