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The Design and Performance of High-Temperature Irradiation Capsules

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Assistant Secretary for Nuclear Energy

Westinghouse
Hanford Company Richland, Washington

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FIFTEENTH SYMPOSIUM ON RADIATION EFFECTS

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TITLE OF PAPER:

The Design and Performance of High-Temperature Irradiation Capsules

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ABSTRACT: Characterization of high-temperature materials behavior in a neutron environment will be required to develop reliable performance prediction models for high-temperature gas-cooled, space power, and fusion reactors. One vehicle by which material behavior in a fast neutron environment can be studied is the Materials Open Test Assembly (MOTA) in the Fast Flux Test Facility (FFTF). Until recently, irradiation temperatures in the MOTA were limited to 1075 K. A recent successful experiment, however, has extended the temperature capability in the MOTA to 1500 K.

This report describes the design and performance of high-temperature capsules that were used in that experiment. Each of eight uniquely designed instrumented capsules (which contained refractory metal specimens) operated at an irradiation temperature between 1290 and 1500 K. Temperatures within ± 10 K of target were maintained in seven of the eight capsules during the 335-day irradiation. Data obtained during the experiment clearly showed the advantages of having a temperature control system for high-temperature irradiation capsules.

KEY WORDS: Fast Flux Test Facility, Materials Open Test Assembly, high-temperature test, irradiation test, gas-gapped capsules, refractory metal, instrumented test, fast test reactor.

Introduction

The characterization of high-temperature materials for potential use in space power, fusion, and high-temperature, gas-cooled reactors will eventually progress from basic material-feasibility studies to the generation of an engineering database for design code development. Well-characterized irradiation-effects databases will be required to develop reliable performance prediction models for these types of power reactors.

The Fast Flux Test Facility (FFTF), located in Richland, Washington, allows investigation of the behavior of fuels and materials in a fast neutron environment. One test vehicle by which material specimens are irradiated in the FFTF is the Materials Open Test Assembly (MOTA). Until recently, irradiation temperatures in the MOTA were limited by stainless steel components to less than 1075 K. A recent successful experiment, however, has expanded MOTA temperature capability by use of refractory metal components to 1500 K. This report describes the design and performance of the high-temperature capsules used in that experiment.

Experiment Summary

The objective of the irradiation experiment was to obtain fast reactor irradiation effects data on refractory materials for the space power program. Temperature control of the experiment was paramount. Specially designed high-temperature capsules (or canisters) in MOTA provided a prototypic

irradiation environment for the various mechanical property specimens that provided engineering data after postirradiation examination and testing.

Specific requirements that directed the experiment design are shown in Table 1. The experiment required eight high-temperature canisters. Each operated at a unique temperature between 1290 K and 1500 K. Irradiation began in November 1987 and concluded in January 1989, permitting 335 full-power days of operation.

Experiment Design

Materials Open Test Assembly Vehicle Design

The experiment was conducted within the MOTA test vehicle.[1] The MOTA is a proven, sophisticated, instrumented test assembly that has been successfully utilized by the national Liquid Metal Fast Breeder Reactor and Fusion Materials Programs for 8 yr.[2]

The MOTA is a 12-m-long test vehicle consisting of a lower 3.7-m-long hexagonal duct assembly that interfaces with the reactor core structure. The duct assembly encloses the test train which consists of a central hanger tube to which eight levels of six specimen canisters are attached by hinged brackets (Fig. 1). The first five canister levels are located in the 0.91-m reactor core region, and three levels are located above the core region. The high-temperature experiment required eight of the 48 canisters; they were located in Levels 4 and 5 near the top of the core.

All MOTA canisters are designed to maintain constant specified temperatures during irradiation. Specific temperatures within the canisters are maintained above ambient by controlling the ratio of helium to argon in an annulus between the inner, heat-generating subcapsule and the outer capsule wall.[3] The specific mixture required is calculated, blended, and sent to the canister utilizing the MOTA instrumentation and control (I&C) system. This system uses continuous feedback from thermocouples located within each MOTA canister. The temperatures are scanned every 10 s, and the gas rebleded automatically if the temperature varies by more than 5 to 10 K from the design temperature.

Canister Design

The canisters for the high-temperature experiment were designed to accommodate the irradiation of niobium, rhenium, and molybdenum alloy specimens at temperatures of 1290 K, 1350 K, 1400 K, and 1500 K in static lithium. This necessitated a redesign of the standard stainless steel MOTA canister which self-filled with reactor sodium (boiling point is 1150 K).

The Level 5 canister, shown in Fig. 2, consisted of a 3.26-cm-diameter outer capsule and 2.75-cm-diameter inner subcapsule separated by an insulating gas gap. The outer capsule was fabricated from Type 316 stainless steel; the subcapsule was fabricated from niobium-1% zirconium (Nb-1Zr) alloy. To achieve an isothermal subcapsule with varying rates of heat generation along its length, variable insulating gas gaps were used. These variable gas gaps (0.45 to 1.5 mm) were achieved by machining the outside diameter of the

subcapsule. Concentricity was maintained within the stainless steel outer capsule by 12 (six at each end), 1.6-mm-diameter, single crystal MgAl_2O_4 pins.

All specimens were loaded within a Nb-1Zr or pure tungsten specimen rack that served to compartmentalize specimens and to increase the heat-generation rate. Approximately 15 g of 99.98 percent lithium-7 was loaded into the specimen region to form a thermal bond between the individual specimens and the subcapsule wall. The subcapsule components and specimens are shown in Fig. 3.

Thermocouple Design

Two thermocouples were used to monitor specimen temperatures in each canister. The thermocouples were of a different thermoelement system to accommodate deficiencies of each: chromel/alumel (Type K) and tungsten-5% rhenium/tungsten-26% rhenium (Type C). The Type-K thermocouple was designated the control thermocouple because of its demonstrated stability during neutron irradiation.[4,5] The possibility of failure of this thermocouple was recognized, however, because the canisters were designed to operate near the upper temperature limit for the Type-K thermoelement system. Thus, the Type-C thermocouple was selected as a backup. The Type-C thermocouple was not designated for temperature control because of its known instability during neutron irradiation caused by the transmutation of the thermoelement constituents.[5,6]

The thermocouple design (Fig. 4) was based on the design of past high-performance thermocouples.[2] Each probe fit into a close-fitting thermowell in the subcapsule located in the middle of the specimen region. Maximum diametral clearance between the probe and thermowell was 0.15 mm. This clearance was selected to alleviate difficulty in assembly and to keep thermocouple-to-thermowell temperature differences acceptably small.

Irradiation Performance of Experiment

Operation of the high-temperature canisters was monitored by analyzing the gas-blend and temperature data that were recorded continuously by the I&C system during irradiation. Analysis of the gas-blend data provided information on temperature stability, absolute reactor power, reactor power changes, and Type-K thermocouple stability. Analysis of the temperature data provided information on temperature controllability (Type-K thermocouple output) and decalibration rates (Type-C thermocouple output) that aided in determining actual temperatures when one of the Type-K thermocouples failed.

Performance Using Gas-Blend Data

A typical gas-blend history for Level-4 and Level-5 canisters is shown in Fig. 5. The breaks in the data correspond to reactor shutdowns. The helium percentages were generally higher than the design values, thus indicating a higher-than-expected heat-generation rate. This may be attributable to a combination of higher nuclear-heating rates and lower-than-expected end losses.

The tendency of helium percentages to increase during a reactor cycle was attributed to control rod withdrawal from the core with fuel burnup. The Level-5 canisters were affected the most; local power increases of several percent were observed. The changes in reactor power were also evident from cycle to cycle. These changes in nuclear heat generation clearly demonstrated the advantage of having the I&C system to control temperatures.

Performance Using Temperature Data

A typical temperature history of a canister is shown in Fig. 6. The downward spikes in the traces correspond to reactor shutdowns. For all except the 1500-K canister (Canister 5F), temperature control within 10 K of the design temperature was maintained. All Type-C thermocouples significantly decalibrated with time; only the Type-K thermocouple in Canister 5F decalibrated and actually failed after approximately 110 days of irradiation.

Because there were no reliable thermocouples in Canister 5F, there was some uncertainty in its actual operating temperature. The nearly identical decalibration rates for all the other Level-5 Type-C thermocouples, however, enabled its operating history to be estimated. Analysis indicated that Canister 5F operated at an average temperature of only 23 K above its design temperature.

Conclusions and Recommendations

The performance of the high-temperature irradiation experiment clearly indicated excellence in the design and fabrication of the canisters and thermocouples. Canister structural integrity was maintained throughout the 335-day irradiation period. All canister temperatures were maintained within 10 K of design except for Canister 5F which operated at 23 K above its design temperature.

Despite the failure of the Type-K thermocouple in Canister 5F, the operating experience of the test will aid in revising the software in the MOTA I&C system to correct gas blends for future high-temperature canisters in the event of thermocouple failure. Furthermore, it is hoped that a reliable irradiation-resistant thermocouple suitable for operation above the Type-K functional range will be developed to replace the Type-K/Type-C system used in this experiment.

Acknowledgements

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TABLE 1--Experiment design criteria.

Test Volume	8 MOTA canisters
Temperature Range	1290 K - 1500 K
Temperature Control Band	± 10 K
Maximum Specimen Temperature Gradient	20 K
Specimen Environment	Static lithium
Fast Fluence ($E > 0.1$ MeV)	$2.3 - 6.7 \times 10^{22}$ n/cm ²
Test Duration	300 days @ 291 MW reactor power

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Figure Captions

Fig. 1--Materials open test assembly test train and canister locations

Fig. 2--Level-5 canister design.

Fig. 3--Level-5 subcapsule components (ready for specimen loading and lithium filling).

Fig. 4--Thermocouple design.

Fig. 4--Gas-blend history of canisters 4A and 5C.

Fig. 6--Temperature history of canister 5C.

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Fig. 1--Materials open test assembly test train and canister locations.

Fig. 2--Level-5 canister design.

CANISTER 5A

Fig. 3--Level-5 subcapsule components (ready for specimen loading and lithium filling.

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Fig. 4--Thermocouple design.

Fig. 5--Gas-blend history of canisters 4A and 5C.

Fig. 6--Temperature history of canister 5C.

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