DYNAMIC IRRADIATION EFFECTS IN ELECTRICAL CONDUCTIVITY OF CERAMIC INSULATORS*

Tatsuo Shikama,** Steven J. Zinkle,*** JUPITER-TRIST-ER Group,*
and Shin Yamamoto****
* Oarai Branch, Institute for Materials Research, Tohoku University,
Oarai, 311-1313 Japan
** Oak Ridge National Laboratory,
P.O. Box 2008, Oak Ridge, TN 37831-6376 USA
**** ITER Joint Work Site,
Garching near Munich, 85748 Germany

Abstract

Electrical properties of ceramic insulators of 12 different kinds of highly pure aluminum oxide (Al_2O_3) were examined in-situ in a High Flux Isotope Reactor with radiation conditions relevant to those in fusion reactors under development. Results indicate that some of the examined aluminum oxide would withstand severe radiation and they can be used as electrical insulators near burning plasma in fusion reactors under development. In the meantime, some unique features in electrial features were observed under irradiation. Examples are non-ohmic behavior, large radiation induced electromotive force, and a large leakage current. They may cause serious engineering problems in fusion reactors and further and extensive works are anticipated especially under international collaborations.

1. INTRODUCTION

Ceramic electrical insulators will play important roles in heavy irradiation environments in nuclear fusion reactors, such as, for heating, controlling and diagnostic measurements of burning plasmas. Engineering Design Activities (EDA) of International Thermonuclear Experimental Reactor (ITER) are revealing important roles of functional ceramic materials near burning plasma [1]. Table 1 shows plasmas diagnostic components under development in ITER, which was summarized by the task force of T246 of ITER-EDA. Among a variety kinds of functions, electrical property is one of important properties as explicitly shown in Table 1. Electrical conductivity of ceramic insulators is known to change dynamically and drastically under irradiation through phenomena such as so-called radiation induced conductivity (RIC). Also, electrical breakdown is apprehended to enhance under irradiation. These degradation phenomena may cause serious engineering problems as shown in Table 1 and extensive radiation tests of functional materials and functional components are needed in fusion relevant radiation environments.

Without actual intense fusion radiation sources, high flux fission reactors are considered the most appropriate radiation sources relevant to fusion irradiation environments. They have a relevant ratio of an electronic excitation rate to an atomic displacement rate. Also, their atomic displacement rates, namely up to about 10^{-6}dpa/s, covers values expected in fusion reactors now under consideration. In-situ type experiments, namely measurements under irradiation, are essential to evaluate dynamic irradiation effects in functional materials and components such as effects on electrical properties.

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* Work performed under Japan Monbusho/USA Department of Energy scientific collaboration in fusion program called a JUPITER program, contact persons of which are T.Shikama for the Japanese side and S.J.Zinkle for the USA side. The other members of JUPITER-TRIST-ER Group are; K.Shiiyama (Kyushu University, Fukuoka, 812 Japan), D.P.White, L.L.Snead, W.S.Eatherly, A.L.Qualls, D.W.Heatherly, R.G.Sitterson, R.L.Wallace, D.G.Raby, M.T.Hurst (Oak Ridge National Laboratory, Oak Ridge, 37831 USA), E.H.Farnum, K.Scaborough (Los Alamos National Laboratory, Los Alamos, 87545 USA), M.Narui (Tohoku University, Oarai, 311-1313 Japan),

Table 1 Physical properties and mechanical properties of key components and degradation mechanisms apprehended

Diagnostic components	Physical and mechanical Properties	Properties to be examined
Ceramics	Electrical	RIED*, RIC**, RIEMF***
	Optical (see Windows)	Radiation related luminescence and absorption
	Thermal	Thermal conductivity
	Mechanical	Sub Critical Crack Growth
	Dimensional stability	Swelling
	Others	Tritium Diffusion and Retention
Windows	Optical	Permanent Absorption, Transient Absorption Radio luminescence, Cerenkov, Thermoluminescence
	Thermal	Thermal conductivity
	Mechanical	(High power laser damage to window)
	Dimensional stability	Swelling
	Others	(Window metal Joint/ Sub Critical Crack Growth)
Optical fibers	Optical	Permanent Absorption, Transient Absorption, Radio luminescence, Cerenkov, Thermoluminescence
	Mechanical	Stability of metal jacket
	Others	(Joint solder)
Mirrors/Reflectors	Optical	Reflection
	Thermal	(High power laser damage to mirrors)
	Mechanical	Adhesion of coated metal (Flaking, Peeling)
	Dimensional stability	Swelling of bulk materials
	Others	(Distortion due to radiation heating)
Wires/Cables	Electrical	RIED*, RIC**, RIEMF*** (MI cables****)
	Mechanical	Stability of coated ceramics
	Others	(Termination of the cable) (Joint solder)

* **RIED**; Radiation Induced Electrical Degradation
** **RIC**; Radiation Induced Conductivity
*** **RIEMF**; Radiation Induced ElectroMotive Force
**** **Mineral Insulating(MI) Cable**; A main candidate as electrical cables

2. EXPERIMENTAL PROCEDURES

Sophisticated experimental techniques were developed to measure electrical conductivity of ceramic insulators in high-flux fission reactors under well-controlled conditions, under the Japan/USA collaboration named JUPITER (Japan USA Project on Irradiation Test using Reactors) project, using experimental fission reactors in Japan and the USA. The final experiment was carried out in a developed irradiation facility called the Temperature Regulated In-Situ Test Facility (TRIST) in the High Flux Isotope Reactor (HFIR) in Oak Ridge National Laboratory (ORNL). The experiment was named as JUPITER-TRIST-ER (electrical Resistivity measurements)[2,3,4].

Twelve different alumina (Al_2O_3) and sapphire (single crystal alumina) specimens, which are candidate insulators in fusion reactors, were irradiated and their electrical conductivity was measured in-situ during the reactor operation extending for about 3 months. The maximum dpa (displacement per atom) was about 2 dpa, which would cover the expected dpa in ceramic insulators in the ITER. The dpa rate of about 3x10-7dpa/s and the dose rate of electronic excitation of about 10kGy/s also cover expected dose rates. The irradiation temperature was about 770K, where the reported phenomenon of serious degradation in electrical insulating ability of ceramic insulators, radiation induced electrical degradation (RIED) would take place most probably, judging from reported experimental results [5,6].

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

Figure 1 shows change of measured electrical conductivity of sapphire in the course of irradiation. The electrical conductivity increased substantially, roughly from a value less than 10^{-9}S/m to about 10^{-6}-10^{-7}S/m at a reactor startup, and then it decreased to a value less than 10^{-9}S/m at a reactor shutdown. Changes were due to the phenomenon of RIC. Values of RIC of 12 different aluminas and sapphires were obtained as a function of electronic excitation dose rate and they satisfied design criterion of RIC being less than 10^{-6} S/m at an electronic excitation rate of 10^{-4}Gy/s [1].

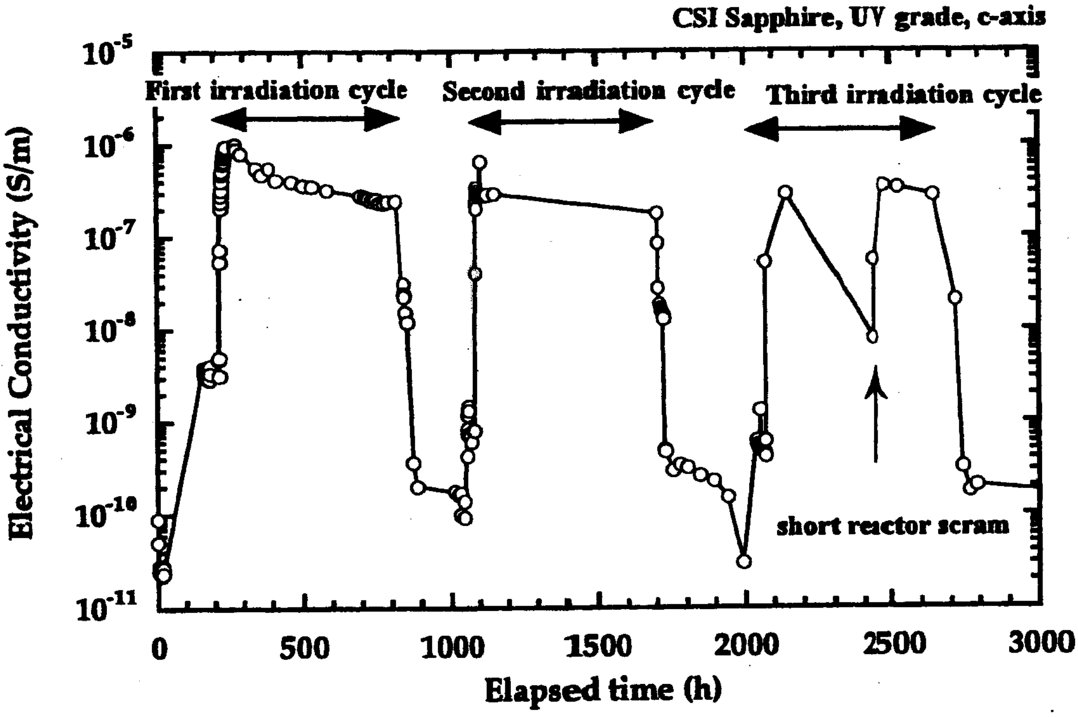

FIG. 1 Electrical conductivity of highly pure sapphire in the course of HFIR irradiation

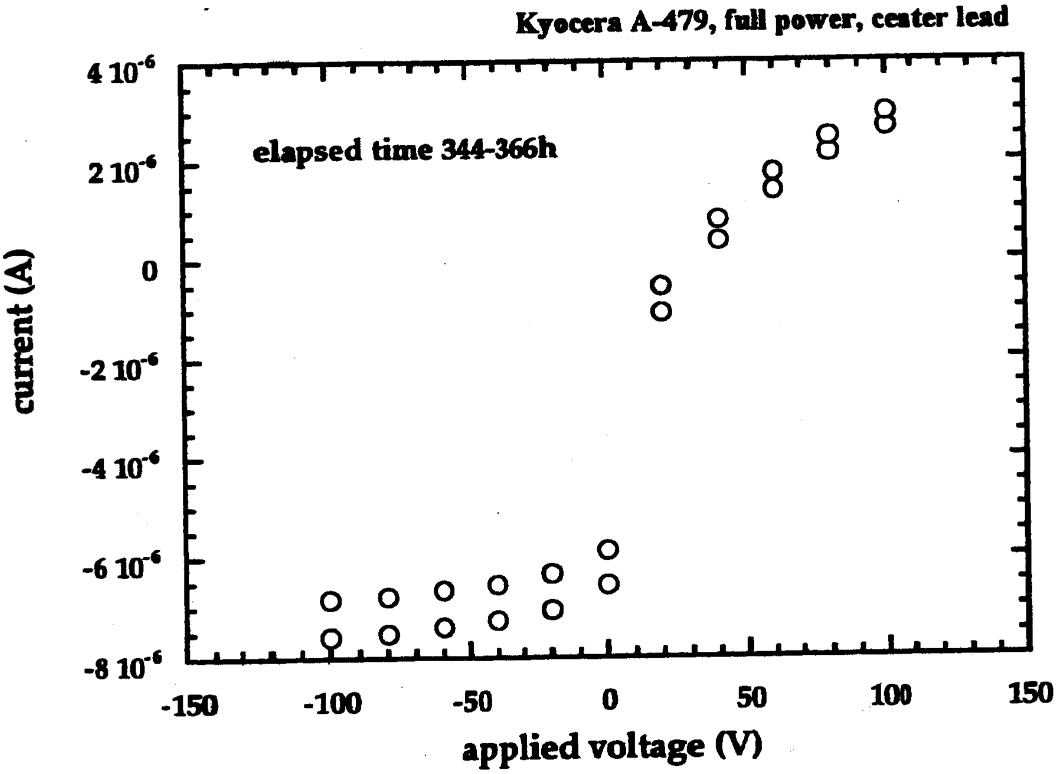

FIG. 2 Non Ohmic behavior of electrical conduction and offset current of alumina in HFIR irradiation

The electrical conductivity under irradiation did not increase substantially in the course of 3 months irradiation as shown in Fig. 1. Some specimens showed moderate increase of electrical conductivity at the beginning of irradiation, however, the observed increase did not proceed to a catastrophic increase and to a resultant electrical breakdown. The results indicated that the RIED would not be a problem in a near and middle term fusion development.

The experiment revealed some unique features of electrical conductivity of ceramic insulators under irradiation. A non-ohmic behavior was observed and a large offset current of up to a few tens micron ampere was measured as shown in Fig. 2. These peculiar behaviors of electrical insulators will impose serious engineering problems especially in plasma diagnostics, such as a magnetic probe. At the same time, these phenomena may reveal interesting physics in a system composed of ceramics and metals under irradiation. Radiation induced electrical current and voltage, which is shown as an offset current at 0 voltage in Fig. 2, is called radiation induced electromotive force (RIEMF). The RIEMF is attracting strong concerns especially in ITER plasma diagnostics [1,7]. A supplementing experiments were proposed and under way in a Japan Materials Testing Reactor (JMTR) in Oarai Research Establishment of Japan Atomic Energy Research Institute, to study these peculiar behaviors and their effects in performance of plasma diagnostic components, under Japan/USA collaboration of the JUPITER.

4. SUMMARY

The experimental results indicated that some of the examined aluminum oxide would withstand severe radiation effects and they can be used as electrical insulators near burning plasma in fusion reactors under development [8]. The present experimental results were analyzed in an international specialist meetings in the framework of IEA Workshop on “Radiation Effects in Ceramic Insulators”, held in Cincinnati in Ohio, in May, 1997. The detailed discussions were complied in Ref. [8].

In the meantime, some unique electrical features were observed under irradiation. Examples are non-ohmic behavior, large radiation induced electromotive force, and a large leakage current. In some of the 15 samples, a leakage current in the range of a few hundreds ampere was observed, whose flowing path was not clearly identified. They may cause serious engineering problems in fusion reactors and further and extensive works are anticipated especially under international collaborations.

REFERENCES

[1] S.Yamamoto, Design Description Document of ITER-EDA, WBS 5.5.M “Radiation Effects”, ITER-JCT Garching, Germany (1998) to be published.
[2] S.J.Zinkle, et al., submitted to J. Nucl. Mater..
[3] T.Shikama et al, presented at the 8th International Conference on Fusion Reactor Materials, October, Sendai, Japan, to be published in J. Nucl. Mater..
[4] T. Shikama and S.J.Zinkle, ibid.
[5] E.R.Hodgson, J. Nucl. Mter., 179-181 (1991) 383,
[6] E.R.Hodgson, J. Nucl. Mater., 212-215 (1994) 1123.
[7] T.Shikama, M.Narui and T.Sagawa, Nucl. Instr. Methds in Phys. Res., B122 (1997) 650.
[8] S.J.Zinkle compiled, Prc. Of “the Ninth IEA Workshop on Radiation Effects in Ceramic Insulators”, May, 1997, Cincinnati, USA, ORNL/M-6068 (1997).