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Journal of Nuclear Materials 258–263 (1998) 407–412

journal of nuclear materials

A varying temperature irradiation experiment for operation in HFIR [1]

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Abstract

An experiment to directly compare the effects of neutron fluence received at steady temperature on the microstructure and mechanical properties of candidate fusion reactor structural materials to the effects of receiving 10% of the fluence at reduced temperature has been designed. The Varying Temperature Experiment is being fabricated for irradiation in a large Removable Beryllium (RB) position of the High Flux Isotope Reactor (HFIR). For 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 distinct temperatures, and half are irradiated at constant temperature. The capsule features to meet these requirements are described. The experiment will operate for ten reactor cycles beginning in early 1998. This project is a collaborative effort under the Japan–USA cooperative program (Jupiter Project). © 1998 Elsevier Science B.V. All rights reserved.

1. Introduction

Experimental results [1] suggest that the microstructures of structural materials being considered for use in fusion reactors are influenced by irradiation at lower temperatures during the start-ups and shutdowns associated with fission reactor irradiation. Similar transients are expected for structural components in the International Thermonuclear Experimental Reactor and the Demonstration Reactor. Experiments have been carried out in the Japan Materials Testing Reactor (JMTR) in which specimens temperatures were intentionally varied in a controlled manner during irradiation [2]. The result showed significant effects of the temperature variation on microstructure and mechanical properties of the materials. Because exposure in the JMTR experiment was low (<0.2 displacements per atom (dpa)), a controlled varying temperature irradiation experiment to a higher fluence is needed for further studies. An experiment to do this has been designed for operation in the High Flux Isotope Reactor (HFIR) under the framework of the Japan–USA cooperative program (Jupiter Project). In the experiment, four specimen sets are irradiated. Two sets are irradiated at lower temperatures and two sets are irradiated at higher temperatures. The paired sets have identical specimen loadings. One set of each pair is irradiated at constant temperature. The other set is irradiated at that same temperature for 90% of the fluence and at reduced temperature for the remaining 10%. Specimens will be irradiated to 5–10 dpa, depending on material and location. The types of specimens irradiated in this experiment are shown in Fig. 1. The capsule design has been presented earlier [3,4], so in this paper, the major features of the capsule are summarized.

Each specimen set is irradiated inside a separate specimen holder within the capsule. The four holders, along with the structural components which separate them, form the experimental region of the capsule as shown in Fig. 2. The experimental region is sealed inside

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PII: S0022-3115(98)00368-7

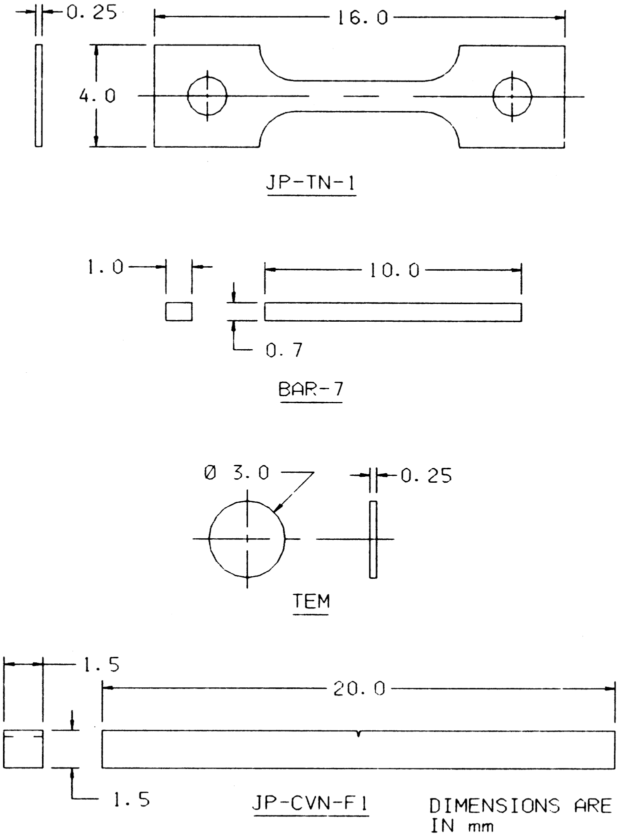

Fig. 1. Specimen types irradiated in the Varying Temperature Experiment. Each holder contains 80 bar-7 specimens, 48 JP-CVN-F1 specimens, approximately 300 JP-TN-1 specimens, and approximately 900 TEM specimens.

an aluminum housing tube. When the capsule is installed into an access hole in the Removable Beryllium (RB) section of the HFIR reflector, the holders are approximately, centered on the axial mid-plane of the reactor, at a radius 29 cm from the centerline of the reactor. The experiment is cooled during irradiation by primary reactor coolant flowing in the annulus between the housing tube and a protective liner/thermal neutron shield in the access hole. Due to the axial symmetry of the fluxes at this location, the specimens located the same distance above and below the reactor mid-plane receive the same fluence. The temperature of the holders below the mid-plane are reduced during the first 10% of each cycle and are then increased to match that of the holder in the corresponding location above the mid-plane which is operated at a constant temperature. The high temperature holders are located closest to the reactor mid-plane. The steady temperature, high temperature holder operates at 500°C, and the variable temperature, high temperature holder operates at 300°C and 500°C. The steady temperature, low temperature holder operates at 350°C, and the variable temperature, low temperature holder operates at 200°C and 350°C.

The low temperature holders are aluminum alloy 6061-T6. The high temperature holders are made of an oxide dispersion strengthened alloy known commercially as DISPAL. The specimens are housed in axial holes in the holders. Fitted sleeves are inserted around the specimens to increase the heat transfer from the specimens to the holder, and the specimens and sleeves are surrounded by static helium inside the sealed holes. In the aluminum holders, aluminum caps (alloy 4043) are laser welded into the specimen holes to seal them. A DISPAL cap compresses a 0.13-mm thick titanium sealing disk against a polished ledge inside the specimen holes of the DISPAL holders to form the seal, as shown in Fig. 3. Titanium was selected as the gasket material because it will getter oxygen if leakage does occur. Mock-ups of the mechanical seal have been tested and were shown to provide leak rates below 10^{-9} ml/s.

2. Heaters

To minimize exposure at low temperature, specimen temperatures will be elevated and controlled by electric

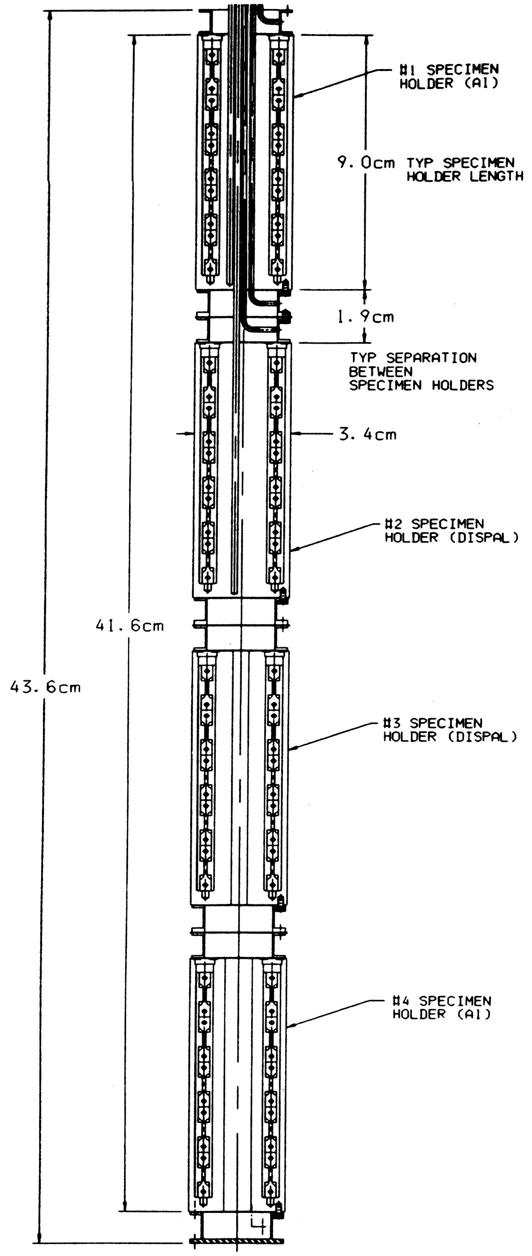

Fig. 2. Experimental region of the Varying Temperature Experiment. Specimens are housed in four holders, which are separated by stainless steel spacers. The top holders operate at constant temperatures and the temperature of the lower holders are varied.

heaters whenever the reactor power is above a limit, tentatively set at 10% of full power. Straight heaters in axial holes in the interior of the holders are used because this arrangement permits the use of many heaters (increasing heater redundancy), simplifies installation, and results in the efficient transfer of heat from the heaters to the holders. Two independent, Nichrome heating elements are contained in the 2-mm o.d., thin-walled, stainless steel sheath of each heater. Each element has an electrical resistance of approximately 1.3 ohms. The heaters can carry over 15 A through a single element or 12 A through both elements simultaneously. The elements and associated extension wiring are physically separated and electrically isolated within the sheath by compressed magnesium oxide powder. Two types of these heaters are used in the capsule. The control heaters have two, slightly overlapping elements which cover the length of approximately 3/4 of a holder. This allows heat to be selectively input into either the upper or lower half of the holder. A common heater has longer elements which are displaced to allow heat to be input into the full length of two adjacent specimen holders. Common heaters are used primarily to provide replacement heat when the reactor is operating at reduced power. Three control heaters and three common heaters contain a total of nine elements in each of the four holders. The elements are wired in series in groups of three and each group is controlled by a separate current controller.

3. Holder temperature isolation

The temperature of each holder must not be influenced by the operation of adjacent holders. Thin-walled, stainless steel spacers provide thermal isolation for individual holders and house the seal that isolates temperature control gas mixtures. The spacers are formed from two stainless steel spool pieces, as shown in Fig. 3. A flexible, graphite laminate, known commercially as GRAFOIL, is compressed between two spool pieces. Material extending beyond the edge of the upper spool piece is compressed against the i.d. of the housing tube as it is passed over the experimental region during the final stage of capsule assembly. The flexible seal centers the spool pieces in the housing tube and forms a symmetric temperature control gas gap between the holder o.d. and housing i.d., and prevents the mixing of temperature control gases from adjacent holders.

4. Temperature control

The operating temperature of each holder is determined by the amount of heat generated within the holder and the thermal conductivity of the gas mixture in the temperature control gas gap. The gas mixture is composed of a flowing mixture of helium and argon. A stainless steel tube supplies all of the capsules' helium to the common interior of all four holders. In the interior, the helium acts as a heat transfer medium from the heaters to holders. The helium flows from the capsule's interior region, through holes in the stainless steel spacers, and into the volume below each holder defined by the spacer, holder and seal. Argon is delivered

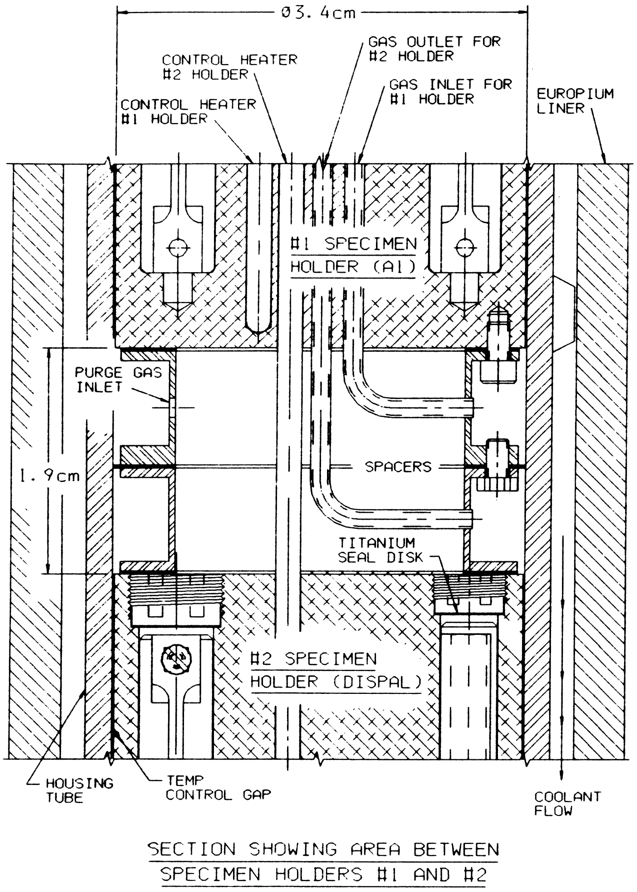

Fig. 3. Sketch of the region between specimen holders. Stainless steel spacers thermally isolate holders and center them in the housing tube. Temperature control gas mixtures are formed below each holder and travel through the gap between the holder and the housing tube to control holder temperatures in conjunction with heat from electric heaters. The gas mixtures of adjacent holders are separated by a seal held by the two pieces of the spacer and compressed against the housing tube.

independently to these volumes through stainless steel tubing connected to flow controllers. The argon and helium form a gas mixture which travels up through the temperature control gas gap to an exhaust tube which carries it out of the experimental region.

The temperature of a holder is monitored in several locations by thermocouples and is controlled by adjusting the flow rate of argon relative to that of helium through the temperature control gas gap. By mixing the gases just before they enter the gas gap, the temperature response to changes in gas flow rates is on the order of tens of seconds. Fast response is required to prevent specimen temperatures from increasing above the desired irradiation temperature during the reactor power increases associated with startup. Fig. 4 shows the temperature response of prototype holder to perturbations in gas mixture adjustments and heater outputs. Note that the temperature reduction associated with the termination of argon flow is essentially as fast as that observed when the heaters are turned off.

Heater outputs and gas flow rates are computer controlled under normal operating conditions, however they can be adjusted manually when required. For temperature control, one of the three heater groups in a holder is selected for use in a feedback control loop. The control heater group (top half, bottom half, or full length) is selected to minimize temperature gradients produced in the holder due to axial variations in the fluxes. The remaining heater groups provide additional heat in the early stages of reactor start-up when little heat is produced in the holders due to neutron and gamma ray exposure.

5. Start-up and operation

The heaters are used for precise temperature control and the gas mixtures allow the heaters to operate within acceptable output levels at all reactor power levels. At startup, high flow rates of argon through the gas gaps

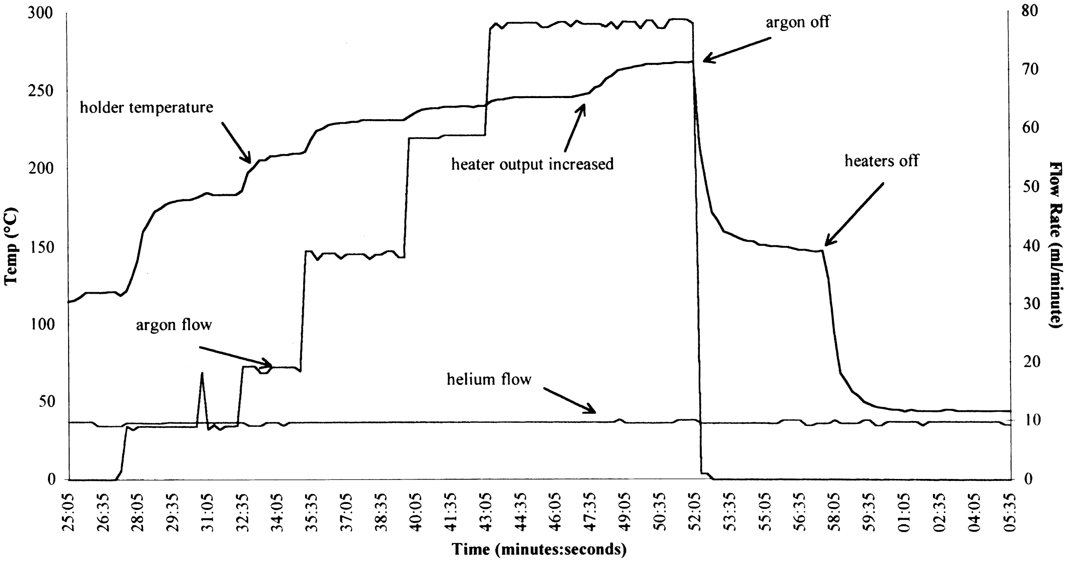

Fig. 4. Response of a prototype holder to a series of perturbations. The response of the temperature to argon flow rate changes is sufficient to prevent the temperature of the specimens from increasing above the required irradiation temperature during reactor power increases.

minimize the required output from the heaters. As the reactor power increases, the amount of heat generated within the holders due to neutron and gamma ray exposure increases. A less thermally conductive gas mixture is exchanged for a more thermally conductive mixture by reducing argon flow rates. The mixing scheme allows this to occur rapidly and independently for all four holders. Once the reactor is at full power, the control gas mixtures are adjusted to control specimen temperatures 5–10°C below the desired operating temperature with the heaters turned off. Additional heat from the heaters elevate specimen temperatures to the desired irradiation temperature. The current required to maintain temperature is monitored to assess the operational state of the experiment. Should the heaters fail, the temperature of the specimens would be temporarily reduced to the value dictated by the gas mixture, which would not significantly impact the results of the experiment. Specimen temperatures can be controlled using only gas mixture adjustments if necessary. The control system can operate the capsule without operator supervision whenever the reactor power is steady and the target temperatures are maintained with the desired heater power levels.

The variable temperature holders are controlled at their respective low temperature during start-up and for approximately the first two days of each cycle, after which the temperatures are increased to match that of the corresponding steady temperature holder. To increase the temperatures, argon flow rates through the gas gaps are increased and the heater controller set points are set to the higher values. The capsule will operate under computer control until the end of the cycle. The computer monitors holder temperature and heater power levels to automatically detect when the reactor has shutdown. At shutdown, the heaters are turned off and argon flow to the capsule is terminated. Helium flows through the capsule at all times.

6. Summary

The design of the varying temperature irradiation experiment for operation in HFIR is complete. This experiment will realize unprecedented comparison of the effects of equal neutron fluence of 5–10 dpa with controlled steady and variable irradiation temperatures. All capsule components are under fabrication. After specimen loading, capsule assembly and connection to the control system, the experiment will begin in early 1998. Ten consecutive reactor cycles of 22–23 days of irradiation and 5–7 days for refueling are planned.

Acknowledgements

Research sponsored by the Office of Fusion Energy Sciences, US Department of Energy, under contract number DE-AC05-96OR22464 with Lockheed Martin Energy Research Corporation.

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