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Section 11. Program overview, design and materials, and materials database

Neutron irradiation experiments for fusion reactor materials through JUPITER program

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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". This is phase-three of the collaborative program, which follows RTNS-II Program (Phase-1: 1982–1986) and FFTF/MOTA Program (Phase-2: 1987–1994). This program is to provide a scientific basis for application of materials performance data, generated by fission reactor experiments, to anticipated fusion environments. Following the systematic study on cumulative irradiation effects, done through FFTF/MOTA Program, JUPITER is emphasizing the importance of dynamic irradiation effects on materials performance in fusion systems. 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.

1. Introduction

Completed joint research projects of the Monbusho (Ministry of Education, Science, Culture and Sports, Japan)-DOE (United States Department of Energy) collaboration include the RTNS-II Program (Phase-1: 1982–1986) and FFTF/MOTA Program (Phase-2: 1987–1994). In the RTNS-II Program the fundamental mechanism of radiation damage was emphasized and "cascade effects" of neutron irradiation were clarified at low fluence levels by using a fusion relevant 14 MeV neutron source. Irradiation experiment included pure metals, model binary alloys and practical alloys with irradiation temperatures ranging from cryogenic to high temperatures. Systematic studies on the microstructural evolution and related irradiation hardening in these metals were performed [1–5].

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In FFTF/MOTA Program, on the other hand, the microstructural development and property changes caused by relatively high dose levels up to about 100 dpa were studied using materials irradiation capsule in the fast reactor. A variety of practical materials were irradiated. They included low activation structural materials (ferritic steels and vanadium alloys), high heat flux materials (Cu alloys and refractory alloys), functional ceramics (oxide ceramics) and their model alloys and compounds. Low activation ferritic steels (9Cr–2W martensitic series) and some vanadium alloys with sufficient high-temperature strength and ductility after heavy irradiation were developed [6–9]. Mechanical properties including tensile, charpy and creep tests were performed using miniature size specimens. Important irradiation techniques such as the dynamic helium charging experiment (DHCE) and in situ measurement of resistivity were developed through this program [10,11].

Fig. 1 shows the fusion environmental factors and neutron fluence in these programs. Phase-1 and Phase-2

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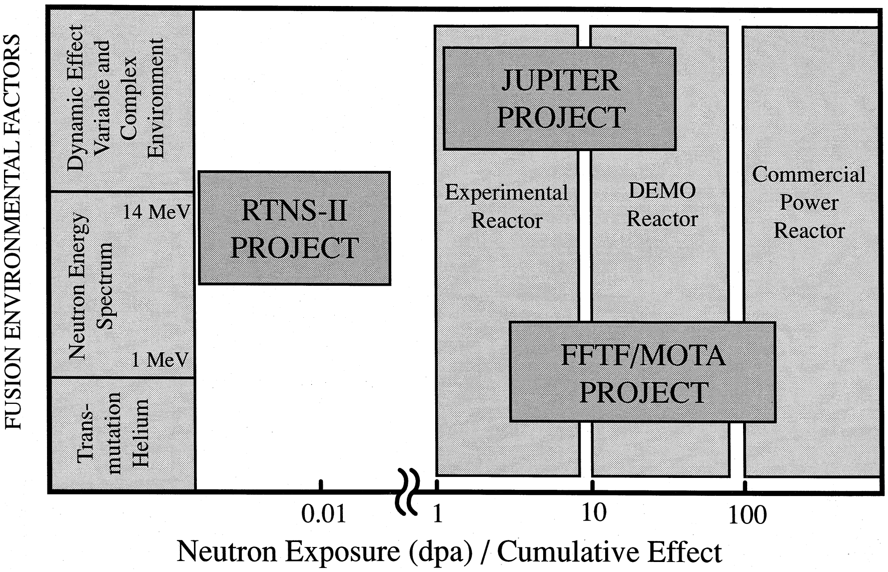

Fig. 1. The fusion environmental factors and neutron exposure.

programs dealt with mainly the property change caused by steady irradiation in the range of low fluence fusion neutrons and high fluence fission neutrons.

The JUPITER Program was designed to study dynamic behavior, variable and complex environmental effects on fusion materials, which are different from cumulative effects after steady state irradiation in the previous programs.

2. Objective and tasks

The objective of the JUPITER Program is the characterization of damage process during reactor operation for structural and functional fusion reactor materials. Dynamic phenomenon in materials and the material response to changes in the irradiation conditions including nuclear transmutations, which are varied corresponding to the steady and transient operation of the reactor are studied. The concept of this program is schematically shown in Fig. 2.

The following seven tasks were set up to organize irradiation experiments effectively. Test matrices focus on low activation structural materials and functional materials, including insulating ceramics and refractory alloys.

(1) *Irradiation creep measurement and mechanical property examination of low activation ferritic steels:* The creep phenomena in the structural materials are caused not only by thermal process but also by irradiation-induced processes and, therefore, should be known precisely to predict the life time of components. The creep deformation is measured using pressurized tube creep tests with a variety of stress levels for the selected low activation ferritic steels. It is necessary to examine microstructures in the tested specimens, in order to correlate the creep strain with defect microstructures.

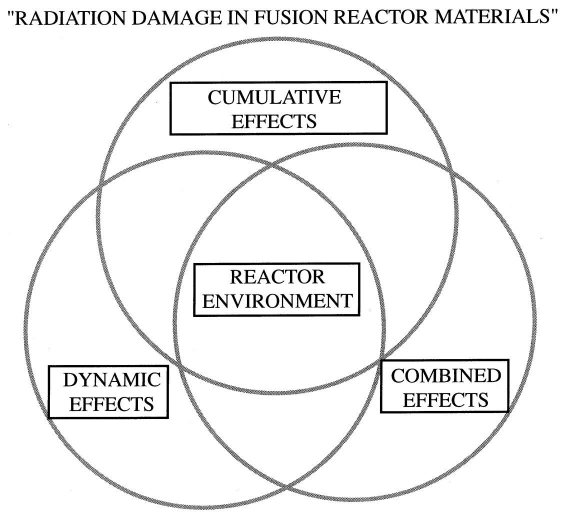

Fig. 2. The schematic concept of JUPITER Program.

(2) *Irradiation effects on mechanical properties and microstructural evolution of vanadium alloys under combined/complex conditions:* In the case of vanadium alloys, fusion relevant synergistic effects of displacement processes and helium production can be studied using the techniques (DHCE) developed in the Phase-2

collaboration Program. The experiment is planned using pressurized creep tube in Li-filled capsules specially designed to produce helium by tritium decay.

(3) *In situ measurement of electrical/thermal conductivity of ceramics:* Transportation properties such as electrical and thermal conductivity can be changed not only by cumulative effects of irradiation but may also be a function of the dynamic effects during irradiation. The change of electrical resistivity of the insulating ceramics will be serious issues in the near term fusion devices as well as the long term one. The in situ measurement in the test reactor core region needs the development of radiation-resistant electrical leads, etc.

(4) *Mechanical properties of cermaics and metal/ceramics joints:* Mechanical property change of ceramics and ceramic composites caused by high-fluence neutron irradiation is one of the important issues to be solved. One candidate low activation structural material, SiC/SiC composites, has special aspects of mechanical behavior compared with metallic materials. Functional ceramics like insulating ceramics have even different required mechanical properties than the composites of metals. Also the coating and bonding between metals and ceramics give rise to the issues relating to the degradation of the interface between them.

(5) *Varying temperature effects on microstructural evolution and mechanical properties under irradiation to high fluences:* It was found that transient temperature history strongly influenced the microstructural development as observed by Kiritani et al. [12,13], and that result was confirmed in the irradiation experiment to high fluences at FFTF/MOTA. The influence of varying irradiation conditions like temperature cycling on property changes may be a serious problem for components under the fusion operating conditions, where the controlled and accidental variation of power level will take place.

(6) *Transmutation effects under complex irradiation condition:* Transmutation reactions in materials irradiated with high energy neutrons will produce solid transmuting elements and gaseous elements like hydrogen isotope and helium. Solid elements will change the chemical composition and related properties, such as chemical compatibility. Gaseous elements can have large influence on the mechanical properties at low and high temperatures. In this program, transmutation effects are studied using various techniques including nuclear reaction with thermal neutrons, tritium doping and pre-implantation methods.

(7) *Modeling and theoretical studies:* In order to study the dynamic effect in addition to the cumulative effect, the experimental test matrix becomes huge. Therefore, mechanistic understanding and theoretical predictions are required to obtain key information through well-planned irradiation experiments with a limited amount of irradiation volume.

3. Irradiation experiments

Irradiation experiments of the JUPITER Program are or will be carried out in the High Flux Isotope Reactor (HIFR) at Oak Ridge National Laboratory (ORNL) and the Advanced Test Reactor (ATR) at Idaho National Engineering and Environment Laboratory (INEEL).

Post-irradiation experiments are performed in hot laboratories at Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory (ANL) and ORNL, and also at hot cells of Oarai Branch of Institute for Material Research (IMR), Tohoku University.

The HFIR provides both a high flux of fast neutrons to produce displacement damage and a high flux of thermal neutrons to produce helium and hydrogen through (n, α) and (n, p) reactions. In some cases of irradiation experiments, we wish to avoid so much transmutation by thermal neutrons. So the number of thermal neutrons are reduced by the inclusion of selected shielding. While the neutron spectrum of ATR is somewhat harder than HFIR, the study on radiation damage in vanadium alloys also requires shielding to suppress the transmutation of vanadium to chromium.

Fig. 3 illustrates the planned schedule of various irradiation experiments. Each irradiation experiment includes design and fabrication of capsules, irradiation in the reactor, cooling of irradiated capsules and the retrieval of specimens, and post irradiation examination (PIE) and analysis.

4. Highlights of accomplishments

JUPITER Program is an on-going program, and experimental results are expected to be obtained in near future. However, there are some results of completed experiments and of technical development. Following are examples:

Electrical properties of ceramics during reactor irradiation (TRIST-ER): In order to perform in situ measurement of electrical conductivity of insulating ceramics, a Temperature Regulated In Situ Test (TRIST) facility was developed and used. Twelve different types of polycrystalline and single crystal Al_2O_3 (alumina and sapphire) specimens of various grades of purity were irradiated for three reactor cycles in a removable beryllium position in HFIR at a temperature of 720–760 K up to a maximum dose of 3 dpa. A dc electric field of 200 V/mm was applied during the irradiation. The details of this experiment are reported in Ref. [14].

A varying temperature irradiation experiment for operation in HFIR: An experiment to compare directly the effects of neutron fluence received at steady temperature and varying temperature on microstructures and mechanical properties of candidate fusion reactor

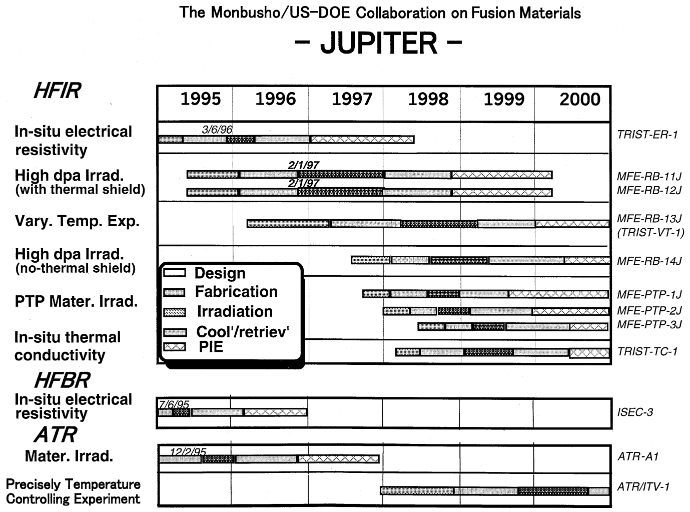

Fig. 3. Irradiation experiments planned in JUPITER Program.

structural materials has been developed. The varying temperature experiment spends 10% of time at a reduced irradiation-temperature. In this experiment, specimen temperatures are elevated and controlled whenever there is substantial neutron fluence to the specimens (reactor power > 10%). Half of the specimens are irradiated at two varying temperatures (300°C/500°C, and 200°C/350°C), and half are irradiated at two constant temperatures (500°C, 350°C). The design of capsule and mock-up test were completed, and the experiment will be performed for ten reactor cycles in 1998. The design features of this experiment are presented in Ref. [15].

5. Conclusion

In order to study the dynamic behavior of fusion reactor materials under irradiation and their response to variable and complex irradiation conditions, a systematic irradiation experiments utilizing fission neutrons at HFIR and ATR have been performed through JUPITER Program. The irradiation experiments in this program included low activation structural materials, functional ceramics and other innovative materials.

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