IAEA-TC-389/6-13

IAEA specialists' meeting on gas-cooled reactor core and high temperature instrumentation
Windermere (UK)
15 - 17 June 1982

DEVELOPMENT ON EXPERIMENTAL VHTR INSTRUMENTATION

N. Wakayama, K. Ara, H. Terada, H. Yamagishi and *T. Tomoda

Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken, 319-11 Japan

Abstract

This paper describes developmental works on the instrumentation of the Experimental VHTR. In the area of the nuclear instrumentation for the reactor control, high temperature fission counter-chambers have been developed. These withstood the accelerated irradiation life tests at 600 ° C, the long term in-reactor operating test at 600 ° C and the 800 ° C-operating tests for several hundred hours in a simulated accident condition.

Platinum-Molybdenum alloy thermocouples have been studied as a neutron-irradiation-resistant high-temperature thermocouple for the in-core temperature distribution monitoring of the VHTR in the temperature range between 1000 °C and 1350 °C. The instability problems of the Pt-5%Mo/Pt-0.1%Mo thermocouple seem to be overcome by introducing a double sheath structure and adopting a getter material to the inner sheath.

A local failure and abnormality monitoring method for the HTR fuel is also studied using a gas-sweeping irradiation rig for the CPF compacts. This study aims mainly at the development of a method to compensate for the dependency of the FP-release rate on the fuel temperature, the neutron flux density, the burn-up and others, in order to increase the detection sensitivity of fuel failures.

1. Introduction

The construction of the Experimental Very High Temperature Gas Cooled Reactor (EVHTR) is projected in Japan as the first step of the development of multi-purpose high-temperature nuclear process-heat utilization. The outlet gas temperature of the EVHTR is planned to be 1000 ° C, as final target, for supplying the secondary process-heat gas of the temperature around 910 ° C (Ref. 1). With relation to this project, the research and developmental works are proceeded widely in the areas of materials, structure, heat-transfer, fuels, reactor physics, instrumentation, and others. In the field of reactor instrumentation, various efforts have been concentrated mainly on developments of high-temperature neutron detectors, high-temperature in-core thermocouples, and fuel failure detection method and system.

2. Development of High-temperature Neutron Detectors

In the nuclear design of the EVHTR, the neutron flux density just outside the pressure vessel was estimated to be about 3×10^7 n $cm^{-2}sec^{-1}$ at

*Mitsubishi Electric Corporation

the rated reactor power. This value is two or three decades lower than the desirable neutron flux level at the setting position of the neutron detectors for the nuclear instrumentation system for the reactor control and protection. For this reason, development of high-temperature resisting neutron detectors was required to install them in the reflector region in the reactor vessel. Neutron detectors to be used for the reactor start-up monitoring channels and/or the wide range monitoring channels and to be installed in the reactor vessel of EVHTR are required to function stably, at the temperature of about 400 °C for the ordinary reactor start-up, at about 600 °C for the restart-up just after the reactor trip and for the rated power range monitoring as a wide range monitoring chamber, and at 800 °C for several hundred hours for the core criticality monitoring during the severe design basis accident such as the large reactivity insertion accident and the primary cooling system depressurization accident.

The gamma-compensated ionisation chambers (CICs) for the power range monitoring channels are planned to be installed on the outside wall of the reactor vessel at present, so that the operating temperature ratings of 400 °C is enough for these CICs, even such accident is considered.

2.1 Fission Counter-Chambers

The following items were considered, studied and applied in the development of high-temperature fission counter-chambers:

1) The use of fast chamber gas in a high-temperature environment was studied in order to obtain large output pulse current and short collection time performances of the chamber with relatively low polarizing voltage in the pulse mode operation. This is very essential to attain performances of a good signal-to-noise ratio, a wide counting range such as 1 to 10^7 cps and a good neutron-to-gamma discrimination characteristic in the start-up channels. This aim was achieved by the use of a combination of the argon-nitrogen mixed gas, Ar-5%N_2-1%He, and the nickel base super alloy, 78%Ni-16%Cr, as electrode and structual metals.

2) The cathode is provided separately from the vessel (ground), as shown in Fig. 1, to make a push-pull operation possible for reducing a common mode noise, mainly consisting of electric interference noises, in the pulse and the mean square (MS) mode (Fig. 2). This arrangement also makes this chamber possible to be used as an ordinary DC chamber in the power range.

3) Furthermore, a double vessel structure is used as shown in Fig. 1. The inner vessel is provided separately and insulated from the outer vessel and it forms the high quality ground connected with the inner sheath of the triaxial MI-cables. The most important reason of the use of the double structure is to protect the metal-ceramic seals from a high pressure at a high temperature. Helium gas is filled between the inner vessel and the outer vessel at the same pressure with that of the chamber gas filled in the inner vessel. Consequently, no large pressure difference is appeared between the inside and the outside of the seals even at the high temeprature. The same technique is also applied to the end seals of the MI cables.

4) Integrated mineral insulated triaxial cables having a copper inner conductor and a copper inner sheath are used to keep the signal transmission loss minimum and to reduce the electric interference noises.

5) Fission material (enriched U-235) is coated on both of electrodes, i.e., cathode and anode, to make chamber size small. Reduction of chamber size is profitable to the structure design against high temperature problems and to the improvement of the neutron-to-gamma sensitivity ratio.

6) When the temperature of neutron detector rises or falls, the thermal

expansion differences appear between electrodes, the inner vessel and the outer vessel. However, no metal spring without relaxation is available in the temperature range above 500 ° C. As a countermeasure against this problem, main internal components of the chamber such as the electrodes and the inner vessel are fixed at the one end, and the another end of the each component is supported by a sliding mechanism to release these thermal expansion stresses.

By adopting the above mentioned techniques, high temperature fission counter-chambers, such as FX-2, FX-2A, and FX-3 having the long term operating temperature ratings of 600 °C, were developed, and the characteristics of these chambers were investigated in detail under high-temperature environments (Ref. 2).

Accelarated neutron irradiation life tests have been carried out in the material testing reactor JMTR and the research reactor JRR-3. The chamber withstood the neutron irradiation of 6.5 x 10^{18} n cm^{-2} at 600 °C (Ref. 2). The over-heat tests in simulated accident conditions have been also carried out for the virgin chambers and the irradiated chamber up to 7.6 x 10^{17} n cm in the JRR-3. These chambers functioned stably at 800 °C for a long time, e.g., 510 hours, without the change of the characteristics. Figure 3 shows a result of a over-heat test at temperature up to 800 °C.

It has been also verified that these fission chambers can measure the low level neutron flux of the order of several n $cm^{-2} sec^{-1}$ under the very high gamma-ray background of the order of several million R/hr (Ref. 2). Furthermore, the long term in-reactor operating test at 600 °C is continued in the research reactor JRR-4 since December 1978 for the fission chambers FX-2A and FX-3. Figure 4 shows one of the results obtained in this test. Figure 5 shows the output linearity of a developed chamber. The flux range between 20 to 8 x 10^6 n $cm^{-2} sec^{-1}$ is measured with the pulse mode (counter mode) and the flux range 3 x 10^3 to 7 x 10^{10} n $cm^{-2} sec^{-1}$ with the MS (Campbelling) mode.

As for these fission chambers, the developmental work has been almost finished. Recently, however, a break-off trouble of the lead connecting with the electrode and the MI cable has experienced in some fission chambers, when the production process had been changed a little. As the countermeasure against this trouble, the improvement of the welding process of the lead is being conducted to increase the reliability and to assure a more complete quality.

2.2 Compensated Ionisation Chambers

Heat-resisting gamma-compensated ionisation chambers are also under development to use them as the sensors for the power range monitoring channels and the safety channels of the VHTR. The final target for the operating ratings of these chambers are 400 ° C in the case of the Experimental VHTR.

1) The principal heat-resisting structure of the CICs is similar to that of the fission chambers described above.

2) The volume compensation method is used because the change of gamma-compensation factor is relatively small with the variation of gamma-ray fluence rate and temperature.

3) Two kinds of metals, titanium and a nickel base super alloy, were tried as the material of the electrodes. There was an evaporation problem of titanium oxide at the off-gas process for the titanium electrodes and a difficulty to obtain the nickel base alloy of low cobalt and manganese contents.

4) Helium is mainly used as the filling gas, but a mixed gas of argon

containing several percent of helium and nitrogen is also tried for the chambers having the nickel base alloy electrodes.

Figure 6 shows the compensating performances of a manufactured CIC as a function of the compensating voltage and gamma-ray fluence rate (a), and temperature (b). Figures 7 and 8 show the plateau characteristics and the output linearity of the CIC at 400 °C and 25 °C.

At the 400 °C-operation, a dark current having a plateau of the order of 3×10^{-10} is observed in Figs. 7 and 8. It seems to be caused by the electron emission from the surfaces of electrodes. The dark current of the CIC increases up to around 2×10^{-8} A at 600 °C, and it means that the chambers can be used only in a large output current range, e.g., 10^{-5} to 10^{-3} A, at 600 °C.

3. Development of In-core High-temperature Thermocouples

3.1 Requirements and Strategy for Development

Measurement of helium-gas temperature distribution at the outlet of in-core fuel region is extremely important for maintaining an uniform in-core temperature distribution inside the EVHTR and for operating it safely with the average outlet gas temperature of 1000 °C within the severe limitation of a high-temperature structure and materials. This brings about a requirement to measure, accurately, an in-core gas temperature of 1000 to 1350 °C over long period of reactor operation. The temperature sensor used must have a long lifetime as well as high reliability. Ordinary high-temperature thermocouples that are commercially available and widely used, however, can not be used as the temperature sensors inside the EVHTR core unless they are subjected to major improvement. After surveys and investigations of temperature sensors, a strategy for development of thermocouples was settled: reliability improvement of W-Re alloy thermocouples as a short term target, and development of Pt-Mo alloy thermocouple as a long term target.

3.2 Tungsten-Rhenium Alloy Thermocouple

The tungsten-rhenium (W-Re) thermocouples are well-known as the highest temperature thermocouples among presently available ones. However, oxidisation and recrystallisation of the W-Re alloy elements are very active at high temperature, and this frequently results in embrittlement and failure of the elements and in drifts of the electromotive forces (EMF). These problems seem to be solved by a proper design of thermocouple structure; thus, development of the stranded-elements thermocouple with CA-composite, as shown in Fig. 9, was started. The CA-composite type thermocouple has been tried to be used by Debeir and the stranded-type thermocouple by Ward and Cornock, respectively, (Ref. 3, 4).

The thermocouple consists of stranded W-26Re/W-5Re elements (0.076 mmØ x 7-21), double sheaths and alumina insulators. The elements are connected to the double CA elements at the point of around 600 °C to minimize the necessary length of the W-Re elements. The inner sheath serves not only as a mechanical protector of the elements but also for gettering impurity gases containing in the filled helium gas and liberating from the insulator, and the outer sheath as a mechanical and chemical protector of the inner sheath against the in-core atmosphere containing somewhat reducing impurities under normal reactor conditions and oxidising impurities under accident conditions.

After trial fabrications of about fifteen thermocouples, out-pile high-temperature tests and in-pile high-temperature irradiation tests were carried out. The out-pile tests of Mo/Ta sheathed 7-stranded thermocouples were carried out at 1000 °C, and no drifts of the EMF were observed. Also, the in-pile tests were carried out at about 1400 °C for TZM/Nb-1%Zr sheath 21-stranded thermocouples. The results of this test are shown in Fig. 10. The EMF drifts due to irradiation were about 2% for the thermal neutron fluence of about 5×10^{20} n cm^{-2}. Further, the post irradiation examinations showed no existences of reactions between the sheaths, the insulators and the elements; but small cracks were found in the thermocouple elements as shown in Photo. 1.

3.3 Pt-Mo Alloy thermocouple

Since the W-Re alloy thermocouples have the inherent problem of nuclear transmutation resulting in drifts of the EMF, its continuous application in the reactor core is limited only for short periods. This makes necessary a frequent exchange of the thermocouples to guarantee the accuracy of temperature measurements. Therefore, an incentive has been born to develop a thermocouple which is free from the transmutation problem. The best candidate seems to be a Pt-Mo alloy thermocouple, since both platinum and molybdenum have ralatively small neutron cross sections and high melting points.

The possibility of applying a Pt-Mo alloy to a thermocouple element was investigated by Nishimura (Ref. 5). Its applicability in the HTGR in-core environments was studied and the combination of Pt-5%Mo/Pt-0.1%Mo elements was introduced by Reichardt (Ref. 6). In-core behaviours of this thermocouple was examined by Rohne (Ref. 7). However, there are still many unknown characteristics of the elements, such as the stability of EMF and their compatibility with insulators and sheath materials, especially in high-temperature environments: investigation of these fundamental characteristics must be essential for applying them practically.

For an investigation of high-temperature environmental compatibility, the bare element wires of Pt-5Mo and Pt-0.1Mo were tested in the atmospheres of commercial-grade pure argon, argon containing about 100 ppm O or 100 ppm H, and of the vacuum, at 1000 - 1400 ° C. Severe corrosions due to selective oxidisation of Mo were observed on Pt-5%Mo element in every cases except in the case of vacuum atmosphere. Photograph 2 shows metallographical changes of the elements after the tests in the pure argon and the vacuum. Oxygen of the amount of less than 1 ppm in pure argon reacted with Mo selectively and actively. This means that a perfectly clean atmosphere is needed for the elements. Figure 11 shows another evidence of this. One of the way for keeping the atmosphere clean around the elements is adoption of a "getter" sheath such as Ta-sheath, Nb-sheath and the like. Ta-sheathed thermocouples were examined at 1200 °C for investigating the effectiveness of this gettering effect. Figure 12 shows the results of this experiment. EMF changes were larger than that recorded in the atmosphere of high-temperature vacuum, but were within 1%, meeting the requirements for practical application in the experimental VHTR. Metallographical changes were similar to those in the vacuum, and no corrosion was observed. As the next stage of work, the double-sheathed CA composite-type Pt-Mo thermocouples are being manufactured for their long term operating tests in a simulated in-vessel atmosphere and the in-pile irradiation life test.

4. Development of Fuel Failure Detection Method for the Coated Particle Fuel for VHTR

Fuel failure detection for the caoted particle fuel (CPF) is extremely difficult as compared with that for the conventional metal cladding fuel. In general, the CPF releases fission products little by little to the primary coolant even during the normal operation condition of HTGR. Therefore, the radiation background level due to FP nuclides in the primary coolant is rather higher than those in conventional type reactors using metal cladding fuels. Moreover, as widely known, the background level changes considerably depending on the fuel temperature, reactor power, burn-up rate, and others. Figure 13 shows a measured example of FP-release characteristic as a function of the fuel temperature (Ref. 8). These facts make it difficult very much to detect the small increase of FP level due to fuel failure of the CPF. Supposing that the ordinary fuel failure detection system for the conventional GCRs would be applied to the EVHTR and the total activities in the primary coolant would be monitored including piled-up long-life nuclides, it is estimated that the system can only distinguish the abnormality in a short time when the CPFs of 8 to 11 % exsisting in the monitoring region would have failed even under the rated power and constant temperature operating condition. Such scale of the fuel failure is not so small from the reactor operation and core management point of view.

In order to solve this problem, development of high sensitive fuel failure detection system for the CPF has been started on the basis of following considerations:

1) In order to reduce the effect of long-life FP-nuclides accumulated in the primary coolant and to make the measurement of newly born FP-nuclides easy, short-life FP-nuclides are monitored selectively.

2) A state equation is established on the concentration of the short-life FP-nuclides in the primary coolant. This is introduced into the FFD in order to distinguish the small change of concentrations of the short-life FP-nuclides, caused by CPF failures, from the variation of the concentration of the same sort of nuclides, caused by the change of the reactor operating state parameters such as fuel temperature and local power density.

The state equation in the normal operation can be represented as follows;

$$G = F(T,P,B,F,Q, - - -),$$

where G: concentration of short-life nuclides or its measured value,
T: fuel temperature,
P: reactor power,
B: burn-up ratio of the CPF,
F: flow rate of the primary coolant helium,
Q: a measure of fuel quality obtained at sampling batch test of the fuel production.

Then the failure of the CPF can be detected by means of judging whether the behaviour of the short-life background measured in a certain reactor operating conditioin is deviating from a certain range given by the state equation or not.

As the first step of the development, a selective detection system for short-life FP-nuclides was made up combining a multi-interval counting system and a wire precipitator. This detection system was connected to the primary circuit of an CPF-irradiation rig under sweeping gas, named FGS, in the JMTR as shown in Fig. 14 (Ref. 9). The irradiation rig supplies sample gas containing FP-nuclides released from CPFs to the precipitator. This irradiation rig was originally prepared for the CPF research and has an ability to irradiate several fuel samples and to control the irradiation condition, such as irradiation temperature and gas flow, individually for each fuel, and has FP-gas analysing system including a gamma-ray spectrometer. Consequentry, it is relatively easy to investigate the quantitative relationship between the irradiation condition of CPF and the counting rate of the precipitator to obtain the state equations for the FP monitoring.

The FFD experimental device system has been installed at the site of the JMTR and the experiment has been started at the end of 1981. Figure 15 shows a typical measured data by this system during a start-up period of the JMTR. In this experiment, it is expected to detect short-life FP-nuclides, for example Kr-89(3.18m), Kr-90(32.3s) and Xe-139(39.7s). Up to now, however, as the irradiated CPF samples have had only low failure rates, detected FP-nuclides are mainly of moderate-life; e.g., Xe-138(14.1m) and Kr-88(2.84h).

This experiment using FGS will be proceeded until the end of 1985 and it is expected to obtain the precise state equation for the high sensitive fuel failure detection system.

5. Future Works

This paper reported the current status of research and development on VHTR instrumentation in Japan. Almost all developmental studies seem to be progressing successfully, but it is also a fact that there are still many big problems to be solved in this area.

Compatibility problems between sheath materials of in-core sensors and graphite should be studied in detail.

Development of in-core neutron chamber is also required by the reactor designing people. Although an in-core chamber having the temperature ratings of 600 °C is commercially available, the in-core chamber to operate at the temperature above 1000 °C is necessary to be developed anew and it must be very difficult work.

Installation and penetration methods for the in-core sensors such as in-core thermocouples and in-core chambers are one of the biggest problems in the design of reactor instrumentation. It is well known that the poor installation of thermocouples gives very large measuring errors in the in-core gas temperature measurement even if the sensor itself has a good accuracy.

Acknowledgements

The authors thank all the people concerned, particularly Messrs. M. Yamada, M. Katagiri, H. Itoh and K. Shimizu of the JAERI, and Messrs. S. Fukakusa and S. Tanaka of the MELCO, for their great contribution to this work.

References

(1) Aochi, T. et al., First Conceptual Design of the Experimental Multi-Purpose High-Temperature Gas-Cooled Reactor (in Japanese), JAERI-M 6845 (1977)

(2) Wakayama, N. et al., Development of Fission Chambers for High-Temperature Reactors, Nuclear Power Plant Control and Instrumentation Vol. II, pp. 243-255, IAEA (1978)

(3) Debeir, R.P., Thermocouples Composites, International Colloquium on High-Temperature In-Pile Thermometry, pp. 89-111, EUR 5395 (1975)
(4) Ward, D. and Cornock, H., High Temperature Stranded Tungsten-Rhenium Thermocouples, ibid., pp. 73-88
(5) Nishimura, H., Investigation of Pt-Mo Alloy (in Japanese), J. Japan. Inst. Metals,Vol. 22, pp. 425-428 (1958)
(6) Reichardt, F.A., Measurement of High Temperatures under Irradiation Conditions, Platinum Metals Rev., Vol. 7, pp. 122-125 (1963)
(7) Rhone, B., High Temperature Thermocouple Applications in the R2 Reactor at Studvik, Sweeden, International Colloquium on High-Temperature In-Pile Thermometry, pp. 477-495, EUR 5395 (1975)
(8) Japan Atomic Energy Research Institute (ed.), Present Status of Researches and Developments on Multi-purpose Very High Temperature Gas Cooled Reactor in JAERI, pp. 219-222 (1979), The data, measured by the Irrad. Sect. II, JMTR Div.
(9) Katagiri, M., Terada, H., and Wakayama, N., Development of Fuel Failure Detection System, Reactor Engineering Division Annual Report, pp. 102-103, JAERI-M 9672 (1981)

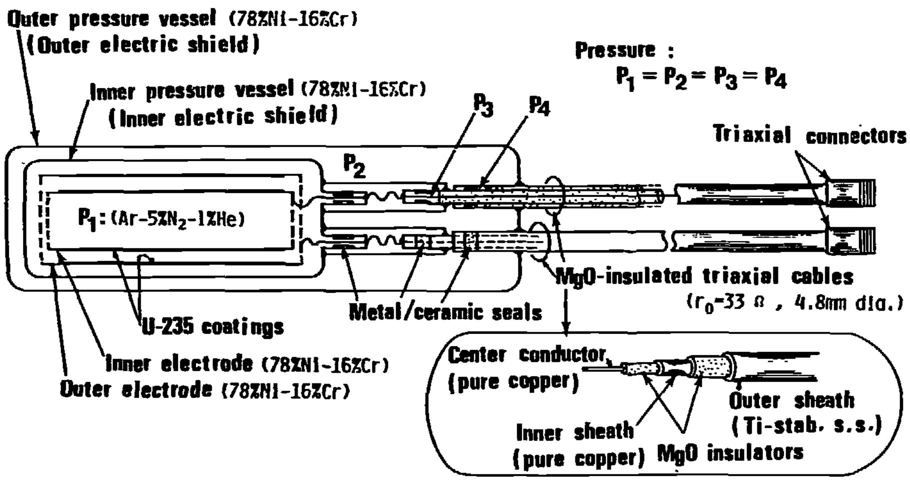


Fig. 1. Conceptual structure of the FX-2 and -3 series fission chambers.

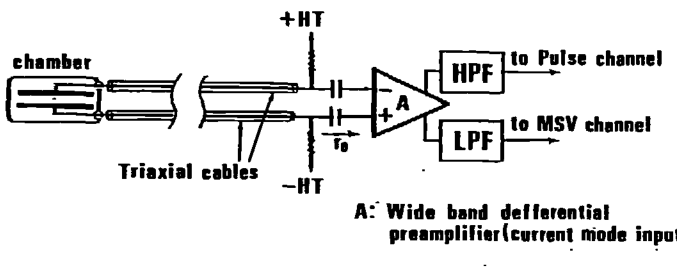


Fig. 2. Push-pull operation of the fission chamber to improve signal-to-noise ratio.

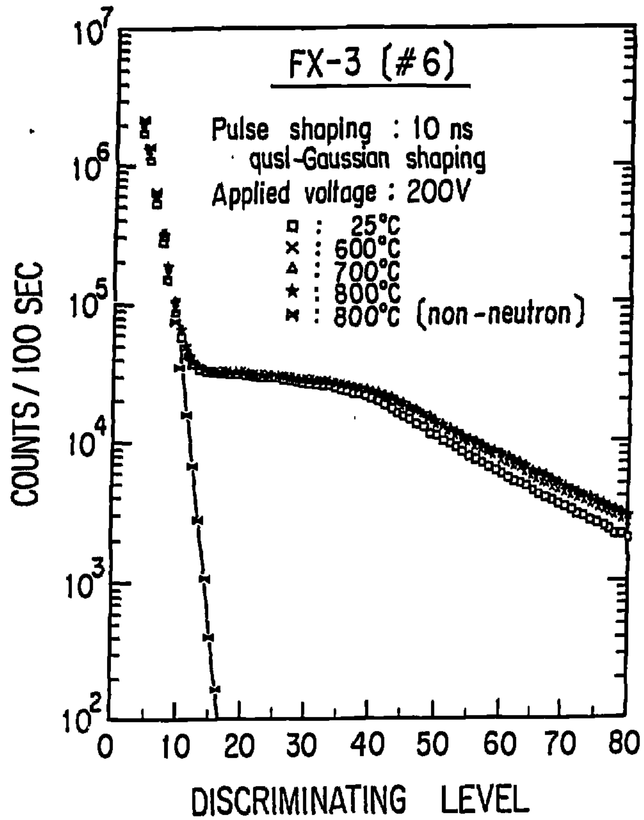


Fig. 3. Integral bias curves of a FX-3 fission chamber at 25, 600, 700 and 800°C.

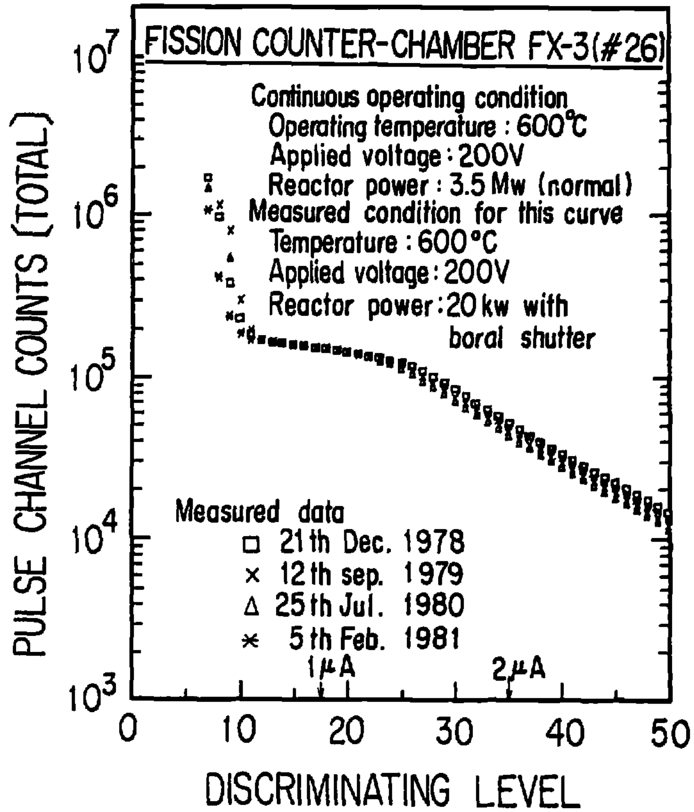


Fig. 4. A results of the long term in-reactor operating tests at 600°C.

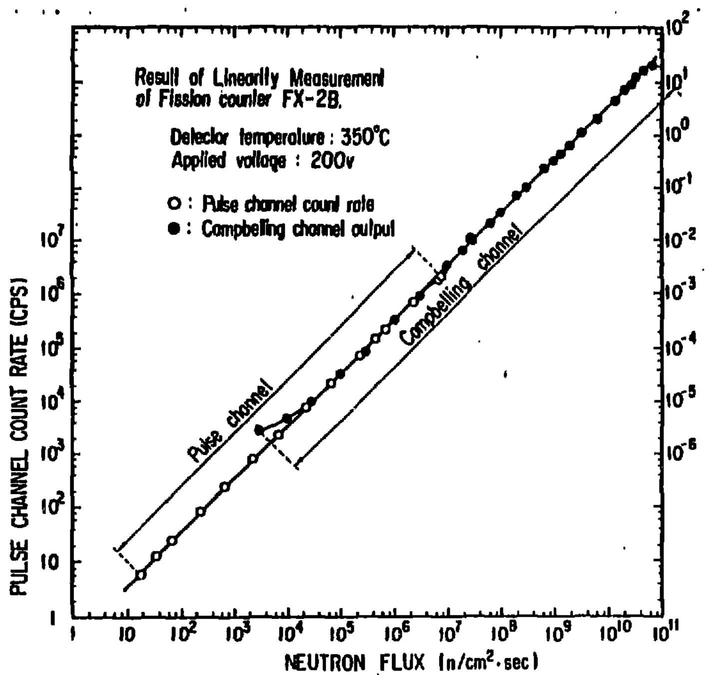
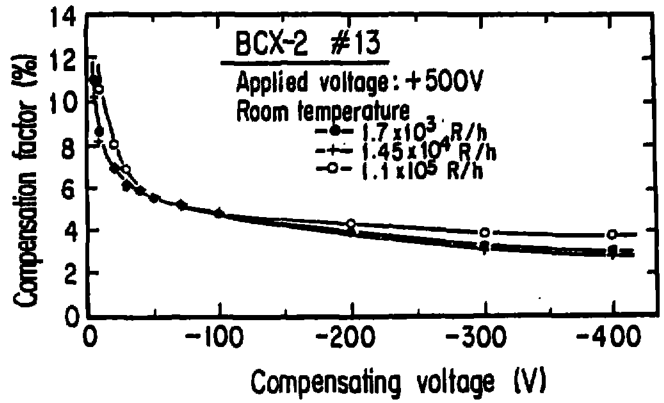
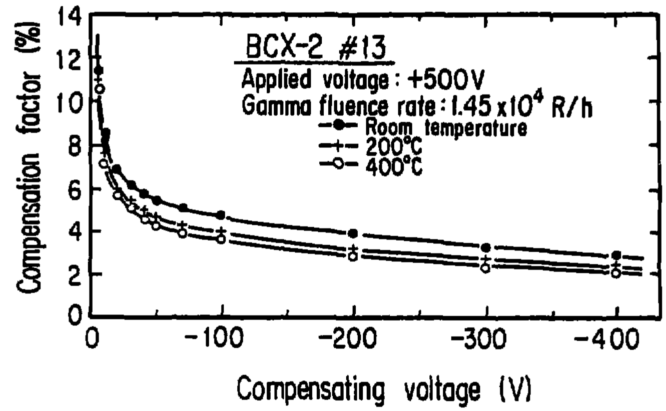


Fig. 5. Output linearity of a fission chamber developed.



(a) Gamma-ray fluence-rate dependency.



(b) Temperature dependency

Fig. 6. Gamma-compensating performance of a BCX-2 chamber as a function of compensating voltage, *gamma*-ray fluence rate and temperature.

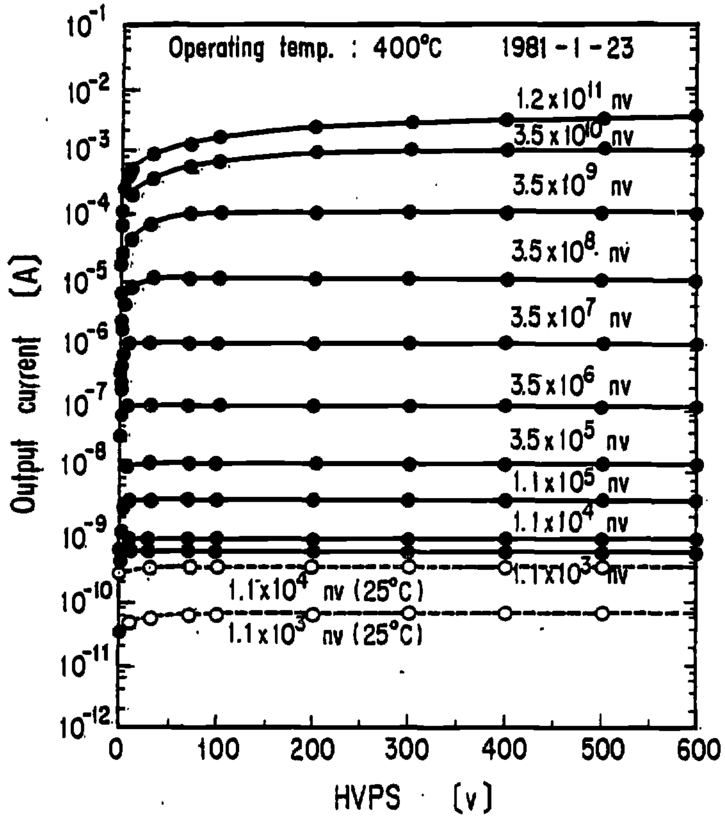


Fig. 7. Plateau characteristics of a BCX-2 chamber at 400°C.

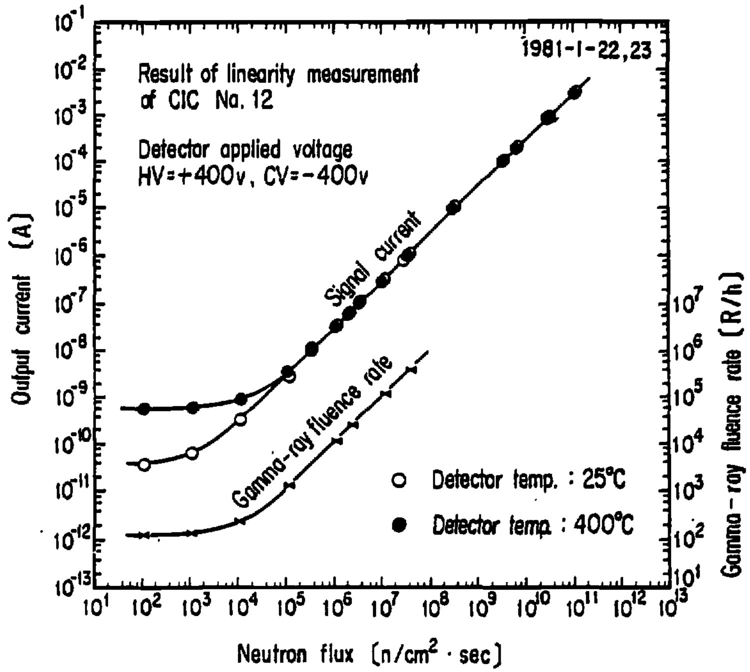


Fig. 8. Output linearity of the BCX-2 chamber at 25°C and 400°C.

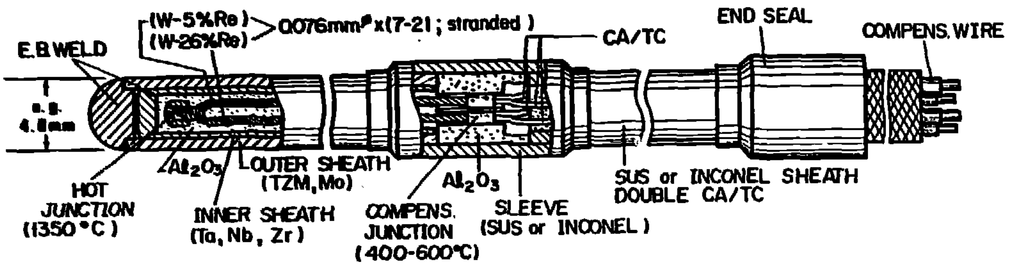


Fig. 9. Structure of stranded-elements W-Re alloy thermocouples with CA-composite.

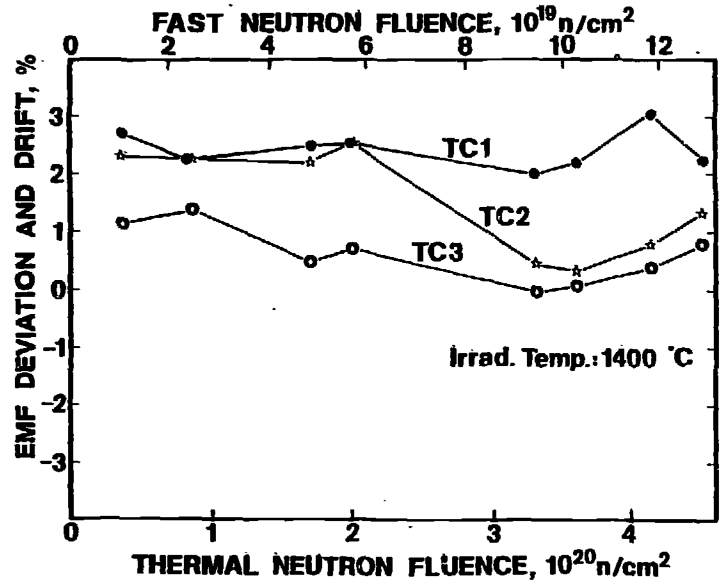


Fig. 10. EMF drifts of TZM/Nb-1%Zr sheathed W-26Re/W-5Re thermocouples in vacuum at 1200°C.

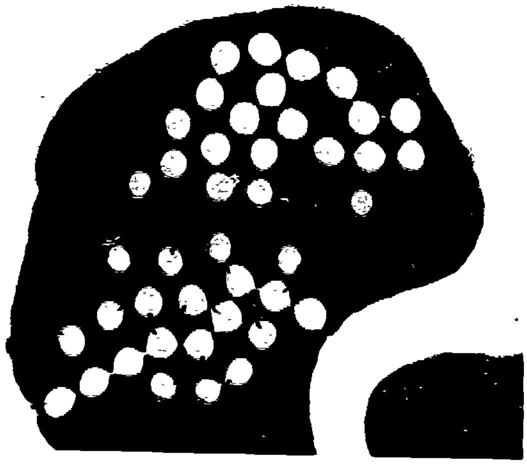


Photo. 1. Microphotography of hot-junction of irradiated W-26Re/W-5Re thermocouple.

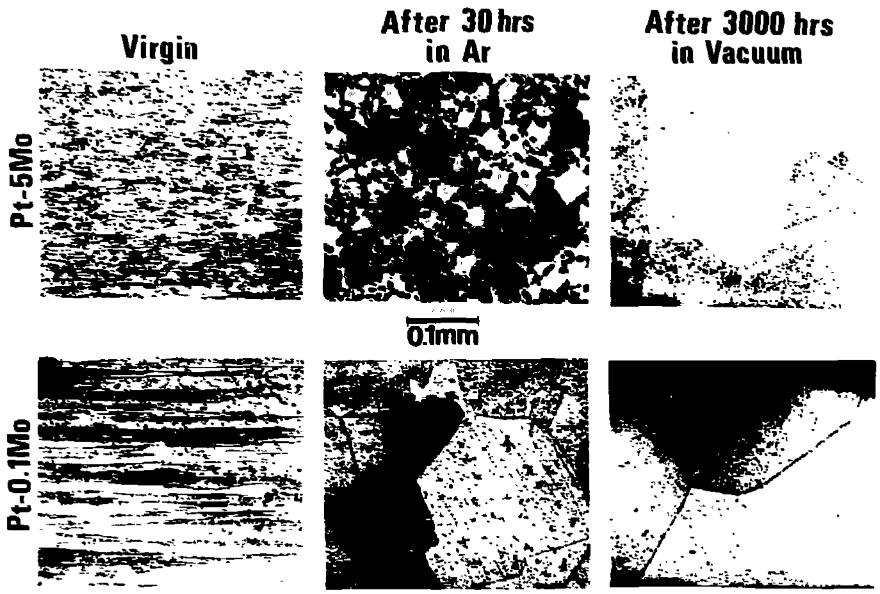


Photo. 2. Metallographical changes of Pt-5Mo/Pt-0.1Mo TC elements at 1200 °C.

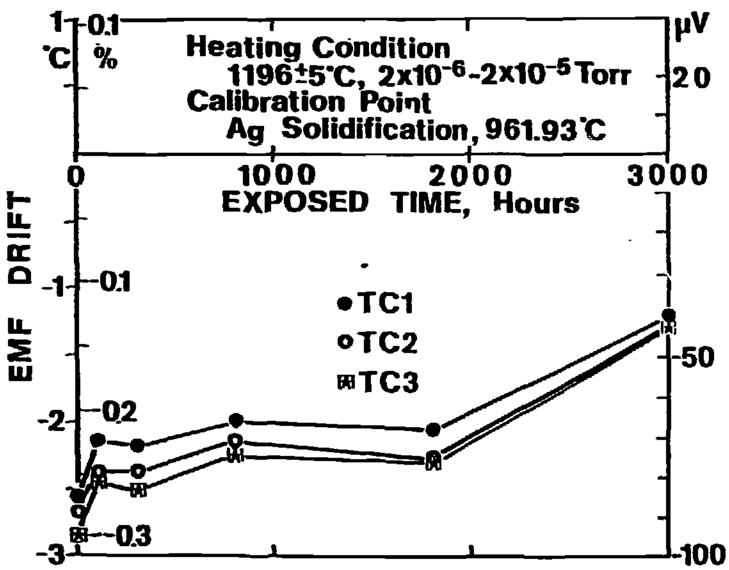


Fig. 11. EMF drifts of bare Pt-5Mo/Pt-0.1Mo thermocouples at 1200°C.

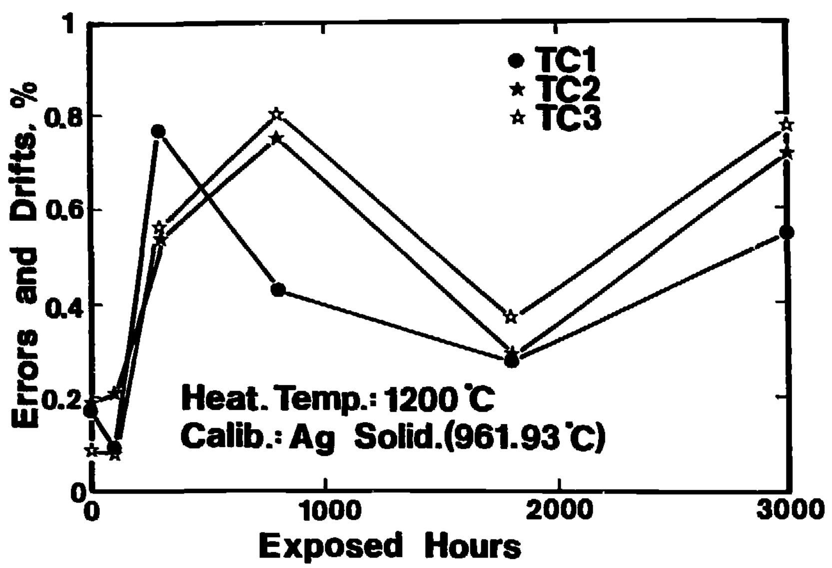


Fig. 12. EMF drifts of Ta-sheathed Pt-5Mo/Pt-0.1Mo thermocouples at 1200°C.

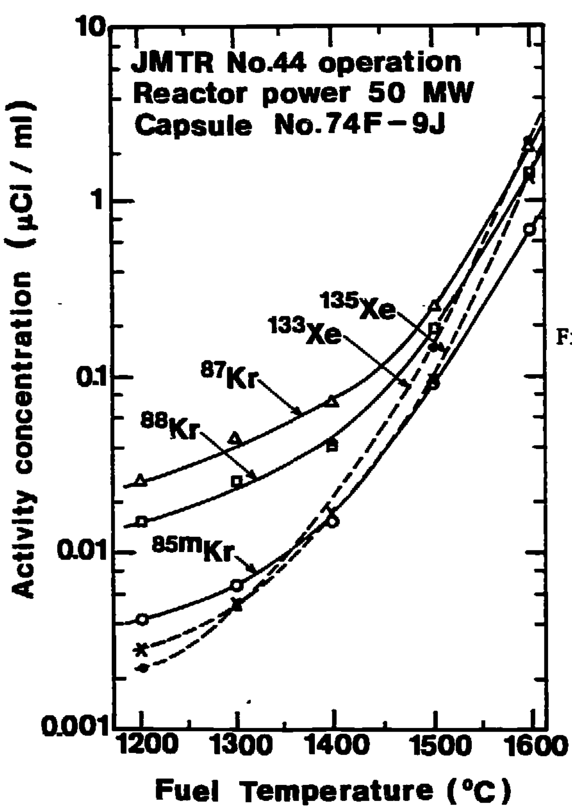


Fig. 13. FP-release characteristic of CPF as a function of the fuel temperature (Ref. 8).

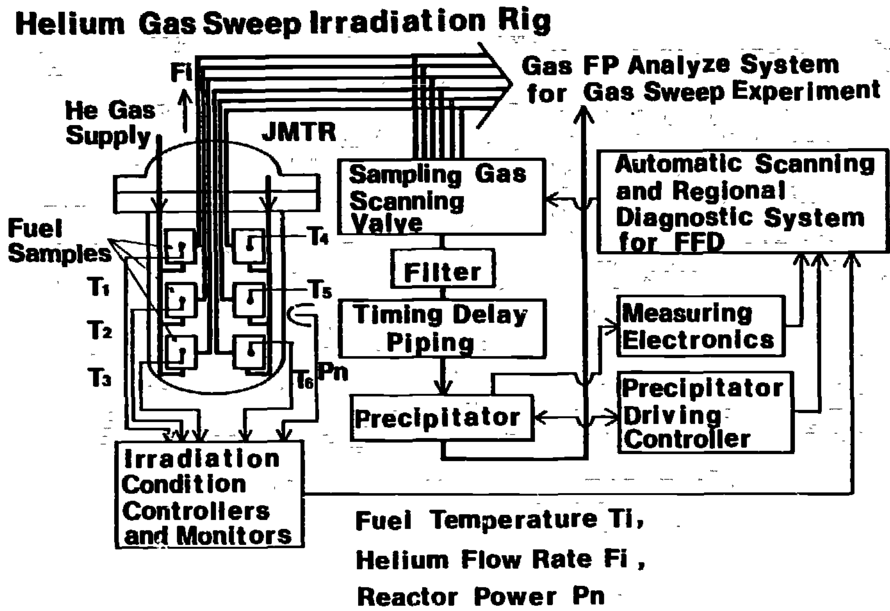


Fig. 14. Schematic diagram of the FFD experimental system.

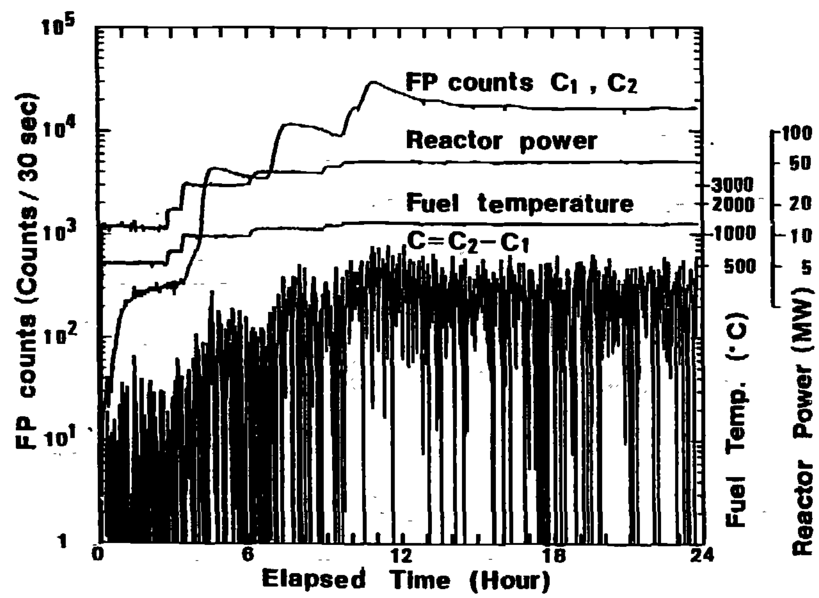


Fig. 15. An example of measured results by the system
during a start-up period of the JMTR.