Study on Dynamic Behavior of Fusion Reactor Materials and Their Response to Variable and Complex Irradiation Environment

K. Abe (1), A. Kohyama (2), C. Namba (3), F. W. Wiffen (4) and R. H. Jones (5)

(1) Department of Quantum Science and Energy Engineering, Tohoku University,
01 Aramaki-aza-Aoba, Aoba-ku, Sendai, 980-8579, Japan
(2) Institute of Advanced Energy, Kyoto University, Gokasho, Uji, 611-0011, Japan
(3) National Institute for Fusion Science, 322-6, Oroshi-cho, Toki, 509-5292, Japan
(4) US Department of Energy, Germantown, MD 20874, USA
(5) Pacific Northwest National Laboratory, Richland, Washington, 99352, USA

Abstract

A Japan-USA Program of irradiation experiments for fusion research, 'JUPITER', has been established as a 6 year program from 1995 to 2000. The goal is to study the dynamic behavior of fusion reactor materials and their response to variable and complex irradiation environment using fission reactors. The irradiation experiments in this program include low activation structural materials, functional ceramics and other innovative materials. The experimental data are analyzed by theoretical modeling and computer simulation to integrate the above effects. The irradiation capsules for in-situ measurement and varying temperature were developed successfully. It was found that insulating ceramics were worked up to 3 dpa. The property changes and related issues in low activation structural materials were summarized.

1. Introduction

Component materials of fusion reactors are exposed to high energy neutrons of 14 MeV with its high wall loading of the level of 2 MW/m^2. It will cause severe radiation damage in the materials due to high amount of atom-displacement and also of transmutation including helium.

Neutron irradiation condition in the reactor is characterized with dynamic effect and varying environment effect. Dynamic effect is caused only during irradiation and different from cumulative property change by irradiation. Varying environment effect is due to the change of irradiation conditions and different from those by steady state irradiation.

A Japan-USA Program of irradiation experiments for fusion research, 'JUPITER', has been established as a 6 year program from 1995 to 2000. The goal is to understand the above dynamic behavior and variable effect in fusion reactor materials [1]. This paper describes the development of irradiation experiment and the related results.

2. Objectives and Research Matrix

The objective of the JUPITER Program is the characterization of damage process during reactor operation for structural and functional fusion materials. Dynamic phenomena under irradiation and the material property changes under irradiation conditions, which are varied correspondingly to the steady and unsteady operation of the reactor and complex condition including the nuclear transmutations are being studied. The research matrix is summarized in Table 1.

2.1. Neutron Irradiation Effects under Fusion Relevant Condition

Typical dynamic effect in ceramic materials is the changes of transport properties such as electrical resistivity and thermal conductivity during irradiation, which must be measured by in-situ type experiment. Important dynamic effect in structural materials is irradiation creep, which can be measured directly by in-situ type experiment or can be estimated by measuring diameter change in pressurized tube.

Varying environment effect is caused by the change in irradiation parameters such as temperature, neutron flux, stress and so on. The most important parameter is irradiation temperature as illustrated later. Therefore, the irradiation temperature is controlled periodically during reactor irradiation. Experiments at relatively low fluence levels were done successfully using JMTR and relatively high-fluence experiment was prepared at HFIR. Transmutation effect is associated with production of gaseous elements according to (n, α) and (n, p) reaction, and also solid element production like Re from W. Varying and transmutation effects will have severe influence on microstructural evolution, and therefore on mechanical property change.

2.2. Specimen Matrix

The matrix focuses on low activation structural materials. Reduced activation ferritics include reference alloys such as JLF-1 and F82H. Vanadium alloys include reference alloy of V-4Ti-4Cr and modified alloy of V-4Ti-4Cr-Si,Al,Y. These two metals were irradiated together with their model alloys in order to study the effect of alloying elements.

Small specimens were made from these materials to utilize effectively the irradiation space and to minimize the radioactivity of specimens. Therefore, small specimen test technology including specimen size effect and finite element analysis is useful. It is important to study the correlation between mechanical properties and microstructure, and the mechanism of microstructure development based on modeling and computer simulation.

3. Irradiation Experiment

Irradiation experiments are carried out in RB* irradiation vehicle of HFIR at ORNL and ATR-Al hole of ATR at INEEL. Irradiation technology was also developed using JMTR as for in-situ type experiment and varying temperature experiment. Post-irradiation experiments have been performed at hot laboratories at PNNL, ORNL and ANL, and also at hot cells of Oarai Branch of IMR, Tohoku University. Fig. 1 illustrates the irradiation experiment performed or planned at US reactors in the program [1].

3.1. Development of Varying Temperature Capsule

Fig. 2 shows schematically the variation of neutron flux and material temperature caused by periodic operation of fusion energy system. The operation temperature is supposed to be between the temperatures where the nucleation and growth of defects are dominant. The temperature is changed periodically between the nucleation and growth dominant temperatures. In such condition, microstructural evolution is influenced markedly as observed at low fluence experiment [2]. Irradiation capsule for high fluence experiment at HFIR with four kinds of temperature zones is illustrated together with planned temperature history in Fig. 3 [3]. In this capsule, thermal neutrons were shielded effectively using europium oxide.

3.2. Development of TRIST capsule

Temperature Regulated In-Situ Test (TRIST) facility was used to measure the electrical conductivity of insulating ceramics. Fig. 4 shows the cross-sectional view of the subcapsule with a sample, leads and thermocouples, which was survived successfully during high flux irradiation [4].

4. Results and Related Issues

4. 1. Electrical Property Changes of Ceramics during Irradiation

Twelve different types of polycrystal aluminas and single crystal sapphires were irradiated for 3 reactor cycles at a temperature of 720-760 K up to a maximum dose of 3 dpa. Fig. 5 shows the change of current under a DC field of 200 V/mm. These results showed that RIED (Radiation Induced Electrical Degradation) was not confirmed up to 3 dpa. It is important that alumina ceramics can be used as an insulator up to the neutron fluence comparable to fusion experimental reactor [4, 5].

4. 2. Microstructural Change due to Varying Temperature Irradiation

Several results showed that temperature history had strong influence on microstructures of metals and alloys, such as in the case of austenitic steels, ferritic steels and vanadium alloys irradiated in JMTR up to 0.13 dpa [6-8]. Since the change in microstructure caused appreciable change in hardening even at low fluence, it is very important to study the varying temperature effect up to high fluence and to predict the degree of such effect in the fusion reactor conditions.

4. 3. Irradiation Behavior of Low Activation Structural Materials

In reduced activation ferritics, the important property change is DBTT shift by neutron irradiation [9, 10]. Up to now, JLF-1 steel showed the smallest increase in DBTT after 35-60 dpa. And also this steel showed relatively small creep strain below 520 ˚C. The influence of He on the DBTT shift and on irradiation creep is the issue to be solved.

As for vanadium, pressurized creep measurement was done successfully after lithium filled capsule irradiated at ATR, where creep strain was not so large below 300 ˚C [11]. The creep experiment at higher temperatures including He effect is the next issue. It was reported that the uniform elongation of vanadium alloy was reduced severely after relatively low-temperature (≤ 400 ˚C) irradiation. However, V-4Ti-4Cr-Si,Al,Y alloy showed relatively large uniform elongation after being irradiated at about 400 ˚C [12]. It is important to improve such radiation embrittlement by means of impurity control by alloying with Y and Al [13]. The next issue is the influence of He at relatively low-temperature range.

In the case of SiC/SiC composite, it is important to develop the materials with high density and high thermal conductivity. Various fabrication methods using high purity materials are now in progress. Very high amount of He production is assumed in fusion conditions. Helium implantation experiment showed that bubbles distributed much differently among fiber, coating and matrix [14]. The future issue is the thermal conductivity change caused by neutron irradiation coupled with He production.

5. Summary

To characterize damage process during reactor operation for structural and functional materials of fusion reactor, dynamic effect only in irradiation and the material property changes in the irradiation conditions, which are varied corresponding to the steady and unsteady operation and complex condition including nuclear transmutation are being studied. The irradiation capsules for in-situ measurement and varying temperature were developed successfully. It was found that insulating ceramics retained their properties up to 3 dpa. The property changes and related issues in low activation structural materials were summarized.

Acknowledgements

This work was carried out under Japan-USA collaborative Program of irradiation experiments for fusion research. Research was sponsored by National Institute for Fusion Science (NIFS) and by the Office of Fusion Energy Sciences, US Department of Energy, under contract number DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

References

[1] ABE, K., et al., “Neutron Irradiation Experiments for Fusion Reactor Materials through JUPITER Program”, J. Nucle. Mater., (1998) in press.

[2] MATSUI, H., et al., IAEA-FI-CN-69/FTP/39, these Proceedings.

[3] QUALLS, A. L. and MUROGA, T., J. Nucl. Mater., (1998) in press.

[4] SHIKAMA, T., et al., J. Nucl. Mater., (1998) in press.

[5] SHIKAMA. T., et al, IAEA-FI-CN-69/FTP/35, these Proceedings.
[6] MUROGA, T., et al., J. Nucl. Mater., (1998) in press.
[7] NITA, N., et al., J. Nucl. Mater., (1998) in press.
[8] KASADA, R., et al., J. Nucl. Mater., (1998) in press.
[9] KOHYAMA, A., et al., J. Nucl. Mat., (1998) in press.
[10] KIMURA, A., et al., IAEA-FI-CN-69/FTP/38
[11] FUKUMOTO, K., et al., J. Nucl. Mat., (1998) in press.
[12] SATOU, M., et al., ASTM-STP, to be published.
[13] SATOU, M., et al., IAEA-FI-CN-69/FTP/36, these Proceedings.
[14] HASEGAWA, A., et al., IAEA-FI-CN-69/FTP/37, these Proceedings.

Table 1. Research matrix of fusion reactor materials through JUPITER program

<table>
<tr><td colspan="2">I. Neutron Irradiation Effects under Fusion Relevant Condition</td></tr>
<tr><td colspan="2">(1) Dynamic Effect on Transport and Mechanical Properties
- in-situ measurement of electrical resistivity, thermal conductivity
- pressurized creep tube experiment</td></tr>
<tr><td colspan="2">(2) Varying Environment Effect on Mechanical Properties
- varying temperature with thermal shield at high fluences (HFIR)
- varying temperature experiment at low fluences (JMTR)</td></tr>
<tr><td colspan="2">(3) Transmutation Effect on Mechanical Properties
- gaseous element (He and H)
- solid element</td></tr>
<tr><td colspan="2">II. Specimen Matrix</td></tr>
<tr><td>Low Activation Structural Materials</td><td>High Heat Flux Materials/Functional Materials</td></tr>
<tr><td>(1) Reduced Activation Ferritics
- JLF-1
- F82H
- Fe-9Cr model alloy etc.</td><td>(1) Refractory Alloys and Cu
- W, W-Re, W-TiC
- Mo, Mo-Re, Mo-TiC
- Cu alloy</td></tr>
<tr><td>(2) Vanadium Alloys
- V-4Ti-4Cr
- V-4Ti-4Cr-Si,Al,Y
- V-Fe-Ti model alloy etc.</td><td rowspan="2">(2) Ceramics
- Al_2O_3
- MgO, $MgAl_2O_4$
- AlN</td></tr>
<tr><td>(3) SiC/SiC Composite
- SiCf/SiC (CVI)
- SiCf/SiC (PIP)
- SiCf/SiC (RS)</td></tr>
<tr><td colspan="2">III. Integrated Analysis and Evaluation Method</td></tr>
<tr><td colspan="2">(1) Modeling and Computer Simulation
- correlation between mechanical properties and microstructure
- mechanism of microstructural development
- molecular dynamics of defect structure</td></tr>
<tr><td colspan="2">(2) Small Specimen Test Technology
- tensile test, Charpy, PCT, DCT etc.
- specimen size effect
- TEM observation of tested specimen</td></tr>
</table>

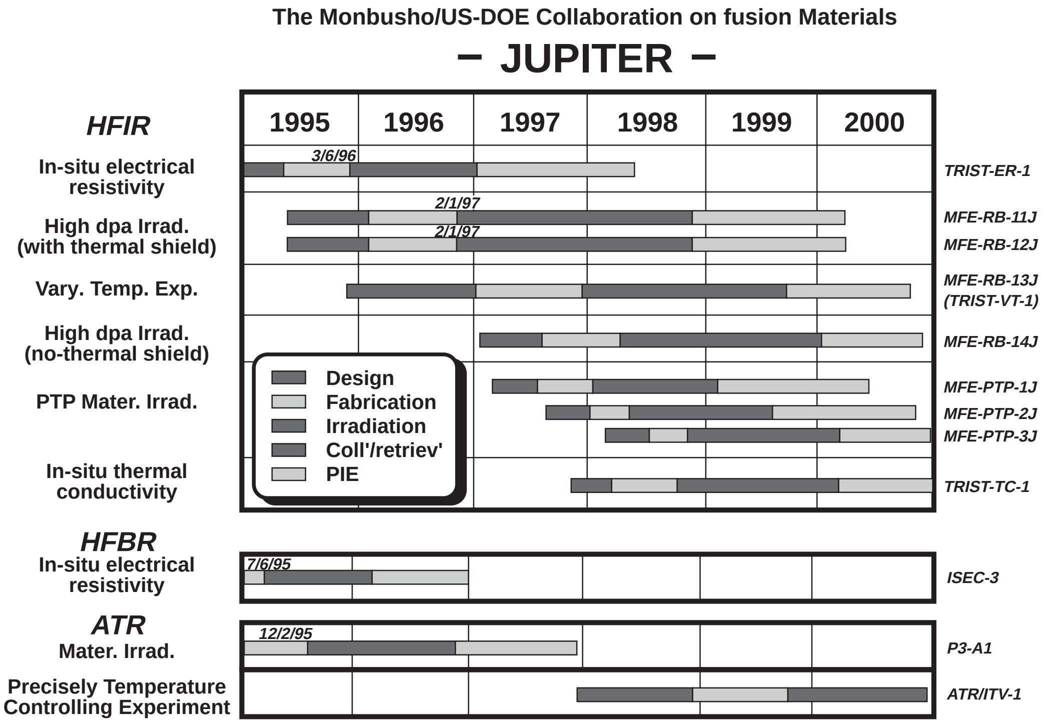

FIG 1. Irradiation experiments performed or scheduled in JUPITER Program.

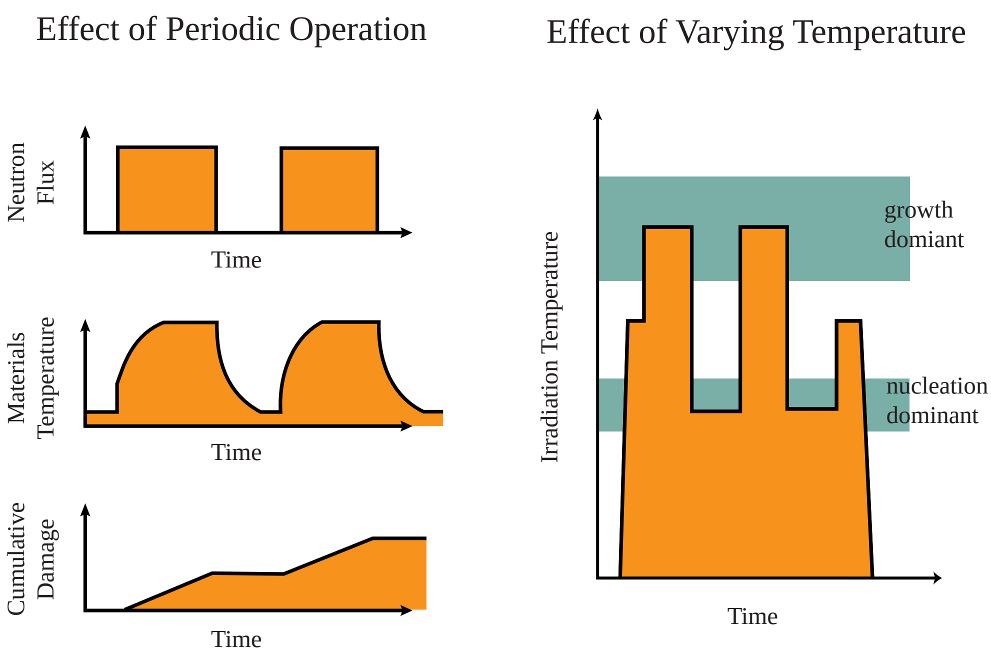

FIG 2. Effect of periodic operation and varying condition

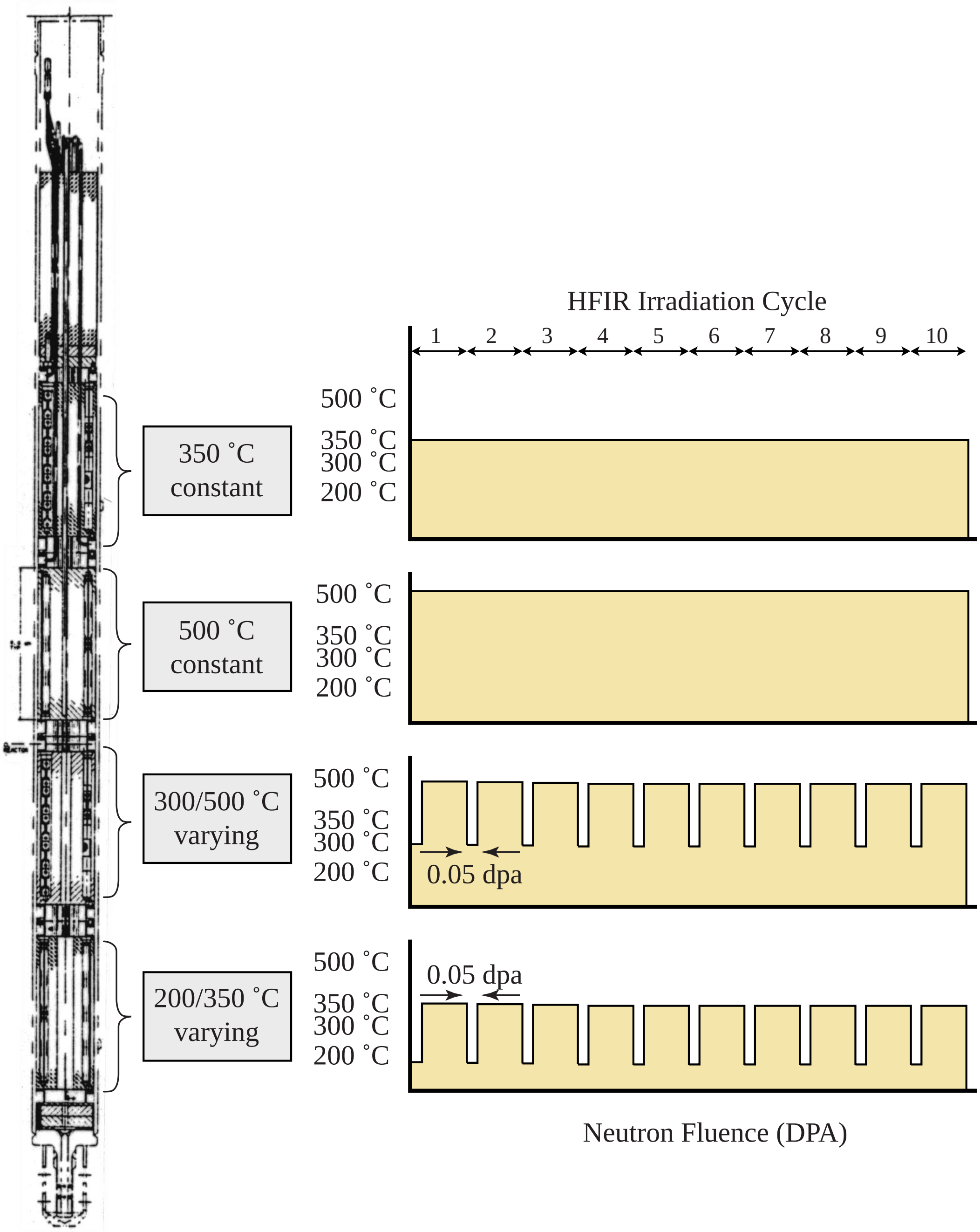

FIG 3. Varying temperature irradiation experiment at HFIR;
capsule (left), temperature history (right)

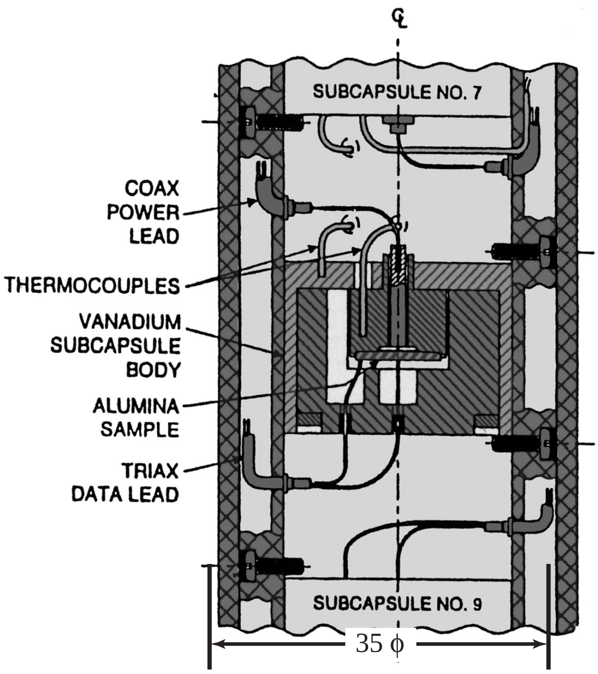

FIG 4. TRIST capsule for in-situ resistivity measurement

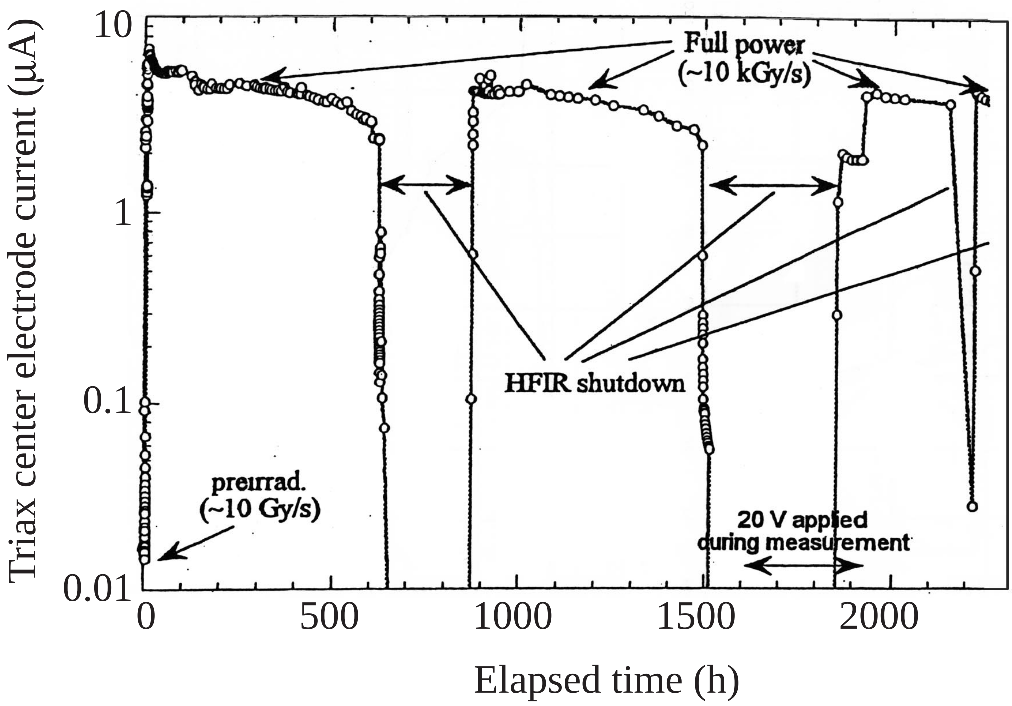

FIG 5. Conductance of Sapphire Measured During HFIR Irradiation
(Cryatal Systems "Hemex" UV grade, c-axids)