Materials Testing in the ICF Test Facility SIRIUS-M

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April 1986

UWFDM-683

Presented at the 2nd International Conference on Fusion Reactor Materials, 14-17 April 1986, Chicago, IL; J. Nucl. Matl. 141-143 (1986) 1039.

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Abstract

The symmetric illumination laser-driven SIRIUS-M test facility provides materials testing in relevant ICF conditions. The test module is placed 2 m away from the target to achieve a goal neutron wall loading of 2 MW/m^2. The 2 mm thick graphite liner reduces the peak dpa rate in the module by only 2.4%. Using a lead reflector results in 50% more damage in the test module compared to a stainless steel reflector. Two circular test modules are used in SIRIUS-M. Each module fits between three beam ports. About 1 MW of nuclear heating is removed by the helium coolant from each module. The peak iron dpa rate is 24 dpa/FPY yielding an accumulated damage of 120 dpa after 5 full power years of operation. A total volume-integrated figure of merit of 14,200 dpa-ℓ can be achieved. The test matrix and testing schedule are described. It is possible to perform all tests needed for the ICF Demo in the two SIRIUS-M test modules.

1. Introduction

There is a need for integrated materials testing in the complex nuclear environment of both magnetic confinement fusion (MCF) and inertial confinement fusion (ICF) reactors. The MCF program has taken the lead in attempting to solve this problem by sponsoring several test reactor studies such as FERF [1], TETR [2], INTOR [3], TASKA [4], TASKA-M [5], TDF [6] and FEF [7] that provide a nuclear and thermal environment similar to that expected in the first demonstration reactor.

On the other hand there has been a lack of near-term test-facility designs in the ICF technology program. The singular exception is a brief scoping study of a device called LA FERF [8]. While it is commonly assumed that the MCF materials program will provide the data needed for designing ICF reactors, the large differences between the damage conditions in ICF and MCF environments [9,10] make it imperative to develop a dedicated ICF materials test facility. The SIRIUS-M facility [11,12] is designed to duplicate the damage structure unique to ICF systems. Detailed description of the facility is given in a companion paper [12].

In order to obtain high integrated fluence in the shortest possible time, the SIRIUS-M test module is placed as close as possible to the target. Furthermore, attempts were made to increase the damage rate in the test module, for the same wall loading, by using different reflector materials and varying the reflector location relative to the test module. The results of this parametric study as well as the damage profiles and testing capability for the SIRIUS-M test module will be presented. The specimen test matrix and test schedule will also be discussed.

2. Comparison Between Damage Conditions in ICF and MCF Reactors

Neutron damage to structural materials in ICF and MCF reactors can be significantly different even when the first wall is exposed to the same level of radiation (quoted in MW-yr/m^2). These discrepancies arise from geometrical, spectral, and temporal effects.

While a cylindrical (or toroidal) chamber surrounds a volumetric distributed neutron source in a MCF reactor, a point neutron source is usually surrounded by a spherical first wall in ICF reactors. All neutrons from the point source in the ICF geometry are incident perpendicular to the spherical wall resulting in less damage in the front and more damage in the back as compared to the MCF case. The damage rate profiles calculated in a 20-cm thick test module for both ICF and MCF geometries demonstrate that the first wall damage in MCF cylindrical geometry is 50% higher than that in ICF spherical geometry for the same neutron wall loading. A faster damage dropoff in the module occurs in the cylindrical chamber.

The radii of ICF and MCF test facilities might also be quite different. For example the tandem mirror MCF test facilities have wall radii in the range 0.2-0.4 m. In contrast, the radius of the ICF test chamber has to be at least 2 m to avoid melting of the first wall during the target explosion. The larger the radius the higher the dpa rate in the first wall for the same neutron wall loading since the first wall has a larger view factor for secondary backscattered neutrons. These geometrical effects combine resulting in 31% more dpa in the first wall of a MCF test facility compared to an ICF test facility.

Whereas the neutrons emanating from a MCF plasma have a well defined energy at 14.1 MeV, those escaping an ICF target have average energies as low as 10 MeV due to neutron-target interactions [13]. Comparing the results for a monoenergetic 14.1 MeV source to those using the SIRIUS-M target spectrum (12.5 MeV average energy) for the same 2 m radius spherical cavity showed that the degraded neutron spectrum results in 9% higher dpa produced in the first wall per MW-yr/m^2.

The geometrical and spectral effects were combined to demonstrate the dependence of the damage conditions on reactor confinement concept. SIRIUS-M parameters were used for the ICF facility while the parameters for a tandem mirror test facility of the TASKA type represent the MCF facility. The damage rate in the first wall of the MCF facility is 21% higher than that for the ICF facility but drops faster as one moves towards the back.

A major difference between the ICF and MCF system is the time over which the displacement and transmutation damage is produced. This results in even larger differences in damage conditions. For SIRIUS-M, with a repetition rate of 10 Hz and 2 MW/m^2 wall loading, the peak instantaneous first wall dpa rate is 14 dpa/s which is 8 orders of magnitude higher than that in MCF facilities. However, most of the damage is produced in less than 10 ns leaving a relatively long time between shots where the damage can anneal out or agglomerate into different microdefects.

It is concluded that materials information generated to meet MCF applications may not be adequate to determine their behavior in ICF environments. Reliance on MCF test facilities may not be in the best interest of the ICF program in the long run, and a dedicated ICF materials test facility is needed.

3. Parametric Studies for the SIRIUS-M Materials Test Module

For the test specimens to accumulate high damage levels in the shortest possible time, the module is located as close as possible to the target. Given a target yield of 13.4 MJ and a repetition rate of 10 Hz, the test module is placed 2 m away from the target to achieve a goal neutron wall loading of 2 MW/m^2 at the module which corresponds to an irradiation of 1 MW-yr/m^2 per calendar year. The test module is protected from the high surface heat flux resulting from x-rays and ion debris (7 J/cm^2) by 1 torr (133 Pa) xenon gas and a graphite liner. The reflector material choice and reflector location relative to the test module impact the neutron flux and spectrum in the test module and hence influence the achievable damage rate. An effort was made to maximize the damage rate by proper choice of reflector material and location.

One-dimensional spherical-geometry ONEDANT [14] calculations were performed to investigate the impact of the graphite liner. A 1 cm thick liner at a radius of 2 m was followed by a 20 cm thick test zone backed by a 40 cm thick steel shield. The liner reduces the dpa rate by 6% with only a 2.4% reduction in helium production. Although a graphite liner thickness of 1 cm was proposed to provide adequate protection for the permanent reactor first wall, a thinner liner can be used for the test module which will be frequently removed for test specimen replacement. A 2 mm thick liner is used for the test module resulting in only a 2.4% drop in the dpa rate and only a 0.5% drop in the helium production rate compared to the case without a graphite liner.

In the early stages of the SIRIUS-M design, a chamber radius of 8 m was proposed with a cantilevered test module that is located at a radius of 2 m. This geometry was modeled for the three-dimensional neutronics calculations using the Monte Carlo code MCNP [15]. A 50 cm thick reflector zone was used in the calculations. Two options were considered for the reflector material: one is a steel reflector made of 90% HT-9 and 10% H_2O and the other is a lead reflector consisting of 90% molten lead and 10% HT-9. The inner surface of the reflector is covered by a 1 cm thick graphite tile. The test module and reflector were connected by a 30-cm cylindrical zone representing the piping and coolant manifolding required for the test module. The effect of the reflector location relative to the test module was analyzed by performing calculations for cavity radii of 8, 4 and 2 m.

A comparison between the values of the peak dpa rate in the test module is shown in Fig. 1. Bringing the reflector closer to the test module results in significant enhancement of the produced damage since the test module has a larger view factor for secondary neutrons reflected from the smaller radius reflector. The effect on helium production is much less pronounced since secondary reflected neutrons contribute very little to helium production.

Neutron multiplication in lead enhances the neutron flux at the test module yielding ~ 50% higher dpa rate than that in the steel reflector case for a 2 m radius cavity. The effect is smaller for larger cavity radii due to the smaller contribution of reflected neutrons. On the other hand, the He production rate remains about the same or becomes slightly smaller as most of the neutrons produced in (n,2n) reactions in Pb have energies below the (n,α) threshold energy.

It is concluded from the results of this section that the damage rate achievable in the test module can be maximized by incorporating the test module into a lead reflector. This design results in doubling the dpa rate

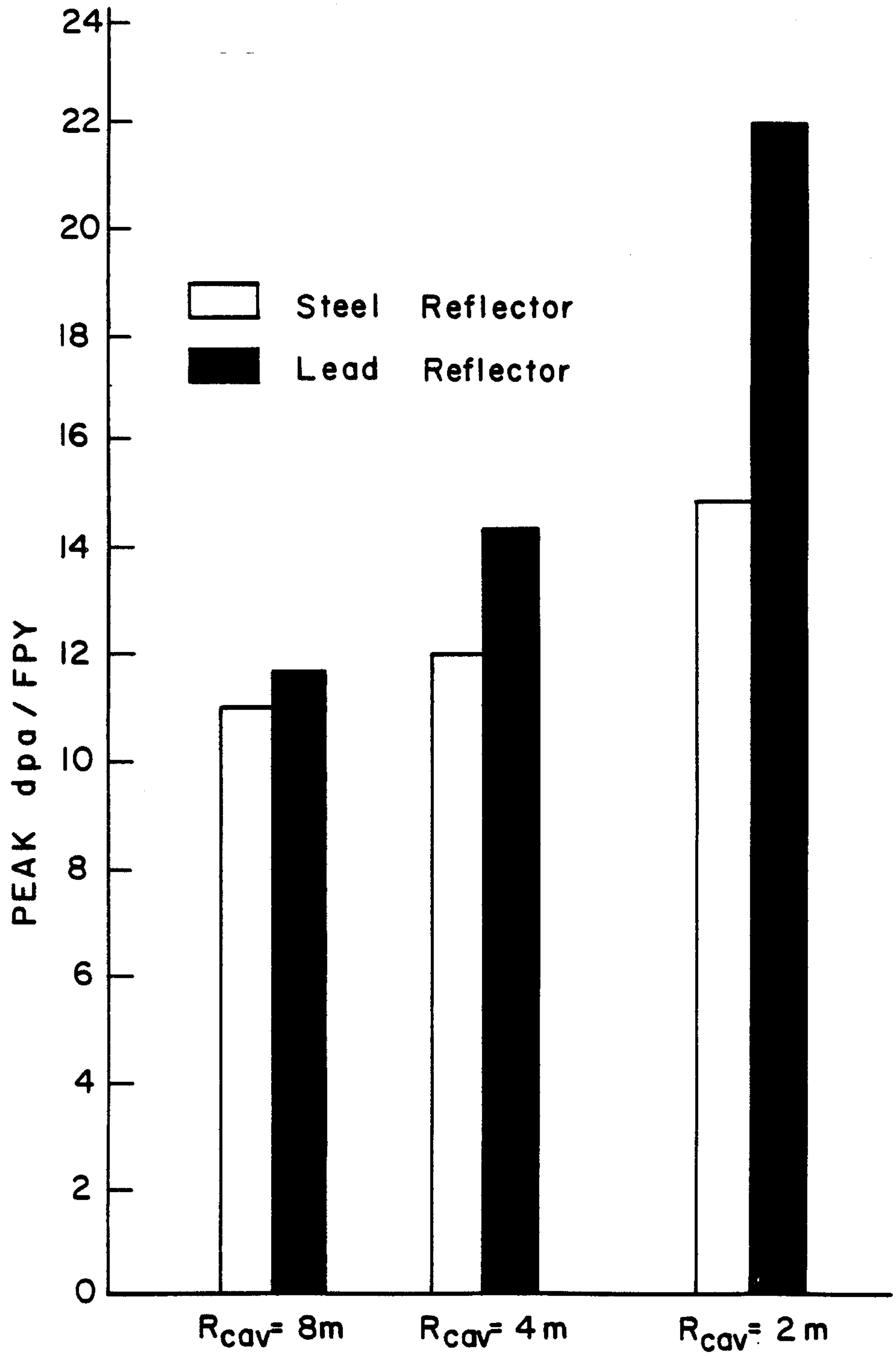

Fig. 1. Effect of cavity radius and reflector material on peak dpa rate in test module.

and testing capability of the module compared to the initial cantilevered test module design with a steel reflector.

4. Neutronics Analysis for the Final SIRIUS-M Materials Test Module Design

Thirty-two laser beams are used to uniformly illuminate the target in SIRIUS-M. The test module fits between three beam ports with a front surface area of 1 m^2 that represents 2% of the solid angle seen by the target. SIRIUS-M utilizes two such modules located at the opposite sides of the chamber.

The test capsules are 5 cm in diameter and 20 cm in length. They are placed perpendicular to the front surface of the module. Each module uses 217 capsules providing 85.4 liters of test volume. This represents 40% of the 213.5 ℓ module volume. The capsules consist of 50% NaK, which is used as a thermal contact material, and 50% 316 SS, which represents the specimens and capsule structure material. The module structure represents 20% of the module volume and is made of HT-9. The helium gas coolant occupies the remaining volume.

The large pressure of the helium coolant (~ 3400 kPa) requires using curved module front surfaces. The test module for SIRIUS-M is composed of two parts: a quick access cylindrical part for short term test samples and a long-term annular part. 3 mm thick HT-9 semi-ellipsoidal pressure heads protruding 8 cm into the chamber are used as shown in Fig. 2. A 2 mm thick graphite liner covers the module.

One-dimensional spherical-geometry neutronics and photonics calculations have been performed to determine the axial variation of power density in the test capsules. In these calculations the front surface of the test module is located at a radius of 1.96 cm which represents the average location of the

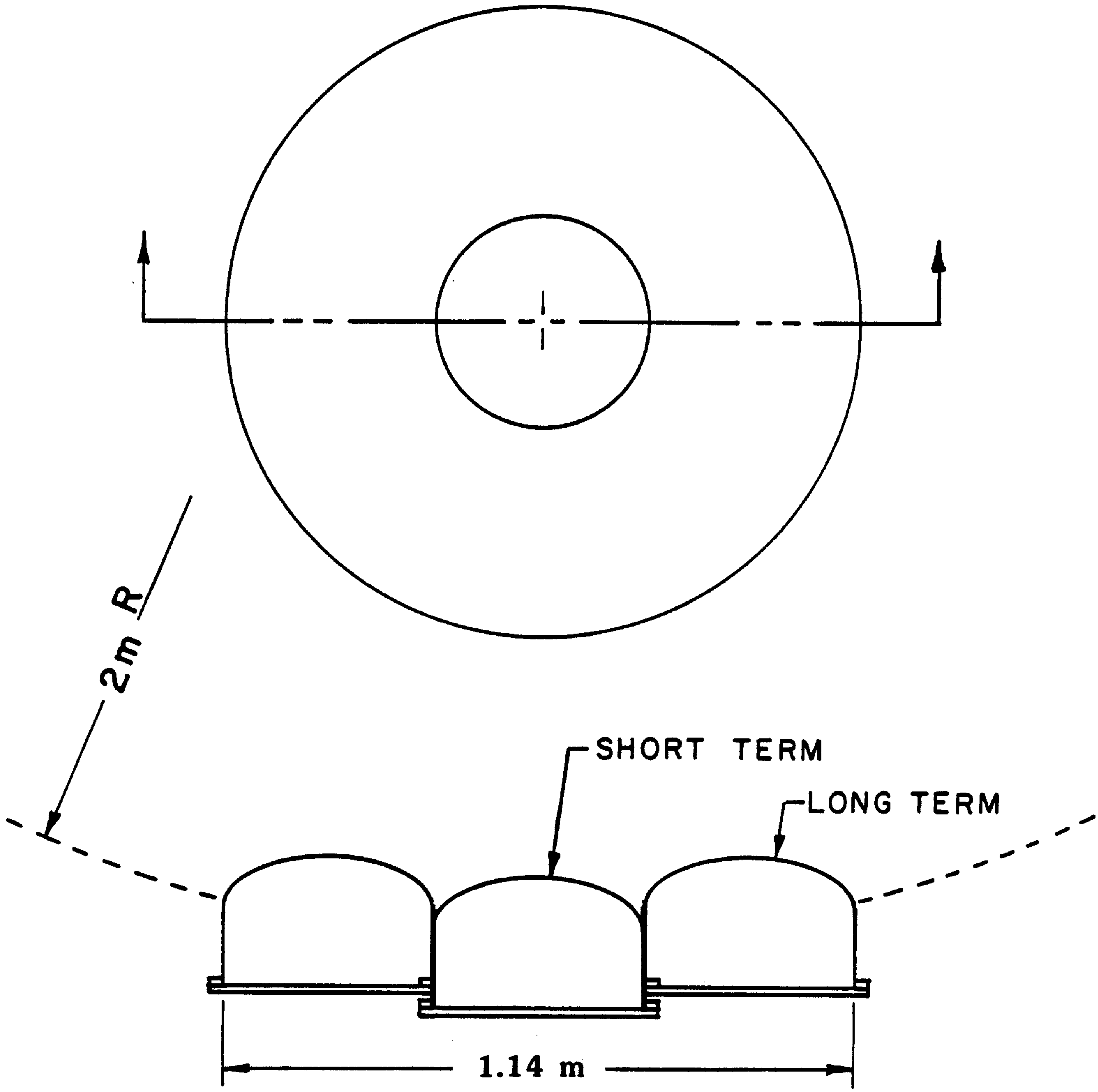

Fig. 2. Geometrical configuration of the test module in SIRIUS-M.

semi-ellipsoidal heads of the module. The test module is followed by a 20-cm thick Pb reflector and a 30-cm thick steel reflector. The peak and average power densities in the test capsule are 11.2 and 8 W/cm^3, respectively. The power to be removed from a single test capsule is 3.2 kW. The power generated from nuclear heating in each test module is 1.3 MW.

Three-dimensional neutronics calculations have been performed to determine the damage profiles and testing capabilities of the materials test modules of SIRIUS-M. Three 10-cm radius beam penetrations surround the test module with 120° azimuthal angle spacing as shown in Fig. 3. Because of symmetry only 1/12 of the reactor was modeled. The part of the test module modeled here is divided into 10 zones to investigate the impact of the beam penetrations on the azimuthal variation of damage. Each zone is divided into six axial segments to determine the axial damage variation. A point source emitting neutrons isotropically with the SIRIUS-M target spectrum is used at the origin. One hundred thousand histories were used leading to statistical uncertainties of less than 5% in the calculated damage rates for each segment.

The results indicate that no significant radial or azimuthal variation in damage occurs within the statistical uncertainty of the calculation. The peak dpa and helium production rates in the module were calculated to be 24 dpa/FPY and 145 He appm/FPY, respectively. The lowest values at the back of the module are 12 dpa/FPY and 36 He appm/FPY. Hence, the dpa and He production rates drop by factors of 2 and 4, respectively, from the front to the back of the module. This is a modest drop compared to that in MCF test facilities [4,5] where the dpa rate drops by factors of 4-7 and the He production rate drops by factors of 7-15 in the same 20-cm thick test module. This is related to the geometrical differences between ICF and MCF test facilities discussed

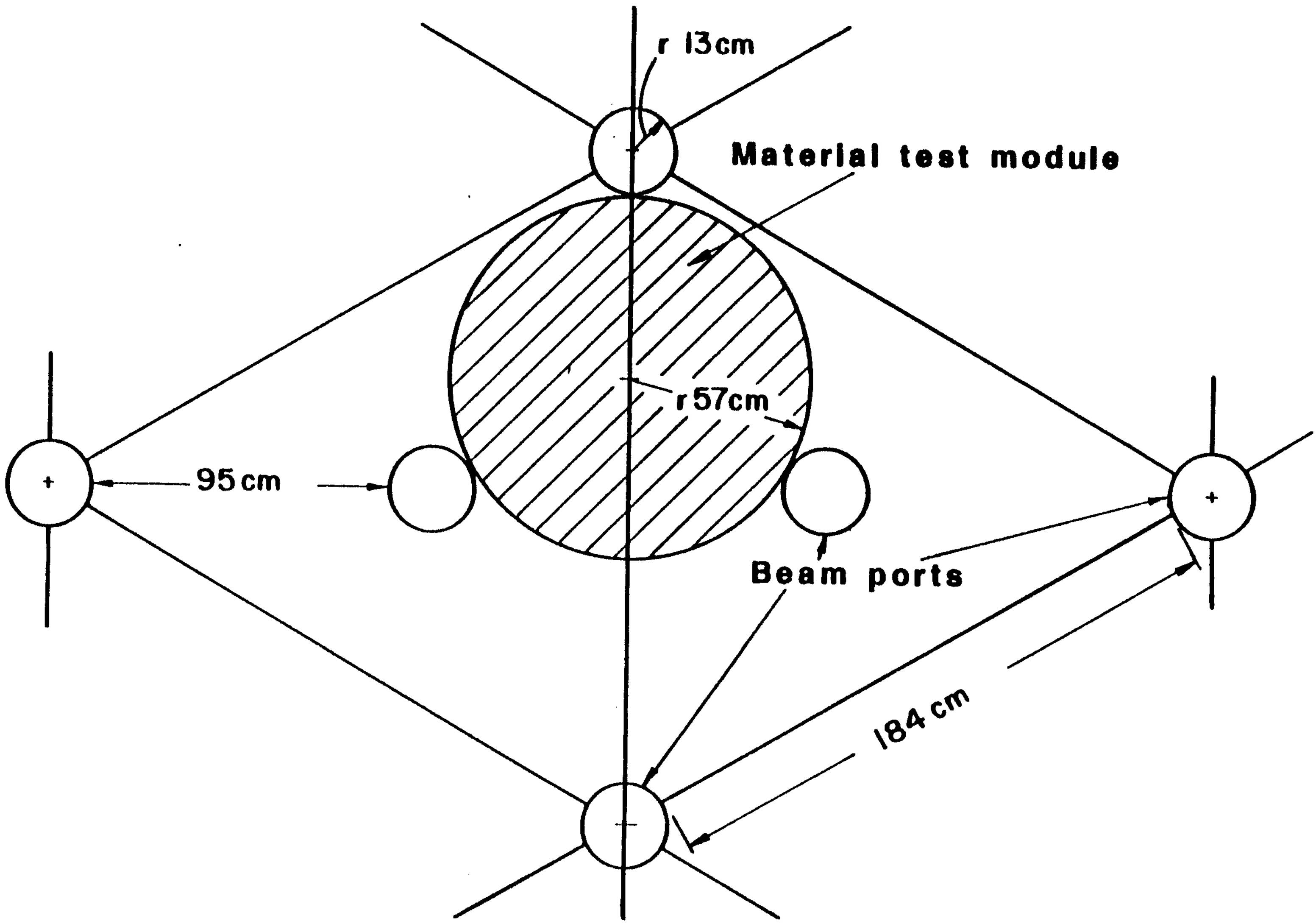

Fig. 3. Two adjacent tiles with beam ports and materials test module.

in Section 2. The peak-to-average dpa ratios in SIRIUS-M, TASKA and TASKA-M are 1.43, 1.56 and 2.74, respectively. The corresponding values for the He production rate are 1.9, 2.16 and 3.72, respectively. The small axial variation of damage in SIRIUS-M suggests that longer test capsules can be utilized in ICF test modules and that the damage variation along a test specimen is smaller in SIRIUS-M compared to magnetic fusion test facilities.

Another way of expressing the damage in the test specimens is to sum the product of the damage level times the volume of the test zone that can produce that damage level. This number reflects the total space available not only for specimens but also for temperature, stress, and environmental control. We have assumed that SIRIUS-M will operate for 10 calendar years at 50% availability. The three-dimensional results were used to determine the values for the volume-integrated damage accumulated at the end of life of the device. The total dpa-ℓ value obtained in the two test modules of SIRIUS-M is 14,200. The corresponding He appm-ℓ value is 65,250. Table 1 gives a comparison between the values of dpa-ℓ per FPY of operation for SIRIUS-M, the proposed MCF test facilities (INTOR, TASKA and TASKA-M), and the high energy neutron-source test facilities (FMIT and RTNS-II). The dpa-ℓ figure of merit in SIRIUS-M is a factor of 1.9 higher than that in TASKA and much higher than the corresponding values in the other test facilities.

5. Test Matrix and Testing Schedule

A test matrix has been devised to provide data for an ICF demonstration reactor on a timely basis [16]. Structural material testing is divided into two categories: scoping and qualification studies. The scoping studies are applied to the top four structural candidates selected by the materials community based on data from fission reactor irradiations, unirradiated

Table 1. Dpa-ℓ Values per FPY of Operation in Different Facilities

Neutron Production Mode	Device	dpa-ℓ/FPY
Accelerator	RTNS-II	0.0003
Accelerator	FMIT	5
Tokamak-Magnetic	INTOR	182
Mirror-Magnetic	TASKA-M	530
Mirror-Magnetic	TASKA	1510
Mirror-Magnetic	FEF	970
Laser-Inertial	SIRIUS-M	2840

properties and high energy neutron irradiation. The qualification tests will concentrate on the two alloys (a primary and a backup) which appear to be the leaders at the beginning of the scoping studies. However, after data from the 25% of goal fluence has been analyzed, a reranking of the alloys could be made, and choice of the top two alloys selected for qualification would be verified or one would start qualification studies on the "new" leaders. These tests would concentrate on a finer temperature mesh and include larger test specimens. Non-structural materials testing can also be performed in SIRIUS-M. This includes accelerated testing (to a few dpa) of laser mirror coatings, mirror support alloys and shielding materials. Long term tests (up to 120 dpa) would include neutron multipliers, solid breeder materials and tiles.

Detailed test matrices were developed for the three testing categories discussed above [16]. The number of test specimens required is based on the numbers of materials variations, temperature variations, fluence variations and post irradiation test conditions. A duplicate specimen is used in each test. Nine types of test specimens were identified for SIRIUS-M testing with volumes ranging from 0.014 cm^3 for microscopy specimens to 13.5 cm^3 for crack growth specimens.

Using the total volume of the required specimens in the test matrix and assuming that each 5-cm diameter by 20-cm long capsule contains 157 cm^3 of specimens, the number of test capsules needed was determined. An initial loading of 32 capsules with additional 24 replacement capsules is needed per alloy in the scoping studies. In the qualification tests, 112 initial capsules and 84 replacement capsules are needed for each of the two alloys. Six capsules are needed for short-term special materials testing and 12 capsules are used for long-term special materials testing with sample removal and reincapsulation at intermediate times. The reincapsulation can be included in the quick access central parts of the test modules. Figure 4 illustrates the testing schedule in SIRIUS-M. The initial load requires 370 capsules out of the 434 available positions. The extra available space can be used for advanced material development.

6. Conclusions

Geometrical and spectral differences between ICF and MCF reactors result in a larger damage in the first wall of MCF facilities but a smaller damage gradient in the test modules of ICF facilities. When the time structure of the damage produced is added to the other effects, it is clear that materials information generated to meet MCF applications may not be adequate to determine their behavior in ICF environments, and a dedicated ICF materials test facility such as SIRIUS-M is needed.

Several parametric studies have been performed for the SIRIUS-M test module. Using a 2 mm thick graphite liner in front of the module reduces the peak dpa rate by only 2.4%. Using a lead reflector surrounding the test module with a chamber radius of 2 m was found to double the achievable damage level in the test module compared to a cantilevered test module design where a steel reflector is located 8 m from the target.

Two circular test modules are used in SIRIUS-M. Each module has a front surface area of 1 m^2 and fits between three beam ports. No significant radial and azimuthal damage variation in the module results from these penetrations. The peak dpa rate is 24 dpa/FPY yielding a peak accumulated damage of 120 dpa at the end of life of the SIRIUS-M facility. A total volume-integrated damage figure of merit of 11,360 dpa-ℓ can be achieved in SIRIUS-M.

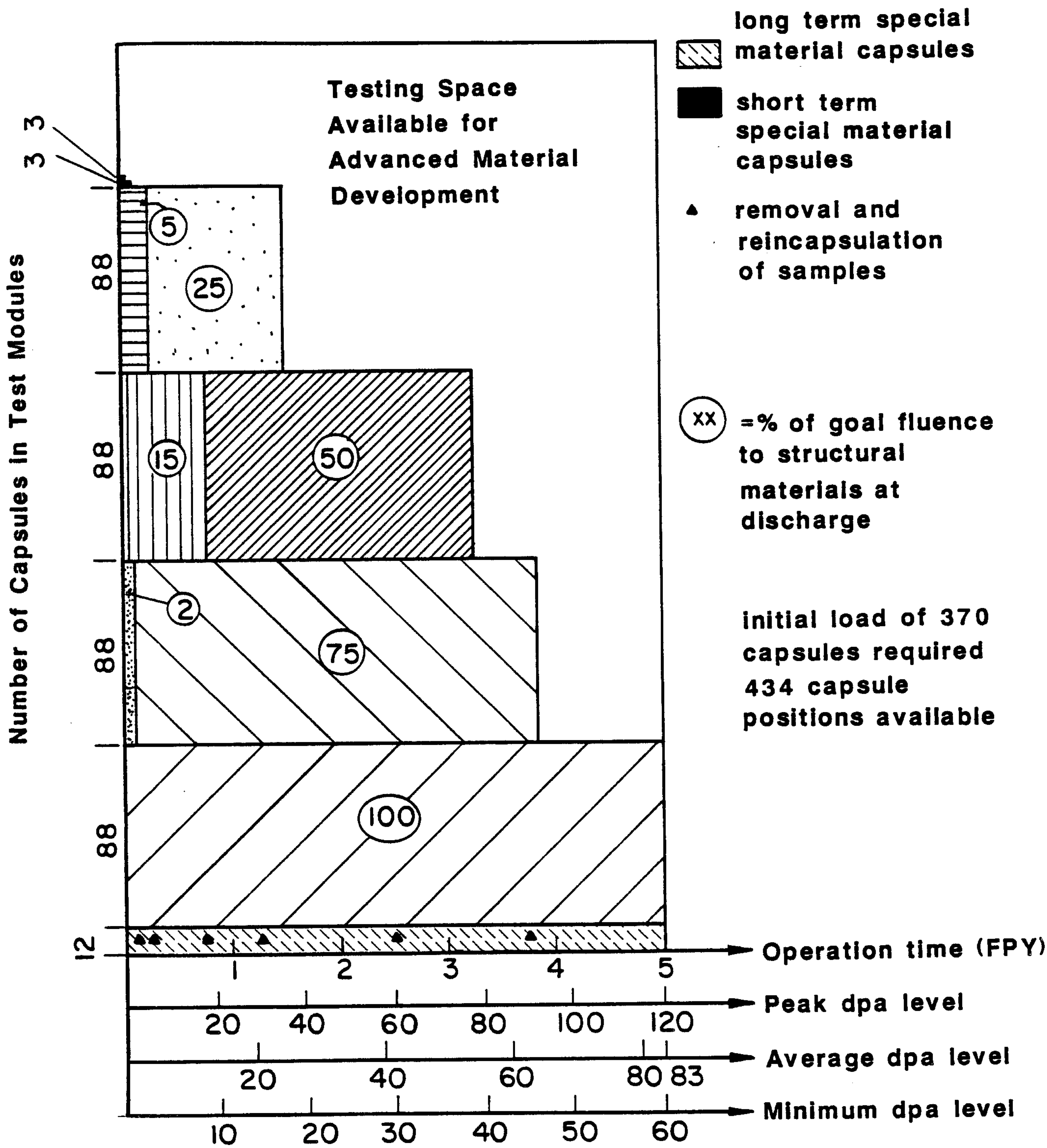

Fig. 4. Materials Testing Schedule in SIRIUS-M.

Test matrices were developed for structural materials scoping studies, structural materials qualification studies, and special materials testing. It was shown that it is possible to perform all tests needed for the ICF Demo in the two SIRIUS-M test modules, each containing 217 capsules.

Acknowledgment

Support for this work has been provided by the U.S. Department of Energy.

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