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Applicability Study of Optical Fiber Distribution Sensing to Nuclear Facilities

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ABSTRACT

Optical fibers have advantages like flexible configuration, intrinsic immunity for electromagnetic fields etc., and they have been used for signal transmission and as optical fiber sensors (OFSs). By some of these sensor techniques, continuous or discrete distribution of physical parameters can be measured. Here, in order to discuss the applicability of these OFSs to nuclear facilities, irradiation experiments to optical fibers were carried out using the fast neutron source reactoe 'YAYOI' and a ^{60}Co γ sourceIt has been shown that, under irradiation with fast neutrons, the radiation induced loss increase almost linearly with the neutron fluence. On the other hand, when irradiated with ^{60}Co γ rays, the loss shows a saturation tendency.

As an example of the OFSs, applicability of the Raman distributed temperature sensor (RDTS) to the monitoring of nuclear facilities has been examined. Two correction techniques for radiation induced errors have been developed and for the demonstration of their feasibility, measurements were carried out along the primary piping system of the experimental fast reactor:JOYO. During the continuous measurements with the total dose of more than 10^7[R], the radiation induced errors showed a saturating tendency and the feasibility of the loss correction technique was demonstrated. Although the time response of the system should be improved, the RDTS can be expected as a noble temperature monitor in nuclear facilities.

1.INTRODUCTION

Otical fibers have advantages like immunity to electromagnetic interference, high data throughout, high multiplexing capability,small dimensions, low weight, installation flexibility andease of maintenance. Beside they are used for data communication systems, they have been also used as sensing elements. As optical fiber sensors (OFSs) have advantageous like the possibility of distribution measurements, they have been applied for industrial monitoring like e.g. temperature distribution measurements along electrical lines, temperature monitoring inside an intelligent building(1).

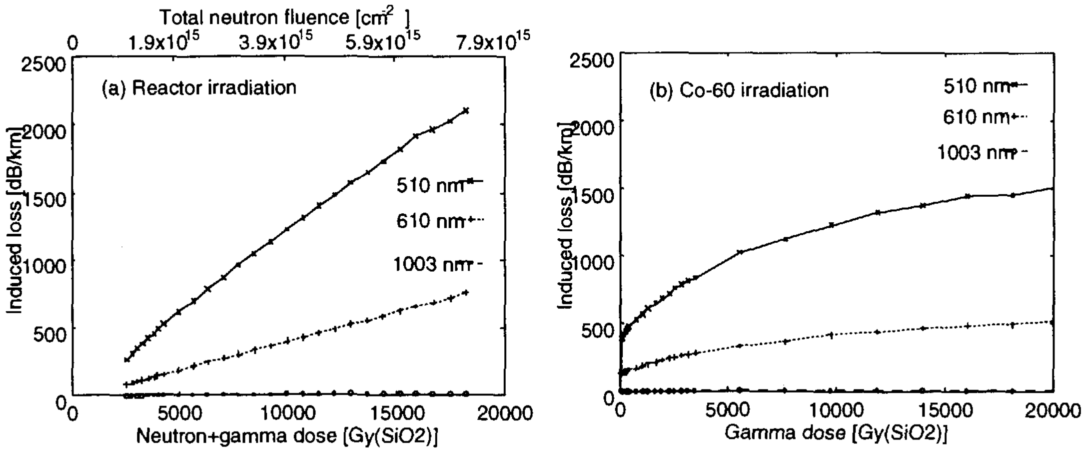
In nuclear facilities, however, as there has been a big problem of radiation induced transmission losses, applicable area of OFSs has been restricted. But, recently, by continuous effort to improve materials and manufacturing process, optical fibers with high resistivity against radiation have been developed(4)(5). The fiber quality has reached enough level to discuss the application to nuclear plants.

In the present study, for examining the applicability of OFSs to nuclear facilities, some irradiation experiments have been carried out using both an experimental reactor and a ^{60}Co γ source. Also, as an example of the OFSs, the feasibility of the Raman Distributed Temperature Sensor (RDTS) has been examined using the experimental fast reactor : JOYO.

2. MEASUREMENTS OF RADIATION INDUCED EFFECTS IN OPTICAL FIBERS

In order to see the radiation hardness of optical fibers, irradiation experiments have been carried out by using the neutron source reactor 'YAYOI' and a ^{60}Co γ source. In the experiments using YAYOI, the fiber samples were set in an experimental hole which is close to the reactore core, where the energy spectrum of the neutrons had its peak at several MeV and the dose from the neurtons and the γ rays were at almost the same level. The sample fibers were the OH doped core type which had been manufactured by the Hitachi Cable Co., LTD.

In Fig.1(a) and Fig.1(b), the measured results of the radiation induced losses are shown. It can be seen that, when irradiated with just γ rays, the loss showed a saturation behavior. On the other hand, in the experiments with YAYOI, the loss increased almost linearly with irradiated dose, which is considered to be the effect from the fast neutron irradiation. From these results, it can be said that application of the optical fibers to the environments with fast neutrons are still difficult and another break through should be made. In the facilities without neutrons, although the loss should increase gradually with long term irradiation, we can expect to use optical fibers with long life time, because of the loss saturation behavior.



(a) Irradiation with YAYOI (Neutron + Gamma)

(b) Irradiation with Co-60 Gamma rays

Fig.1 Radiation induced loss behaviours of the fluorine doped core optical fibers.

3. PRINCIPLE OF RDTS AND THE RADIATION INDUCED ERRORS

When strong light is launched into optical fibers, most of the back scattered light originates from Rayleigh scattering with the same wavelength. A small fraction of the scattered light, however, is due to spontaneous Raman scattering resulting from interactions of the light with the lattice vibration modes. The Raman scattered light consists of two components, with different shifts of wavenumber that are one of characteristics for the fiber material. The component with higher wavenumber is called Raman Stokes (Stokes for short), and the other is called Raman anti-Stokes (anti-Stokes for short).

The ratio between the anti-Stokes and Stokes lines is dependent on the temperature as follows:

$$R(T) = (\frac{\lambda_s}{\lambda_a})^4 \exp(-\frac{hc\tilde{\nu}}{kT}), \tag{1}$$

where λ_a and λ_s are the measured anti-Stokes and Stokes wavelengths, respectively, $\tilde{\nu}$ the wavenumber shift from the launched wavelength, h the Planck's constant, c the velocity of light in the optical fiber, k the Boltzmann's constant and T the absolute temperature of the core of the fiber, respectively. Using Eq.(1), we can measure the temperature at the position where the Raman scattering occurred. In order to know the temperature distribution along the fiber, Optical Time Domain Reflectometry (OTDR) method is applied, where distribution of physical parameters are measured with the backscattered waveform of injected pulsed light(3).

In RDTS, the difference of radiation induced losses for the Stokes and the anti-Stokes lights causes incorrect temperature estimation. In currently available commercial fibers, there is a general tendency that, at wavelength from visible to near IR region up to about 1100nm, radiation induced loss decreases with increasing wavelength(8)(9). In this case, from Eq.(1), measured temperature appears lower than the correct value. In order to apply RDTSs to nuclear power plants as a reliable and stable temperature monitor, special correction technique is necessary to be developed. Here, we propose two methods for the correction.

4. CORRECTION TECHNIQUES FOR RADIATION INDUCED ERRORS

4.1 Correction with Two Thermocouple Data

To apply RDTS to areas where dose rate and temperature are almost uniform, a correction method using the results measured with two thermocouples (TCs) has been studied. In this method, besides measurements by the RDTS, temperatures are monitored at points A and B, respectively, by thermocouples. Here, point C is an arbitrary point between points A and B. By assuming that the radiation induced loss is spacially uniform between the points A and B, the temperature at an arbitrary point C ($T(C)$) can be calculated as follows:

$$\frac{1}{T(C)} = \frac{1}{TR(C)} + \frac{1}{T(A)} - \frac{1}{TR(A)} - \frac{l_{AC}}{l_{AB}}\{\frac{1}{T(A)} - \frac{1}{T(B)} - \frac{1}{TR(A)} + \frac{1}{TR(B)}\}. \tag{2}$$

where, l_{AB} and l_{AC} denote the distance of A-B and A-C, respectively. T(X) and TR(X) are the measured temperatures by the thermocouples and the RDTS for the point X.

4.2 Correction with Loop Arrangement

In the method shown in 4.1, uniformity of dose rate and temperature has been assumed. When this assumption is incorrect, temperatures cannot be correctly measured. For the correction of the errors caused by spatially distributed irradiation, a loop-like arrangement has been proposed(10). In this technique, a sensor fiber is set as shown in Fig.2.

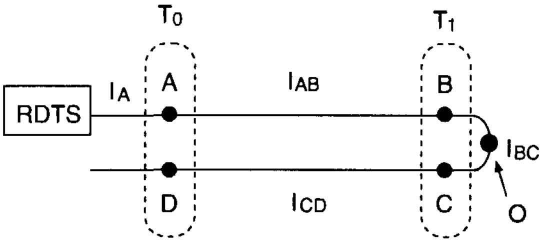


Fig.2 Setup for the correction with loop arrangement

The fiber is composed of two parts, which are between A and O (A-O), and between O and D (O-D), respectively. The two parts are set as close as possible and the temperature so that the radiation condition on these two parts can be assumed to be the same. Accordingly, the distribution of radiation induced losses along these two parts can also be considered to be the same.

By comparing the measured results for the points A and D, the effect of radiation induced losses between A and D can be calculated. Also, from the results for the points B and C, the effect caused in B-C can be known. From the above two effects, we can estimate the radiation induced effects in A-B, which should be the same as that in C-D. By setting the RDTS and the fiber part from the RDTS to point A in an environment without irradiation, correct temperature at the point A ($T(A)$) can be measured. From $T(A)$ and the radiation induced effect in A-B, correct temperature for the point B ($T(B)$) can be calculated as follows:

$$I_{Ba0}/I_{Bs0} = I_{Ba}/I_{Bs}\sqrt{\frac{(I_{Aa}/I_{As})(I_{Ca}/I_{Cs})}{(I_{Da}/I_{Ds})(I_{Ba}/I_{Bs})}}, \qquad (3)$$

where I_{Xa} and I_{Xs} denote the Anti-Stokes and Stokes light intensitis for the point X with the effects of the irradiation, and I_{Ba0} and I_{Bs0} are the Anti-Stokes and Stokes light intensities for the point B after correction of the radiation induced effects. As all the parameters on the right hand side can be known from the measured results, the correct temperature, $T(B)$, can be calculated from Eq.(1).

We have carried out an experiment using a ^{60}Co γ source to check the feasibility of this technique. It has been clearly shown that radiation induced effects can be corrected fairly well.

5. DEMONSTRATION EXPERIMENTS AT AN EXISTING NUCLEAR PLANTS

5.1 Experimental Setup and the Measured Results

In order to study the effects of long term irradiation and to examine the feasibility of the correction method, further experiment at the experimental fast reactor, JOYO, has been carried out. As shown in Fig.6, the sensor fiber was wound along the outside surface of the thermal insulation SUS layer of the primary system piping with 50cm pitch. Backscattered Raman lights were measured by the commercial RDTS system (Hitachi Cable, Ltd., FTR110) with the laser wavelength of 1047 nm.

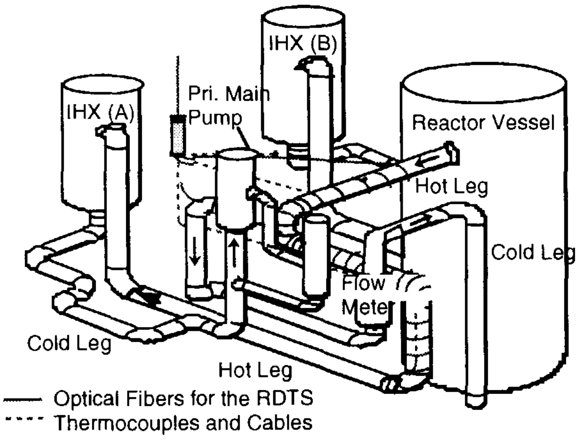


Fig.3 Experimenta setup in the primary loop area of JOYO.

The sensor fiber was pure silica core polyimide jacketed one with core diameter of 50μm, which had been manufactured by Hitachi Cable, Ltd. Thermocouples were set at three points (TC-1 ~ TC-3) along the fiber, and the temperatures were monitored for comparison with the FTR measurements. The distances between the FTR and the thermocouples were 102m for TC-1, 62m for TC-2 and 47m for TC-3. The measurements were continued through the 30th and the 31th operation cycles of JOYO for about 5,000 hours. The 30th operation cycle was from March 3 to May 20 of 1997, the 31th cycle was from July 14 to September 12 and the 32th cycle was from December 16 to February 24, 1998..

In Fig.4, the measured temperature distributions are shown. The large fluctuations in the measured temperature profile are considered to be due to the difference of the thermal insulator thickness. Solid line denotes the results of before the start up the 30th operation cycle and the dashed line shows the results of February 24, just before the shutdown of the 32th cycle. The accumulated dose on February 24 reached more than 10^7 R.. Irradiation induced negative errors were clearly observed in the results of February 24.

Figure 5 shows the time dependence of the temperatures measured with FTR and thermocouples at the thermocouple positions. Because of the accumulation of the radiation induced effects along the fiber, discrepancies were larger at the position of longer distance from the FTR. At the beginning of the 30th operation cycle, the errors reached almost 30 °C quickly, but after this initial growth, they showed a saturation tendency.

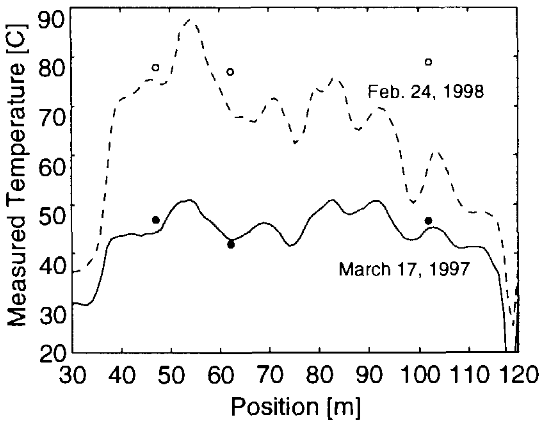


Fig.4 Measreud temperature distribution with the FTR.

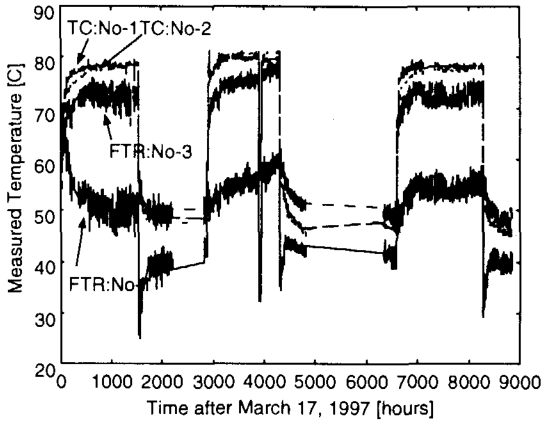


Fig.5 Time dependencies of measured temperature.

It has been shown that the dose rates in the primary loop area of JOYO are between 6.4x10^3 [R/h] and 7.7x10^3 [R/h]$^{(11)}$, and it can be assumed to be nearly constant. Moreover, the temperatures on the surface of the piping are expected to be almost uniform in a stable reactor-operation. Therefore, the correction method assuming uniform loss distribution was applied. Using the data of TC-1 and TC-3, the temperatures measured at other points were corrected.

The results are shown in Fig.6 for the data of February 24. Without correction, the temperature errors reached about 8 °C at the position of TC-2. On the other hand, with correction, they were reduced to about 2.5 °C.

As the correction method is based on the thermocouple data at TC-1 and TC-3, the error of the temperature is larger at the middle part of the total length i.e. at the TC-2 position. Although large errors appeared at the shutdown periods, the average errors during the stable operation were about 2.5 °C and remained almost constant. These results have indicated that, by using this correction method, FTR can be applied to the temperature distribution monitoring along the primary system piping of JOYO.

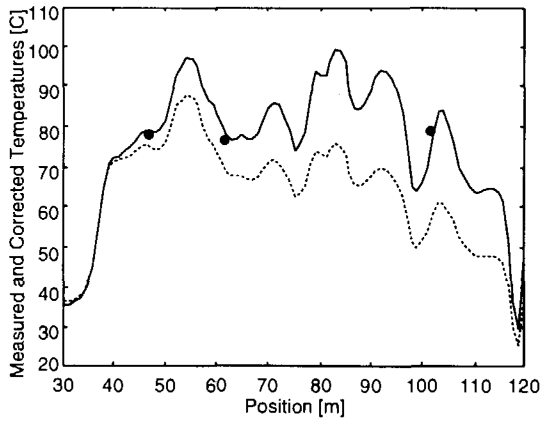


Fig.6 Measured and corrected temperature distribution.

5.2 Discussion on the Feasibility of RDTS

In our experiments, temperature distributions were measured by averaging the backscattered signals of 2^{20} times and it took about 90 seconds for one output. Accordingly, the RDTS has poor applicability as an accident monitor, where the accidents proceed very fast. However, as a monitor for the accidents which proceed gradually, like small leakage of the coolant from the pipings etc., RDTS will be useful. Also, by using larger core sensor fibers, the S/N ratios can be improoved and quicker response can be achieved.

Another problem is its poor spatial resolution of several meters. If temperature changes in a very restricted area, the correct temperature distribution cannot be measured with the RDTS . For overcoming this difficulty, the way of fiber setting should be improved by winding the fiber around the piping closely, by which the temperature changes at a longer length of fiber than in the case of simple straight setting.

The total dose in these experiments reached more than 10^7 [R]. When fibers are set in the primary loop area of light water reactors, this value corresponds to the total dose of more than

10 years. From these results, we can say that the RDTS system can be installed into light water reactors with enough life time. Also, for fast reactors, life time of more than several years can be expected, because the increase of radiation induced errors has been already saturated.

6.CONCLUSIONS

From the irradiation experiments using a neutron source reactor and a ^{60}Co γ source, it has been shown that the radiation induced loss increases in quite different tendencies for the two radiation sources. Besides the linear loss increase with the accumulated dose for the fast neutrons, the loss showed a satulation tendency under irradiation with γ rays.

As an example of the OFSs, the applicability of the RDTS to nuclear facilities has been examined. In order to evaluate the effects of long term irradiation and to see the applicability of RDTS to nuclear facilities, temperature distribution along the primary system piping of JOYO has been measured continuously. Although maximum temperature errors reached almost 30 °C at the end of the 100m-long sensor fiber, they showed a saturation tendency after the rapid growth at the beginning of the measurements. Correction technique using two thermocouples has been tried and, because of the uniformity of the temperature and the dose rate, it has been shown that temperature distribution can be measured fairly well with this technique. From these results, it can be said that RDTS can be applied as a temperature distribution monitor in nuclear facilities.

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