FEASIBILITY OF CONDUCTING A DYNAMIC HELIUM CHARGING EXPERIMENT FOR VANADIUM ALLOYS IN THE ADVANCED TEST REACTOR*

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SUMMARY

The feasibility of conducting a dynamic helium charging experiment (DHCE) for vanadium alloys in the water-cooled Advanced Test Reactor (ATR) is being investigated as part of the U.S./Monbusho collaboration. Preliminary findings suggest that such an experiment is feasible, with certain constraints. Creating a suitable irradiation position in the ATR, designing an effective thermal neutron filter, incorporating thermocouples for limited specimen temperature monitoring, and handling of tritium during various phases of the assembly and reactor operation all appear to be feasible. An issue that would require special attention, however, is tritium permeation loss through the capsule wall at the higher design temperatures (>≈600°C). If permeation is excessive, the reduced amount of tritium entering the test specimens would limit the helium generation rates in them. At the lower design temperatures (<≈425°C), sodium, instead of lithium, may have to be used as the bond material to overcome the tritium solubility limitation.

OBJECTIVE

The objective of this task is to determine the feasibility of conducting a dynamic helium charging experiment in the water-cooled ATR for the recently procured large heats of vanadium alloys. This test would be a follow-up to the previous DHCE that was conducted in the MOTA-2B experiment in the Fast Flux Test Facility (FFTF).

General Design Considerations of the ATR-DHCE Experiment

The purpose of a DHCE is to study the effects of concurrent helium generation and neutron damage in vanadium alloys that may be used to construct first-wall/blanket structures in a fusion device. Target temperature range for the proposed ATR-DHCE experiment, denoted ATR-A2, is ≈350 to 650°C. The goal fluence is ≈10 dpa and the desired helium generation rate is ≈4-5 appm/dpa.

The concept of conducting a DHCE in the ATR would be similar to that of the MOTA-2B in the FFTF. During the experiment assembly, tritium that had been predissolved in a mother alloy would be added to the lithium-bonded subcapsules containing the vanadium test specimens. During irradiation, diffusion of the tritium into the test specimens would occur and some of the diffused-in tritium would decay ($T_{1/2}$ = 12.3 yr) in-situ, forming ^{3}He. In this manner, helium generation from the (n,a) reactions in a fusion device would be simulated in the vanadium alloy material.

The major difference between the ATR and the FFTF is the neutron spectrum. Because of the thermal flux in the water-cooled ATR, the proposed A2 experiment would require effective thermal neutron filtering to mitigate two undesirable, thermal-flux dominated events: (1) vanadium-to-chromium transmutation and (2) annihilation of ^{3}He already generated in the vanadium alloy. The latter becomes more significant at higher dpa levels when the concentrations of accumulated ^{3}He in the specimens are high. Material compatibility and burnout concerns dictate that the filter be placed outside the capsule where it can be replaced, if necessary.

Permeation loss through the subcapsule wall would reduce the tritium partial pressure, and hence the helium generation rate in vanadium, with time. TZM, a molybdenum-based alloy with better permeation resistance than that of stainless steel, would be used for the subcapsule. Still, premenation loss could be significant at

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higher temperatures. To compensate, natural lithium (7.5% ^{6}Li) or enriched lithium could be used as the bond material to generate additional tritium from the ^{6}Li(n,T)^{4}He reactions. The drawback of tritium breeding is the cogeneration of ^{4}He, which would cause capsule pressurization.

The rate of helium generation in vanadium specimens depends on the concentration of tritium in V, i.e., the partial pressure of tritium in the subcapsule. The distribution of tritium between vanadium and lithium is temperature-dependent and varies with vanadium alloy composition. Within the solubility limit, the partial pressure of tritium is proportional to the concentration of tritium in lithium. At the low design temperatures, the low solubility limit of tritium in lithium may prevent the required tritium partial pressure from being attained for the desired He generation. An alternative would be to use sodium, instead of lithium, as the bond. The favorable distribution of tritium in a V/Na system is such that the required tritium content would be much lower than in a V/Li system.

Preliminary Findings

Reactor-Related Feasibility Issues

A study conducted by ATR staff indicated that a new irradiation channel with desirable attributes (high fast flux, low thermal flux, adequate test volume, etc.) could be created in the East Flux Trap. An aluminum flux trap insert would have to be built. Preliminary calculations indicated that the flux spectrum in the new channel would be comparable to that in the A-10 channel, where the first fusion structural material experiment, ATR-A1, was conducted. Approximately 11 dpa per calendar year in vanadium is projected based on a 30 MW lobe power in the East Flux Trap and an 80% ATR duty factor.

ATR concluded that lithium could be used as the bond material, as it was in the ATR-A1 experiment. Incorporation of sodium as the low-temperature subcapsule bond is possible but would require additional safety evaluation. The magnitude of permeation of tritium from the ATR-A2 experiment would not be a concern because the facility is capable of handling significantly greater quantities of tritium from other sources in reactor.

Vehicle-Related Feasibility Issues

The diameter of the new irradiation channel would be 26.2 mm, sufficient to accommodate a reasonably-sized capsule with an external thermal neutron filter. The cross section of a conceptual capsule design is shown in Fig. 1. The capsule would have several axial segments, each containing several subcapsules in an arrangement similar to that of the ATR-A1. The gas gaps between the capsule and subcapsules would determine the specimen temperatures. Specimens would be bonded with lithium (or sodium) in the subcapsules. The top segment of the capsule would have annular subcapsules, allowing thermocouples to penetrate along the centerline. These thermocouples would provide the needed data to corroborate the temperatures predicted by modeling. Handling and routing the thermocouples out of the reactor vessel for measurement appears to be feasible from the standpoint of reactor operation.

The external filter assembly would be a cylindrical shell made as an integral part of the basket holding the capsule during irradiation. It would contain thermal-flux-absorbing material jacketed in stainless steel sheets. Several filtering materials have been considered, and Eu_2O_3 appears to be the best choice in terms of blackness and lifetime. Simulated Eu_2O_3 packing tests with a mockup assembly have been conducted and the results show that Eu_2O_3 powders can be packed to the desired ≈50% theoretical density.

The subcapsules would be constructed with a TZM alloy (0.5%Ti, 0.07%Zr, balance Mo) that has a superior tritium-retention capability compared to that of other construction materials. Preliminary welding tests showed the TZM can be satisfactorily welded with the electron-beam welder available at the ANL assembly laboratory. The capsule would be constructed of 304 stainless steel and will meet the ASME Pressure Vessel and Boiler Code, Section III, as required by ATR.

The total test specimen volume in the experiment would be ≈10-25% greater than that in ATR-A1, depending on the detailed design.

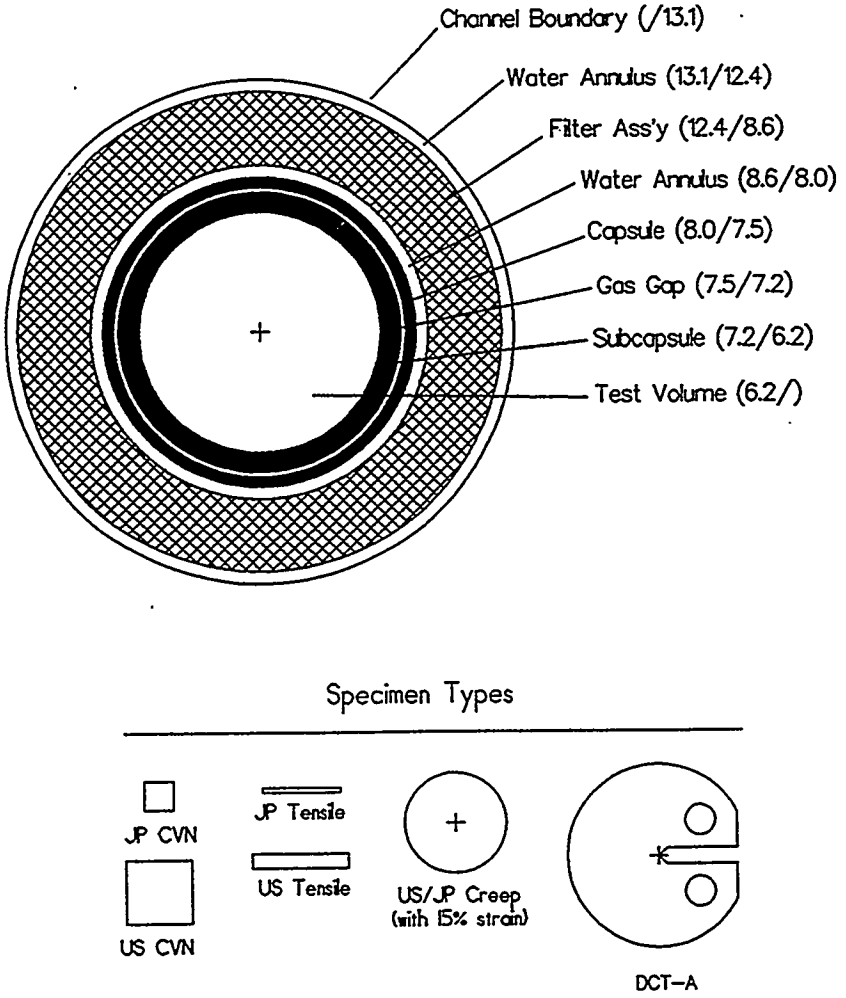

Fig. 1. Cross section of a conceptual ATR-A2 capsule design. Numbers in parentheses are inside and outside radii, respectively, in mm. Sizes of all components are to proportion.

Issues Related to Helium Generation

Physics scoping calculations are being conducted to evaluate the effects of the following intertwining parameters on He/dpa ratios: temperature, tritium distribution coefficient, filtering material and thickness, fluence, initial tritium charge, ^{6}Li enrichment, and subcapsule wall thickness (which affects tritium permeation). To address the uncertainties in the distribution coefficients (C_V/C_{Li}), which directly affect the rates of helium generation in vanadium, a range of 0.002-0.02 (by weight) was used in the present study. These values are ≈5 times smaller than those used in the design of MOTA-2B to correct the deficiencies found in the helium generation rates in the MOTA-2B specimens. It is imperative that before the construction of ATR-A2, the distribution coefficients for all major vanadium alloys are experimentally determined to remove these uncertainties.

At 400°C, the ^3T saturation partial pressure in a Li/H system is low and probably would limit the achievable He appm/dpa ratio in vanadium to ≈1.3. The lowest temperature where the target ratio of 5 is attainable is ≈425-450°C. If temperatures lower than ≈425-450°C are desired in the ATR-A2 experiment, an alternative, such as a Na/H system, would be necessary. (In the 300-400°C range, the ^3T saturation pressure in a Na/H system is approximately 10^3 higher than in a Li/H system.) Preliminary results indicated that Na-bonded subcapsules can be fabricated and would produce the desired He appm/dpa ratio of ≈5. Impurity uptake by vanadium alloy specimens in sodium is not expected to be a problem at these low temperatures. Tritium leakage loss likewise would also be low.

At 500°C, DHCE appears to be feasible for lithium-bonded subcapsules for a wide range of possible distribution coefficients. Tritium leakage loss would be modest, ≈10% of the initial charge, at a nominal TZM wall thickness of 1 mm.

At temperatures >≈600°C, tritium leakage through the TZM subcapsule becomes significant as the permeability constant increases rapidly with temperature. Because as much as ≈60% of the initial tritium loading may be lost at the end of the 10 dpa irradiation (with 1-mm nominal TZM wall), achieving a steady He appm/dpa ratio during irradiation would require bonding with enriched lithium. Preliminary calculations indicate that the achievable He appm/dpa ratio at 600°C would be ≈3.3-4.3, depending on the distribution coefficient. While increasing the wall thickness would reduce the tritium loss, it would have adverse effects on specimen volume and temperature. The more desirable solution would be to use innovative materials for construction to reduce the permeation, such as more permeation-resistant material (e.g., tungsten-based alloys) or an external permeation-inhibiting coating for the subcapsules. Alternatively, it may be possible to construct the outer capsule of aluminum, a material with low permeation coefficient, to form a secondary barrier for tritium.

FUTURE ACTIVITIES

Refined flux spectrum data for the East flux trap channel will be obtained from ATR. Further parametric studies on the helium generation rates will be conducted. The feasibility of using sodium as the bond material for the low-temperature subcapsules will be studied in greater detail. Alternative materials of construction will be examined to address the high-temperature tritium permeation issue.