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Electrical current and voltatge induced in MI-cable under irradiation in JMTR*

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Radiation induced electrical current and voltage in MI-cables were measured under JMTR irradiation. The negative voltage of about 10V was generated in the center lead. The voltage increased with increasing irradiation dose with about -14V with a total dose of 1.1×10^{10}Gy ionizing irradiation and $1.1 \times 10^{24} n/m^2$ fast neutron irradiation. The observed electromotive force was a so-called current driven source and the measured current was linearly dependent on the reactor power and was about 50nA for the 0.7m long MI-cables at 573K. Under a reactor full power, irradiation conditions were 6 W/g of a gamma flux(6×10^3Gy/s ionizing dose rate) for iron and $5 \times 10^{17} n/m^2s$ and $1.1 \times 10^{18} n/m^2s$ fast and thermal neutron fluxes, respectively.

KEYWORDS: Radiation Induced Electromotive Force, Mineral Insulated Cable, Diagnostic Components, Reactor Irradiation

I. Introduction

Diagnostics in high irradiation environments are becoming important. The irradiation environments will cause various disturbances such as degradation of electrical insulation and generation of parasitic electrical currents and voltages. Advancement of nuclear fusion reactor development is arousing strong interests in the radiation induced electromotive force(RIEMF), which may be generated in the MI(mineral insulated)-cables under the irradiation. The RIEMF may disturb the plasma diagnostics which are crucial to establish the nuclear fusion science and technology. Recent in-situ research experiments have evoked concerns about the RIEMF which would affect the measurements. Some studies[1,2] did not observe the RIEMF, but some[3,4] did. The ITER(International Thermonuclear Experimental Reactor) workshop on radiation effects on diagnostic components[5] expressed strong concerns about the RIEMF.

In this study, the irradiation induced electrical current and voltage (hereafter denoted as RIEMF; radiation induced electromotive force) were measured in the MI-cables which were irradiated in the JMTR(Japan Materials Testing Reactor) fission reactor.

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II. Experimental Procedures

U-shaped MI-cables of about 5m in length were accommodated in an instrumented rig and were inserted into the JMTR core region. The MI-cable sheath was made of 316 SS and their center leads were nickel. The MI-cables of 1.6mm outer diameter; specimen A, and 2.3mm outer diameter; specimens B and C, were irradiated. Electrical resistance between the sheath and the center lead of three MI-cables was larger than 50GΩ before they were inserted into the reactor core. The irradiation length was about 750mm in total. Two terminals of each cables were sealed with glass and were placed out of the irradiation region. The glass-sealed terminals were about 2m above the reactor core edge, where the fast neutron flux and the gamma dose rate are negligibly low. The temperature there was about 320K during the reactor operation. A DC voltage of +250 and -300V was applied to specimen A and B during the irradiation to study effects of applied electric field. The voltage of +250V was applied for the first 14 days and then -300V was applied for the rest of the irradiation period.

The rig was filled with helium and the irradiation temperature could be changed by changing the helium gas pressure and by an electric heater. The base irradiation temperature was designed to be 573K and the temperature could be raised up to 750K. The neutron flux was $5 \times 10^{17} n/m^2s$ and $1.1 \times 10^{17} n/m^2s$ for fast(E>1.0MeV) and thermal(E<0.687eV) neutrons, respectively, at the reactor full power. The gamma dose rate at the reactor full power was 6 W/g for iron($6x10^3$Gy/s ionizing dose rate).

The voltage and current generated between the center lead and the grounded sheath was measured by Keithley 2001 multimeter and by Keithley 6517 electrometer, respectively. Measurements showed that the resistance of the MI-cables were about 160-500MΩ under the reactor-full-power irradiation. So, the voltage measurements were carried out in the measurement range of 20V for the Keithley 2001, where the internal impedance is larger than 50GΩ. No electrical switch was used to get rid of additional parasitic voltage and current and the switching procedures were done manually.

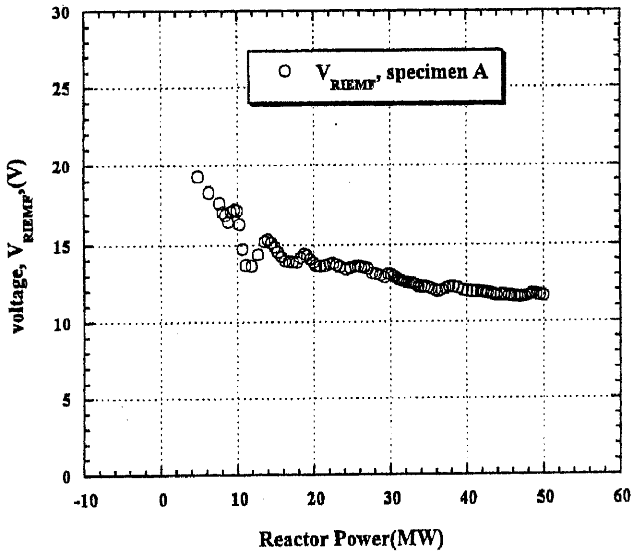

Figure 2 Voltage as a function of reactor power at reactor shutdown.

III. Experimental Results

The JMTR started up at 9:00 on the 22nd, June, 1996. The reactor power was raised up to 50MW in a step-by- step mode. The reactor attained its full power at 20:40 on the same day. The reactor maintained its 50MW power through the irradiation cycle. The base irradiation temperature was 573K. The reactor shutdown procedures started at 10:30 on the 17th, July and finished at 12:15. The total irradiation duration was 24.854rfpd(reactor full power day: 596.5h).

The RIEMF measurements were started after the reactor power reached 10MW and the irradiation conditions were stabilized. Figure 1 shows the measured voltage, V_{RIEMF} through the irradiation cycle. The temperatures during the measurement period changed from 573K to 750K during the reactor full-power operation. Before the irradiation, the voltage of less than ±0.2V and the current of less than ±0.01nA were measured. In general, electrical measurements are noisy in the reactor core and these values are thought to be background noises, though there is residual gamma-ray of about 0.1mW/g. Under the reactor-full-power irradiation, the V_{RIEMF} of -5.5V

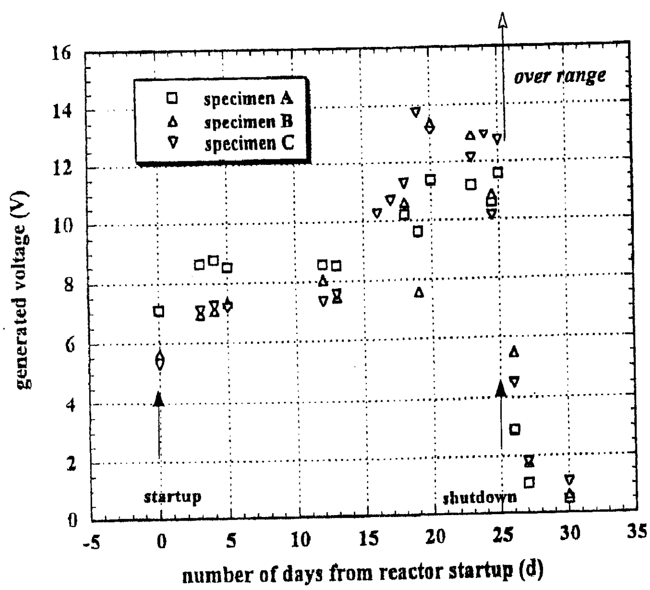

Figure 1 Voltage as a function of irradiation time.

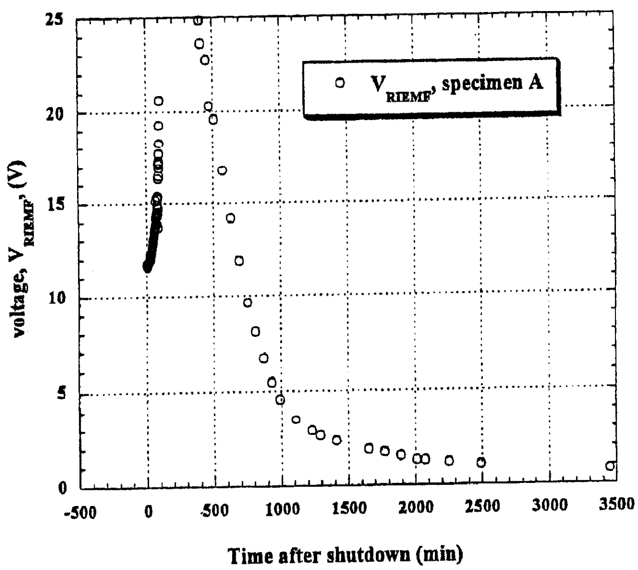

Figure 3 Voltage as a function of time after abrupt reactor shutdown.

to -14V was observed as shown in Fig. 1. The V_{RIEMF} had a tendency to increase as the irradiation proceeded. Specimens B and C showed similar behavior in the course of the irradiation. Thus, the RIEMF was not affected by the applied external electric fields.

At the reactor-shutdown, the V_{RIEMF} showed very weak reactor-power dependence as shown in Fig. 2. Rather, the V_{RIEMF} showed a slight increase with the decrease of reactor power. Here, the irradiation temperature was kept at 590 ± 20K independent of the reactor power down to 8MW. The reactor power decreased at a rate of 0.5MW/min.

At the reactor power of 8MW, the additional control rod was inserted and the reactor shutdown was abruptly completed. At this point, temperature control became impossible and the irradiation temperature went down abruptly from 580K to 460K. Then, the V_{RIEMF} increased abruptly and over-ranged -25V. A few hours after the abrupt reactor shutdown, the V_{RIEMF} decreased to 25V and decreased further with time. Here, the temperature was nearly constant at 330 ± 15K. The V_{RIEMF} is shown in Fig. 3 after the abrupt shutdown. Here, it should be noted that the voltage measurements after the reactor shutdown was inappropriate because the resistance of the MI-cables became larger than the internal impedance of the instrument. The measured resistance of the MI-cables, specimen B, was 6×10^{10} and $3\times10^{12}\Omega$ at ten minutes and three days after the shutdown, respectively.

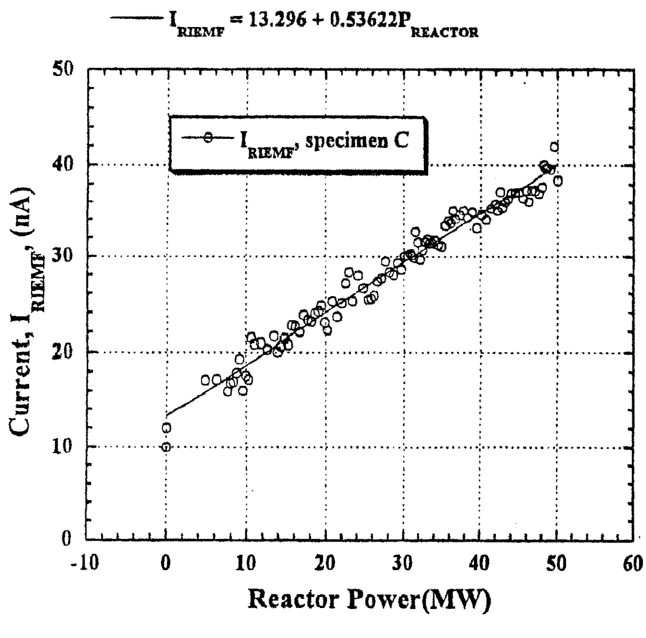

Figure 4 Current as a function of reactor power at reactor shutdown.

The measured current, I_{RIEMF}, was nearly constant through the irradiation. Larger diameter MI-cables, specimens B and C have larger current than smaller diameter specimen A. The current during the shutdown is shown in Fig. 4. Here, the temperature was nearly constant at 590K as described above except for the point at 0 MW of the reactor power. The current, I_{RIEMF}, decreased nearly linearly with the reactor power, but there still existed the current of about 10nA at 0 MW. The V_{RIEMF} and the I_{RIEMF} decreased further after the shutdown. The V_{RIEMF} and the I_{RIEMF}, 5 days after the shutdown, is less than 1V and 0.1 nA, respectively as shown in Fig. 3. Here, the capsule was still in the shutdown reactor core and was exposed to the residual gamma.

IV. Discussions

The present experiments have shown that there exists the RIEMF in MI-cables under the reactor irradiation. The results revealed that the observed RIEMF is current-driven with a high internal impedance. The effects of applied voltage of +250V and -300V was not observed on the RIEMF. Under the 6×10^3Gy/s ionizing irradiation and the 5×10^{17}n/m^2 fast neutron irradiation, the observed V_{RIEMF} was about -5.5V to -14V and the I_{RIEMF} was about -25nA to -50nA at 573K.

The larger diameter MI-cables seemed to have a larger current. Or, it should be interpreted that the MI-cable having lower resistance between its center lead and sheath has the larger current. The electrical resistance between the center lead and the sheath was measured to be about 325MΩ for specimen A and 180MΩ for specimens B and C in the voltage range of -250 to +250V at the 14 rfpd. As described above, the resistance was larger than 50GΩ before the irradiation which means that the resistance of the glass seal termination is larger than 50GΩ. As the termination is out of the irradiation region in the dry helium at about 320K, there are few reasons to think that the resistance of the termination would degrade in the course of the irradiation. So, the measured resistance is thought to represent the resistance between the sheath and the center lead of a irradiated part of MI-cables. The measured resistance depended linearly on the reactor power, which is expected from the phenomenon called radiation induced conductivity.

As the present RIEMF is current driven with high internal impedance, the measurements need to use a high internal impedance electrometer. When the RIEMF was measured by the Keithley 2001 at 200V range with the internal impedance of about 10MΩ, the V_{RIEMF} of only about 0.5V could be detected. Major reason of the previous failure[2] to observe the

RIEMF would be an inappropriate selection of the measuring instruments.

Irradiation would generate the electric current from the center lead to the sheath of about -25nA to -50nA. Applied voltage vs. its induced current between the center lead and the sheath showed good linear relationship in the present experiment in the voltage range of -250V to +250V. The observed V_{RIEMF} and its current, I_{RIEMF} fit this ohmic behavior well. The V_{RIEMF} looks independent of reactor-power as shown in Fig. 2, where the temperature was kept nearly constant at about 590K. Also, the measured V_{RIEMF} at the reactor startup was nearly constant at -6V for specimen A and -8V for specimens B and C in the reactor power above 10MW. Here, the temperature rose with the reactor power from 400K to 590K.

The voltage of the RIEMF, V_{RIEMF} and its current I_{RIEMF} satisfies the ohmic relationship and the I_{RIEMF} depends on the reactor power, $P_{REACTOR}$, as

$$V_{RIEMF} = R * I_{RIEMF} \quad (1)$$

$$I_{RIEMF} = a * P_{REACTOR} + b_{current} \quad (2).$$

Here, R is the resistance of the MI-cable. In the meantime, the resistance, R, depends on the reactor power, $P_{REACTOR}$, as

$$1/R = c * (P_{REACTOR})^n \quad (3).$$

This is the relationship so-called radiation induced conductivity, RIC[6] and n was measured to be nearly unity in this experiment[7].

Then, the relationship between the RIEMF and the reactor power would be

$$V_{RIEMF} = (a*P_{REACTOR}+b)/(c * (P_{REACTOR})) \quad (4)\text{-}1$$

$$= a/c + (b_{current}/c)*(1/ P_{REACTOR}) \quad (4)\text{-}2.$$

The relationship (4) shows that the V_{RIEMF} is nearly a constant of a/c, being independent of the reactor power, when the reactor power is high. When the reactor power decreases, the second term in (4)-2 will contribute substantially and the V_{RIEMF} will increase with decrease of the reactor power.The relationship (4) explains the behavior of the RIEMF at the reactor shutdown.

The observed increase of the V_{RIEMF} in the course of the irradiation shown in Fig. 1 would indicate the increase of the resistance, R, and/or the increase of the induced current, I_{RIEMF}. In the present experiment, the measurements of the I_{RIEMF} and of the resistance, R, were carried out extensively only after 14 rfpd and the measured current, I_{RIEMF}, did not show the distinct dependence on the temperature nor the accumulation dose.

In the meantime, the measured resistance, R, at 573K, increased from 160-170MΩ for specimens B and C and 320-330MΩ for specimen A at 14 rfpd, to 320-330MΩ for specimens B&C and 450-480MΩ for specimen A at 24 rfpd. This increase of the resistance could explain in major part for the increase of the V_{RIEMF} after 14 rfpd. However, the results may also suggest the increase of I_{RIEMF} in the course of the irradiation. The absence of the over-range behavior of the V_{RIEMF} at the reactor-startup may suggest the negligible contribution from the second term, b_{RIEMF}, of the relation (4) at the beginning of the irradiation

The origin of the b_{RIEMF} was not identified in this experiment. The magnitude of the residual current, the b_{RIEMF}, at zero reactor power was about 10nA, which was 1/5 of that at the reactor full power, could not be explained by the residual gamma dose rate. The gamma dose rate just after the shutdown was about 100Gy/s, being about 1/50 of the gamma dose rate at the reactor full power. In contrast, the resistance, R, increased from 450MΩ to 20GΩ, namely about 50 times, at shutdown, being in good agreement with the decrease of the gamma dose rate.

The b_{RIEMF} decreased rapidly after the completion of the shutdown. The I_{RIEMF} decreased down to less than 0.1 nA after the shutdown. The decreasing behavior of I_{RIEMF} seemed consistent with the decrease of the strength of residual gamma dose rate from a few hours after the shutdown. Further detailed analysis would reveal the behavior of the I_{RIEMF} after the shutdown.

As described above, the measurements of V_{RIEMF} was inappropriate after the reactor shutdown, because of the high resistance of the MI cables. The resistance of the MI-cable, specimen B was measured to be about $3x10^{12}$Ω and the measured I_{RIEMF} was 0.1nA, at 5 days after the reactor shutdown. Then, the V_{RIEMF} would be calculated to be about 300V. So, if a higher impedance were measured , a V_{RIEMF} far larger than the measured value of a few V may be observed after the reactor shutdown. Further study of the RIEMF would be needed when the resistance of the MI-cables are larger than 10 GΩ. Also, the behavior of I_{RIEMF} should be studied extensively as a function of irradiation dose.

At present, a cause of the RIEMF could not be determined. It could be said from the present results that the observed electromotive force was not thermally caused. The observed V_{RIEMF} decreased with rise of the temperature. Also, under a constant temperature, the I_{RIEMF} decreased with decrease of the reactor power. It is possible that an irradiation related phenomenon could drive electrons to the center lead under the irradiation and this driving force should be stronger than a few tens V, probably larger than a few hundreds .

Detailed results of the present experiment will be found elsewhere [7,8].

V. Conclusion

The radiation induced electromotive force(RIEMF) was measured in the MI-cables under the JMTR reactor irradiation. The voltage of -5.5V to -14 V was observed on the nickel center lead of the

MI cables whose sheath was made of SUS 304 and was grounded. The observed voltage of RIEMF, V_{RIEMF} was nearly independent of the reactor power. In the meantime, the observed current of the RIEMF, I_{RIEMF}, was about 50nA at the reactor full power and was dependent nearly linearly on the reactor power, but with a substantial current being independent of the reactor power, $I_{RIEMF} = a*P_{REACTOR} + b_{current}$. The observed I_{RIEMF} decreased down to less than 0.1nA after the reactor shutdown, presumably as the residual gamma dose rate decreased. However, the observed V_{RIEMF} tended to increase with decrease of the ionizing dose rate after the irradiation and it was estimated to be about 300V at the ionizing dose rate of a few Gy/s after the irradiation.

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