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Journal of Nuclear Materials 258–263 (1998) 400–406

journal of nuclear materials

Design concept for the IFMIF test assemblies [1]

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Abstract

According to specific materials testing needs, the available irradiation volume of the International Fusion Materials Irradiation Facility (IFMIF) has been partitioned into a high-flux region that has an irradiation damage rate for iron of greater than 20 displacements per atom (dpa) per full-power year (fpy), a medium-flux region with 1–20 dpa/fpy, a low-flux region with fluence levels between 0.1 and 1 dpa/fpy, and a very low-flux zone with an annual accumulation of less than 0.1 dpa. A set of test assemblies, which is located immediately downstream from the neutron producing Li-target, vertically supports (1) test modules used for long-term irradiation of specimens in the high- and medium-flux regions, and (2) an array of tubes used for inserting test capsules in the low- and very low-flux regions. Based on this arrangement and on small specimen test technologies, IFMIF is capable of providing sufficient volume and appropriate irradiation environments to meet the requirements defined by the user community.

1. Introduction

The need to develop a structural material that can withstand the high-energy neutron flux environment expected for the first wall and blanket regions of deuterium–tritium (D–T) fusion reactors is recognized as one of the key challenges remaining in producing commercial fusion power. In response to this need, the International Fusion Materials Irradiation Facility (IFMIF) project started in 1994 under sponsorship of the International Energy Agency (IEA). IFMIF's mission is to (1) provide a neutron source with an energy spectrum simulating that of fusion neutrons at sufficient intensity and irradiation volume to test samples of candidate materials up to about the full lifetime of anticipated use in a fusion DEMO reactor and (2) calibrate data generated from fission reactors and particle accelerators. The international design team formed to conduct the Conceptual Design Activity (CDA) phase of IFMIF completed a conceptual design and initial cost estimate for all major IFMIF systems and facilities in 1996 [1].

Earlier efforts, including the Fusion Materials Irradiation Test (FMIT) facility project [2] and the technical evaluation project activity of the Energy Selective Neutron Irradiation Test (ESNIT) facility [3], concluded that the most cost-effective approach for providing the necessary test conditions in terms of technical feasibility of the irradiation facility and suitability for fusion materials testing utilizes a high-energy deuteron beam, which generates neutrons in a nuclear stripping reaction with a liquid lithium target. The deuteron accelerator and lithium target systems proposed for IFMIF are described elsewhere [1]. This paper addresses the design concepts for the IFMIF materials irradiation test assemblies and establishes that these test assemblies are able to fulfill major user requirements. More detailed discussions of the requirements set by the user community and an overview of the entire test facilities (including the two-test cells that house the test assemblies, remote handling equipment, and hot-cell facilities) are presented in related papers [4,5].

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[1] Research sponsored by the Office of Fusion Energy Science, US Department of Energy, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

PII: S0022-3115(98)00367-5

2. Key test assembly requirements

The materials under consideration for fusion energy systems encompass a variety of metals and nonmetals and a broad range of loading conditions. According to materials testing needs, the available irradiation volume of IFMIF has been partitioned into a high-flux region which has an irradiation damage rate for iron of greater than 20 displacements per atom (dpa) per full-power year (fpy), a medium-flux region with 1–20 dpa/fpy, a low-flux region with fluence levels between 0.1 and 1 dpa/fpy, and a very low-flux zone with an annual accumulation of less than 0.1 dpa. The IFMIF test cell and specimen testing areas must accommodate the wide range of environments associated with fusion reactor materials [6–8]. The test assemblies in the high-flux region must be capable of providing an irradiation environment that maintains test specimens at temperatures between 520 and 1270 K, whereas the facility must be capable of irradiation temperatures of 520–1070 K in the medium-flux region, 80–800 K in the low-flux region, and 4–600 K in the very low-flux region.

Seven different miniaturized specimen geometries were identified [1,4,9] for use in the high-flux region IFMIF during the past years. These specimens will determine key properties such as density and microstructure, tensile strength, creep-fatigue endurance, fracture toughness, crack growth, impact behavior, and irradiation creep. The overall dimensions and quantity for each type of specimen in a "standard" loading with enough specimens to obtain data at three-different temperatures are identified in Table 1. This loading contains almost 1400 specimens. The total volume occupied by the packets in the reference loading is estimated to be 325 ml. Additional space required for the module structure and coolant brings the total volume of the high-flux module to about 0.5 l. It should be emphasized that to ensure an effective use of this high-flux volume and to establish an international standardization of testing procedures, ongoing collaborative efforts towards further development of miniaturized specimens and related testing techniques are necessary.

Sufficient access and space for in situ testing must be provided in the medium- (1–20 dpa/fpy), low- (0.1–1 dpa/fpy), and very low-flux (0.01–0.1 dpa/fpy) regions of IFMIF. Anticipated in situ tests in the medium-flux regions include creep-fatigue, stress-corrosion, and crack-growth tests on metals and tritium-release measurements in ceramic breeding materials. In situ tests that may be performed in the low-flux regions include electrical resistivity and dielectric property (loss tangent at about 50 MHz to 100 GHz) measurements on ceramic insulators, optical property measurements on optical fibers and window materials, and in situ tests of diagnostic components. Cryogenic in situ irradiation tests on organic insulation and superconducting materials would be performed in the very low-flux regions.

3. Test assembly design

As described in more detail in Ref. [5], vertical test assemblies (VTAs) will accommodate test modules for specimens in the high- and medium-flux regions, while vertical irradiation tubes (VITs) are foreseen for test capsules in the low- and very low-flux regions. In the reference design the high-flux region consists of either sodium–potassium eutectic (NaK) cooled test modules for low and medium irradiation temperatures or helium gas-cooled test modules for high-temperature applications with the strong option to replace the NaK-cooled version after the feasibility of the helium concept has been demonstrated through a series of fabrication and thermal-hydraulic tests. The major advantages of helium gas instead of NaK are flexibility with respect to irradiation temperatures and safety and maintenance considerations. Either simultaneous in situ push–pull creep-fatigue tests on three individual specimens or in situ tritium-release tests on breeder materials are foreseen in the medium-flux region. The VIT system in

Table 1
Material test specimens in a reference high-flux module

Type of test specimen	Geometry (mm)	No. of specimens [a]/vol. of specimen packets (cm^3)
Microstructure	TEM disk (3 diam. × 0.25)	800/4
Tensile	Sheet tensile specimens (25 × 4.8 × 0.76)	156/45.2
Fatigue	Cylindrical specimens (25 × 4.8 × 1.52)	96/55.7
Fracture toughness	Disk compact tension (11.5 × 11.5 × 4.6)	66/89.1
Crack growth	Disk compact tension (11.5 × 11.5 × 2.3)	40/31.5
Dynamic fracture toughness	Notched bar (3.3 × 3.3 × 25)	120/61.6
Creep	Pressurized tube (25 × 2.5 diam.)	104/37.4
	Total	1382/325

[a] Dimensions were determined according to standard packing arrangements used for fission neutron irradiation capsules.

the low- and very low-flux region is presently dedicated to special purpose materials like ceramic insulators, radio frequency (rf) windows, diagnostic materials, or superconducting materials. Design details of the two types of VTAs and the VIT are described in Sections 3.1–3.3.

3.1. High-flux test assemblies

VTA-1 contains the 0.5 l high-flux (volume with a damage rate of greater than 20 dpa/fpy for iron) module. The shielding portion of the VTAs consists of a stepped, stainless steel liner that is filled with concrete. Steps in the test cell shield plug and removable cover conform to the steps in the shielding portion of each VTA to prevent radiation streaming. The coolant supply and return lines for the high-flux module are contained within the shielding body of VTA-1. Conceptual designs for both helium-cooled and NaK-cooled versions of this test assembly have been developed. Because of materials compatibility issues associated with NaK, helium must be used for high-temperature irradiation loadings ($\geqslant$ 870 K). Although the detailed arrangement and temperature control of test specimens are quite different for these two coolant schemes, the overall configuration for VTA-1 is nearly identical for both coolants. Details of these arrangements were worked out for both coolant types and are discussed in other documents [1,10]. For purposes of brevity, only the helium-cooled version of VTA-1 is discussed further here.

Typical nuclear heating densities in the high-flux region are about 5 W/g (40 W/cm^3) in ferritic/martensitic steels (i.e., a linear power density of about 75 W/cm). For the sake of comparison, linear power densities in modern pressurized-water fussion reactors (PWRs) are about 400 W/cm, while typical power densities in Materials Testing Fission Reactors (MTRs) are about 10 W/g. Comparison of the heating rates in IFMIF with these present-day applications indicates that helium is a viable option for the coolant in the high-flux regions of the IFMIF test cell.

As shown in Fig. 1, the helium-cooled irradiation module is a vessel with irradiation rigs. Each rig contains the encapsulated specimens at the desired irradiation temperature. Temperature control is the key parameter defining the specimen's irradiation environment. Specific irradiation temperatures can be achieved with the use of gas gaps, a common procedure in most MTRs. This keeps the overall test-cell structure (capsules, rigs, vessel structure) at operating temperatures well below the specimen temperature. The use of gas gaps to raise the specimen temperatures means that the entire irradiation temperature window (520–1270 K) is independently available for each rig. Precise control of the size of these gas gaps, which range from 0.1 to 0.5 mm, during fabrication and installation of the rigs is a critical issue that will be investigated in the next phase of the IFMIF project.

Apart from the passive temperature control, it is desirable during normal operation that 15–25% of the

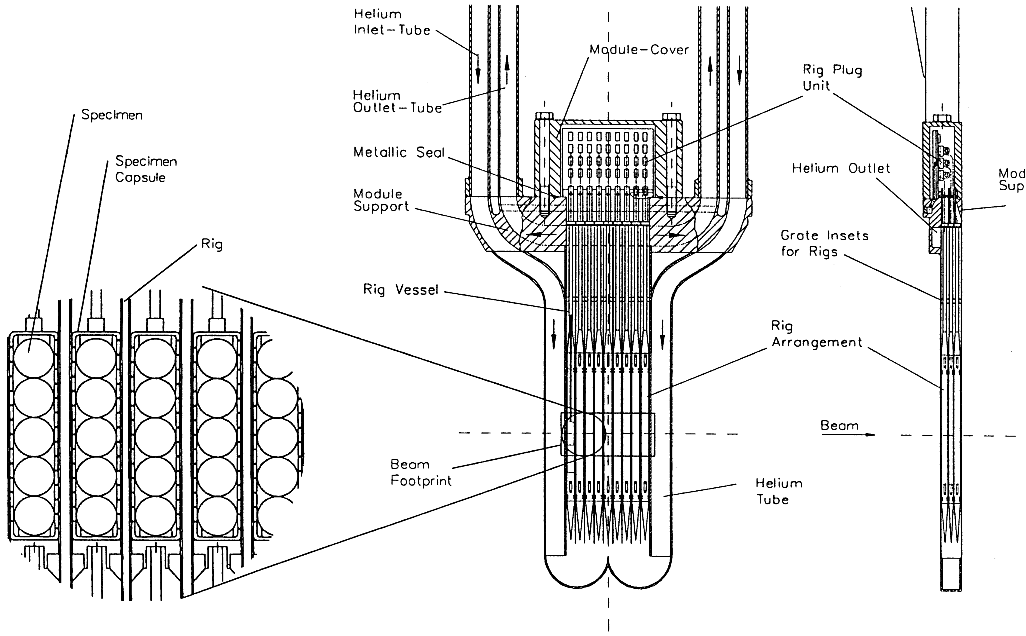

Fig. 1. Helium-cooled, high-flux test module with vertical rigs that accommodate the encapsulated specimens.

total heat deposition in the specimens should be provided by ohmic rather than by nuclear heating. Therefore, it is planned to integrate an ohmic heating system into the specimen capsules. Long-term experience in various cyclotron irradiation facilities has shown that temperature shifts because of beam density instabilities can be compensated with such a technology. This system is also used for temperature control in beam-off scenarios.

The irradiation rigs contain the capsules that house the specimens. The internal portions of the rigs are pressurized with gas (normally helium or argon) to the coolant pressure to minimize the thickness of the rig wall. There is a capsule for each type of specimen. The design goals for the specimen encapsulation include minimization of thermal gradients and optimization of coolant surface and available specimen volume.

Helium properties are retained even at temperatures well above those limits acceptable for structures and materials. The coolant itself does not, therefore, impose a limit on allowable temperatures. However, limits are imposed on the coolant parameters so that the flow maintains the structure and components within design limits. Considering these limits, the helium-flow parameters are shown in Table 2. Based on these parameters, the requirements placed on the coolant and associated subsystems (compressors, heat exchangers) are quite conventional. Existing, well-proven technology is adequate and cost effective for helium-cooling requirements. Together with the flow bypass, the temperature control system is able to maintain specimen temperatures within accepted limits, even for a complete loss-of-heating power (both beams off), flux and energy oscillations, and increases in nuclear power.

3.2. Medium-flux test assemblies

VTA-2 is located directly behind the high-flux module and houses the medium-flux experiments. The useful volume of VTA-2 (i.e., volume with a damage rate of greater than 1 dpa/fpy for iron) is 6 l. Several different types of in situ tests are anticipated to be performed in the medium-flux region, including creep-fatigue testing of structural materials, tritium-release performance tests of ceramic breeder materials, and electrical conductivity tests on ceramic insulators. In addition, it is likely that some irradiations of vacuum vessel structural materials and functional (mostly ceramic) materials may be performed in VTA-2. Gaseous helium will be used as the medium-flux module coolant for all irradiation temperatures because the available irradiation volume is rather large, and tritium released from ceramic breeding materials can be easily separated from helium. It is anticipated that specimens in both VTA-1 and VTA-2 would be changed out rather infrequently, with typical irradiation campaign cycles of about 1 yr.

Table 2
Thermohydraulic parameters for the helium coolant

Coolant inlet pressure (head)	0.12–0.35 MPa
Equivalent average hydraulic diam.	10.5 mm
Coolant pumping velocity	11.0–25.0 m/s
Reynolds number	3×10^4
Ultimate film coefficient	1030 W/m^2 K
Mass flow rate	0.2 kg/s
Volumetric flow rate	0.17 m^3/s
Coolant inlet temperature	50°C
Coolant outlet temperature	62°C
Pressure drop	<0.04 MPa
Required compression ratio	1.2
Temperature increase due to compression	10 K

Design concepts for two-specific types of irradiation experiments (i.e., in situ creep-fatigue experiments on structural materials and in situ tritium-release experiments on ceramic breeders) were developed during the CDA phase of the IFMIF project. To effectively use the available irradiation volume, VTA-2 will be equipped with two independent test modules, such as a creep-fatigue module and a ceramic-breeder module. Concepts for these two types of test modules are described in the following.

The creep-fatigue behavior of structural materials during irradiation in inert or chemical environments will be examined with a push–pull, creep-fatigue testing machine (Fig. 2). The specimen is a hollow tube with coolant flow in the interior to maintain a uniform temperature. In addition, in situ slow-strain-rate tensile tests may also be performed using a similar test apparatus. The effect of chemical environments such as those presented by liquid-metal coolants may be used to examine the impact of stress corrosion processes on the creep-fatigue and stress-corrosion cracking behavior during irradiation. It is desirable to have the capability to perform tests with water as the coolant; however, this option will require a detailed safety evaluation before implementation because water is incompatible with lithium and NaK. The approximate size of the in situ test equipment is 100-mm high, 80-mm thick, and 400-mm wide. Three creep-fatigue specimens may be tested independently at one time in this equipment. A suitable specimen design has already been developed, and a more detailed description of in situ creep-fatigue tests is given in [1,11,12] together with a possible test matrix.

The tritium-release test module can be located at the position just behind that for the in situ creep-fatigue test, or when the creep-fatigue test is not performed, another tritium-release module may be equipped for tests at the high-flux position. After completing the irradiation, the module will be disassembled to examine the compatibility and integrity of the specimens.

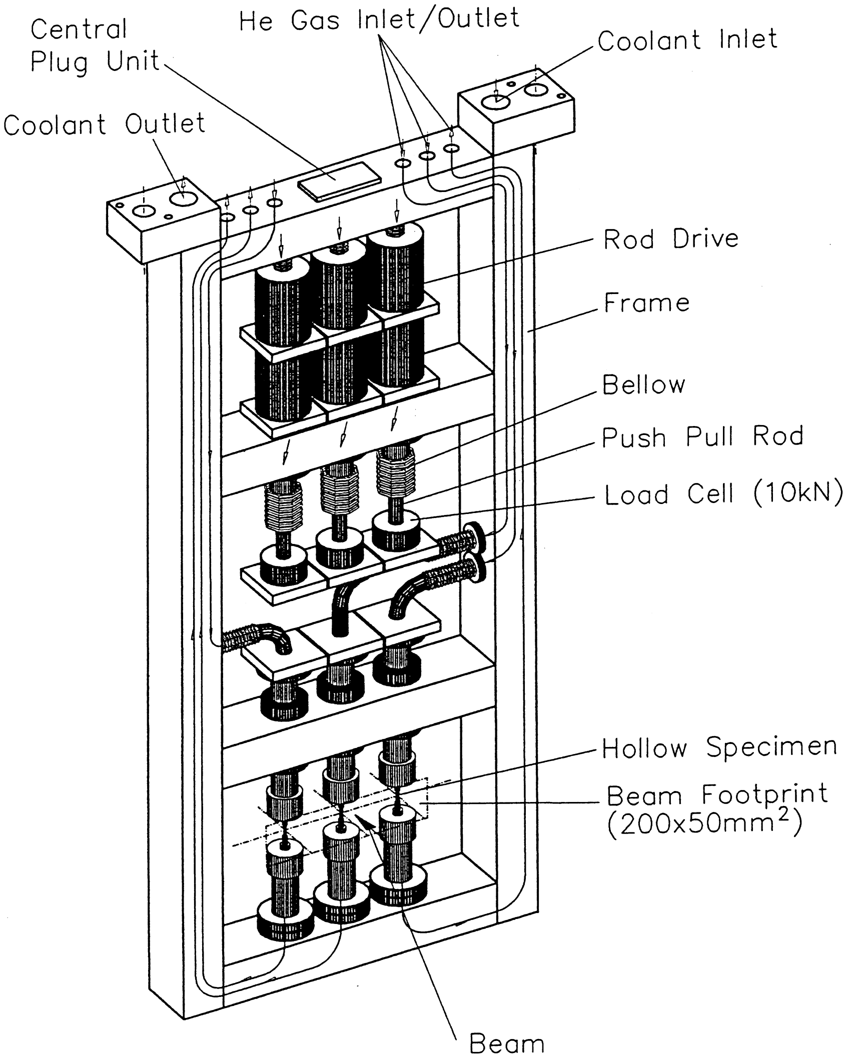

Fig. 2. Test module for in situ creep-fatigue experiments on three independent specimens in the medium-flux position.

Four subtest modules and the capsules placed in these subtest modules are contained in the overall tritium-release test module (Fig. 3). Ceramic specimens in the shape of disks, pellets, and pebbles are contained in each capsule. Three subtest modules are used for tritium-release and compatibility tests with disk specimens, and one subtest module is used for tritium-release tests with pellet and pebble specimens. Tritium released by the specimens in the capsules will be swept up by helium gas flowing through the capsules and will be carried through pipes in VTA-2 to the analyzing equipment located in the test cell control room. The dimensions of the subtest modules for pellet/pebble specimens and disk specimens (including compatibility specimens) are $64 \times 95 \times 273$ mm^3 and $58 \times 33 \times 273$ mm^3, respectively. The irradiation temperature will be controlled by the gas gap parallel to the specimen surface, and the specimens will be irradiated at three temperature levels ranging from 570 to about 1170 K. Evaluation of the compatibility between breeding and structural materials will also be carried out with disk specimens. Ceramic specimens and the disk-shaped specimens of metallic structural materials are encapsulated side by side in a similar capsule. The capsule for the pebble specimens will be used to evaluate the performance of the concept including tritium-release behavior and durability of the breeding materials during irradiation.

Instead of ceramic breeders, the subtest modules can also be equipped with any other instrumented PIE specimens. It is also anticipated that in situ tests of

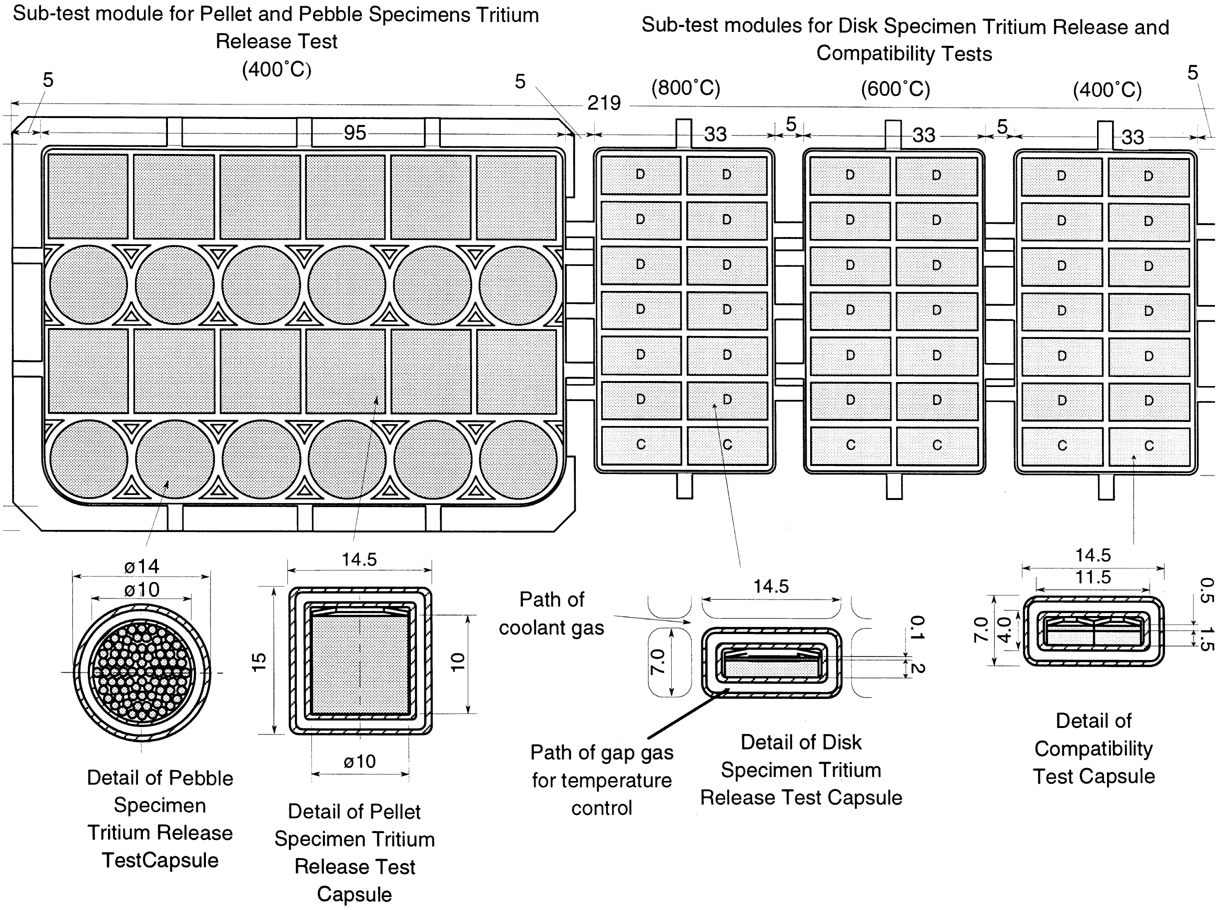

Fig. 3. Configuration of tritium-release subtest module and capsules for disk, pellet, and pebble specimens. The subtest module for disk specimens and for pellet and pebble specimens houses 14 and 24 capsules, respectively. Tritium released by the specimens in the capsules will be swept up by helium gas flowing through the capsules (all dimensions are in mm).

blanket insulators in contact with liquid metal coolant may be performed in this region. The anticipated irradiation capsule size is about 100-mm high, 50-mm thick, and 80-mm wide.

3.3. Low- and very low-flux test assemblies

The VIT system – which consists of an array of tubes, pneumatic pumps, valves, and heat exchangers – is designed for rapid insertion and removal of test specimens in the low-flux (damage rate between 0.1 and 1 dpa/fpy) and very low-flux (damage rate between 0.01 and 0.1 dpa/fpy) regions of the test cell. This arrangement is particularly useful for in situ test, and short-term irradiations of damage-sensitive materials such as superconductors, optical components, organic insulators, etc.

Because tests in these regions are expected to examine materials used in cryogenic environments as well as materials operating at elevated temperatures in fusion reactor blanket and vacuum vessel regions, the temperature range is expected to be from 4 to 700 K. Liquid helium or nitrogen or gaseous helium will be used as coolants. The capability to maintain cryogenic temperatures following irradiation (to prevent annealing of the radiation damage in specimens irradiated below room temperature) is considered to be an important feature for the VIT system. Typical in situ tests to be performed in this region include dielectric loss measurements on ceramics and diagnostic materials, optical absorption of optical fibers and windows, and PIE tests of superconducting magnet materials, including conductors, insulators, and dielectric materials. It is anticipated that samples can be rapidly inserted and removed from the irradiation tubes thereby facilitating low-fluence tests.

4. Conclusions

Based on user-defined test requirements, a conceptual design was developed for a set of test assemblies that incorporate the required miniaturized test specimens, coolant, and support structure. These assemblies from an array of three VTAs that provide a test bed for instrumented and/or in situ experiments in metals and nonmetals for irradiation loading regimes ranging from 50 to 0.01 dpa/fpy.

The test assembly, VTA-1, positioned in the high-flux region of the test cell, has a usable volume of about 0.5 l where the damage rate (for Fe) is more than 20 dpa/fpy. Design concepts using either NaK or helium as the coolant media were developed for VTA-1. More than 1000 miniaturized materials testing specimens are provided in this high-flux region to gather the data required for developing and qualifying blanket and first wall structural materials for advanced fusion devices such as the so-called DEMO.

The second test assembly, VTA-2, is located directly behind VTA-1 and is dedicated to more sophisticated experiments to measure the materials properties under real-loading conditions. Conceptual designs have been developed to perform long-term in situ tritium-release investigations, selected in situ creep-fatigue tests, or other instrumented experiments in this region.

An array of tubes, referred to as the VIT assembly, is used for inserting test capsules in the low- and very low-flux regions. Because tests in this region are expected to examine materials used in cryogenic environments as well as materials operating at elevated temperatures, both cryogenic liquids and gaseous helium will be used as coolants.

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