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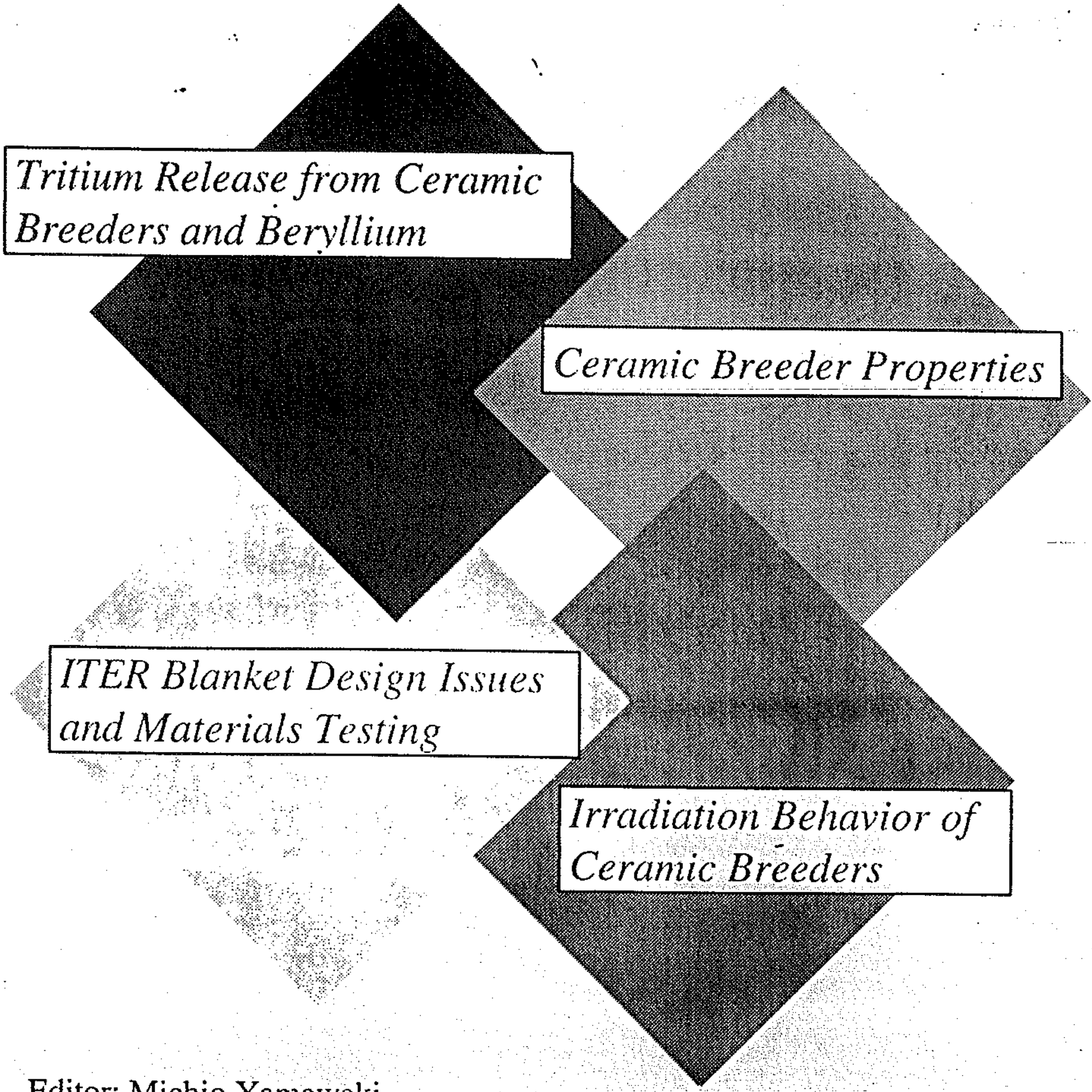

Tritium Release from Ceramic Breeders and Beryllium

Ceramic Breeder Properties

ITER Blanket Design Issues and Materials Testing

Irradiation Behavior of Ceramic Breeders

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ITER Test Module Design for DEMO Reference Solid Breeder Blanket

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Abstract

Engineering scaling requirements needed to represent a prototypical DEMO solid breeder blanket concept were applied to an ITER test module design. The detail DEMO phenomena to be studied through testing include tritium generation and release, tritium inventory and permeation losses, breeder/multiplier thermomechanical behavior, material compatibility, mass transfer, and structural response. Correct simulations of the aforementioned phenomena dictate the use of correct materials, purge gas flow and chemistry conditions, prototypical coolant pressure and temperature. The ITER test module would then have dimensions in conjunction with appropriate boundary conditions such that temperature magnitudes, temperature differences, and associated stress states in various blanket elements can be reproduced under ITER test configuration and environmental conditions.

2D thermomechanical analyses coupled with 1-D neutronics analysis have been performed for the first wall and a blanket unit cell associated with the proposed reference helium-cooled Li_2TiO_3/Be/FS concept. These results are used to guide the design of ITER test blanket internal configuration and first wall. It is found that reproducing DEMO operating conditions is feasible under ITER redued operating conditions if engineering scaling rules are applied to the ITER test module design.

1.0 Introdution

As ITER provides the first opportunity for fusion integrated testing, it is important to maximize the utilization of the facility to meet the testing objectives. The main objectives of blanket testing in ITER are to provide test data for DEMO/reactor relevant blanket concepts. Since the major operating parameters of DEMO/reactor (e.g., surface heat flux, neutron wall load) are generally higher than those of ITER, as shown in Table 1 for comparison[1,2], the test module must be designed carefully using engineering scaling rules in order to obtain meaningful test information.

The design of the test modules involves considerations of both the internal and external design. The external design considerations involve issues that directly affect the design of other ITER systems, which will not be addressed in this paper. The primary issues associated with the internal design are how to optimize the configuration (coolant channel dimensions, structural configuration, etc.) to obtain relevant data for advanced reactors at the reduced operating parameters of ITER and what size test module required to adequately simulate the integrated behavior of candidate blankets. Moreover, the test port configuration is generally non-prototypical. For example, the ITER test port as shown in Figure 1 does not have an adequate poloidal variaiton to address poloidally-cooled blanket concepts. The results of tests in ITER will need to be extrapolated to estimate performance under DEMO load. A closer simulation of reactor behavior reduces the level of extrapolation and the degree of uncertainty. Consistently, a role-back approach is used, which starts with a reference blanket concept followed by the exercise of the engineering scaling rules and finally a design of a scaled module to be tested in ITER.

Table 1 Operating Parameters of ITER and DEMO for Testing Purpose

Parameter	DEMO	ITER at test port
Neutron wall load (MW/m^2)	3-5/2-3 (peak/average)	1.2
Surface heat flux (MW/m^2)	1/0.5 (peak/average)	0.25
Leifetime fluence (MWy/m^2)	5-20	0.1-1

2.0 Engineering Scaling Rules for ITER Test Module Design

Engineering scaling is the process of developing a scaled test which is a particular test module design that seeks to preserve aspects of DEMO blanket behavior (conditions or phenomena) under non-reference operating conditions. There is often no unique scaled test, depending on what is considered important and worth preserving from the test objective point of view. Thus, an engineering scaling process for test article design involves: 1) identifying important features (conditions or phenomena) worth preserving under a test; 2) understanding the relationships between the device parameters (ITER) and the identified features; 3) evaluating methods for preserving these features under changed device parameters; and 4) balancing conflicting requirements for stated test objectives[3]. This process leads to an understanding of the usefulness of the test under stated test conditions. Major device parameters, with a strong influence on solid breeder test article behaviors, include: surface heat flux, neutron wall load and burn/dwell times. These parameters will drive the test article into some operating conditions (e.g., temperature, stress, tritium generation rate, accumulated swelling) and may activate phenomena (e.g., sintering of the solid breeder, fatigue failure).

The major classes of issues for solid breeder blankets are: tritium breeding (self-sufficiency); breeder/multiplier/structure interactive effects under nuclear heating, chemistry and irradiation; tritium inventory, recovery and permeation; thermomechanical response and thermal control; mass transfer; failure modes, effects, and rates; mechanical loads caused by major plasma disruption and response to off-normal conditions. Correct simulation of DEMO operating conditions to address the aforementioned issues dictates the use of correct materials, prototypical temperature magnitudes and temperature profiles within the breeder and multiplier, purge gas flow and chemistry conditions and coolant pressure and temperature. In general, to preserve the temperature difference in the specified region under a reduced neutron wall load (N) such as ITER, a regional thickness, Δ, shall be increased according to the scaled law of:

$$\Delta_{ITER} = \Delta_{DEMO} \times [\dot{Q}_{vDEMO}/\dot{Q}_{vITER}]^{0.5} \approx \Delta_{DEMO} \times [N_{DEMO}/N_{ITER}]^{0.5}$$

where Δ_{DEMO} is the breeder/multiplier zone thickness in DEMO reactor, $\dot{Q}_{vDEMO}$ and $\dot{Q}_{vITER}$ are volumetric heating rates in breeder/multiplier zones under DEMO, ITER neutron wall loads. Δ_{DEMO} will be determined based on the allowable maximum operating temperature and thermal stress constraint imposed by the temperature difference for the material considered. If Δ_{DEMO} is 1 cm in the DEMO design, the test article in ITER would have Δ_{ITER} of about 1.58 cm (for a neutron wall load of 3 MW/m^2).

The temperature magnitude in the breeder zone needs to be preserved for tritium release and thermal mechanical behavior, in which its mean value in a slab geometry is determined by:

$$\bar{T} = T_c + \Delta T_{film} + \Delta T_{interface} + \frac{\Delta T_{breeder}}{3} + \Delta T_{clad} + \Delta T_{gap}$$

where ΔTs are temperature drop across film, interface, breeder and thermal gap (if any).

The scaling law of preserving $\bar{T}$ in the case of same temperature difference in the breeder region requires that:

$$(T_c + \Delta T_{film} + \Delta T_{interface} + \Delta T_{clad} + \Delta T_{gap})_{DEMO} = (T_c + \Delta T_{film} + \Delta T_{interface} + \Delta T_{clad} + \Delta T_{gap})_{ITER}$$

If the safety consideration requires the coolant temperature in ITER to be lower than that in DEMO, it is necessary to increase temperature drop across the film by reducing the coolant velocity while increasing the coolant channel width. Yet this is inadequate, the mechanism for raising the temperature differences across the interface, clad, and/or gap could only be adopted without destroying the mechanical boundary conditions. Arbitrary increases of the gap and clad thicknesses to preserve the temperature magnitude would add artificial (or fault) operating conditions into the test article (for example, relaxing the mechanical force in the breeder zone). Mechanical and thermal boundary conditions are other important elements to be considered in the test article design for thermomechanical performance evaluation.

The test information to be obtained from operating the test module will be highly location dependent due from ITER pulsed operation mode. For example, tritium release characteristics under pulsed operating conditions will not only be time dependent but also location dependent. This is becuase the thermal time constant in the blanket front zone is typically much shorter than that of the rear region. Thus, a less number of continuous cycles is required for the breeder in the front zone to reach a semi-steady state tritium release (depending on the length of the dwell time) as compared to those located at the back. Consequently, it is necessary to instrument the test article "locally (defined based on thermal time constant for example)," in order to better interpret the test results. A large instrumentation requirement would add complexity into the test article design and could perturb the data to be obtained.

3.0 Reference DEMO Solid Breeder Blanket Design

The reference DEMO solid breeder blanket design to be tested in ITER utilizes breeder-out-of-tube (BOT) concept, with ferritic steel as structural material, helium as coolant, Li_2TiO_3 as breeder material and beryllium as multiplier. Both the solid breeder and the Be are in form of sphere-packed beds, while they are separated by radially oriented coolant panels. The blanket is cooled poloidally with helium enters the blanket at the top and exits at the bottom (or the equatorial plane) in order to minimize the number of high pressure coolant joints. Each of the outboard blanket segment is divided into an upper and a lower module. Nominal dimensions of the module are 3.7 m length poloidally, 1 m width toroidally and 54 cm depth measured radially away from the plasma. As shown in Figure 2, the interior of the blanket is all breeding zone: for outboard, the first 35 cm of the zone consists of alternating layers of Li_2TiO_3 breeder and Be neutron multiplier separated by radially oriented coolant-panels. Packing density for the breeder region is about 62% and about 72% for Be zone. The remaining 19 cm of the breeding zone is filled with sphere-pac breeder only.

The first wall and blanket are all poloidally cooled to minimize the number of coolant joint connections. Lateral and depth wise spacing of the tubes in the breeder region is graded in accordance with local nuclear heating rates, material thermal properties and allowable temperature limits of the surrounding materials. A coolant pressure of 10 MPa is chosen for helium in order to reduce the pressure drop and to have a compact design. The fractional pressure drop is about 5%. More description is given in Ref. 4.

4.0 Test Module Design

The test article design would incorporate the essential features of the DEMO solid breeder blanket design and contain breeder, neutron multiplier, structure, and coolant in a subscaled configuration prototypical to that of the reference blanekt concept. The approach adopted for meeting objective of the solid breeder test program involves the use of act-alike test articles. This implies that the test article would be designed so as to reproduce key DEMO-like parameters, such as the breeder temperature magnitude and difference. However, complete reproduction of power reactor conditions is impossible in a fully integrated test module. Engineering scaling of a particular parameter often adversely affects other parameters. For example, temperature gradient at the first wall can not be reproduced at lower power densities, and increasing the first wall thickness to reproduce the temperature drop across the first wall reduces the already modest neutron flux at the back of the first wall. Consequently, the functions of integrated testing would have to be distributed over several act-alike test modules, with each test article emphasizes a group of issuse/phenomena. Moreover, multiple test articles are generally needed to distinguish any statistical variation.

4.1 Test Module Breeding Zone Design

The ITER sloid breeder blanket test module design imitates the reference blanket design and consists of a series of parallel stacked coolant panels with alternate breeder and multiplier sandwiched between them (see Figure 3). The test article is cooled poloidally with helium entering at the top and exiting at the bottom. In order to evaluate the effects of poloidal temperature and load variations on the gross thermal-mechanical responses of coolant panel performance and packed bed behavior, it is necessary to simulate the full poloidal effects. By assumming that similar blanket behavior would be seen in the bulk region, the size of the test module could be smaller in the toroidal direction. However, the test article should be large enough such that the boundary effects would not impact the test results and the resolution of the experimental measurements (e.g., tritium concentration in the purge stream) could be adequate for interpreting the test data. Previous analysis has shown that at least about 15 cm is needed to eliminate the effects of surrounding non-breeding blanket materials on the neutronics parameters. This leads to a 50 cm width of the test module in the toroidal direction.

Similar to that of the reference blanket design, the test module breeding zone is subdivided into two regions. The first 35 cm consists of an alternating zone of beryllium/breeder packed beds and the rest of 19 cm is filled with pure breeder pebbles. Because of the less amount of volumetric heat generated inside the breeding zones, the radial and lateral colant tube spacings are enlarged to allow the breeder operated under DEMO temperature conditions. Iterative thermal analysis coupled with neutronics analysis is needed in order to determine the correct test module tube spacing and zone thicknesses. The calculated volumetric heating rate profiles are shown in Figure 4 for DEMO reference design and in Figure 5 (Conf. 1) for ITER test module design. The calculated volumetric heating rates per neutron of ITER test module are slightly lower than those of DEMO values (~4%) due from the changes of the material volumetric fraction distributions.

As shown in Figure 6, the DEMO blanket unit cell temperature distribution can be reproduced by using larger zone thicknesses and less number of coolant tubes in the test module breeding areas. The maximum temperature for both cases is about 1000 C and is found at about 3.4 cm away from the ITER test module first wall (for a 12 coolant-tubes arrangement) while is about 5.4 cm away in the reference design. The ITER test module zone thickness is increased by a factor of about 1.35. A larger space available in ITER test moudle provides a flexibility for achieving a more uniform temperature distribution in the breeder zone as shown in Figure 6.

4.2 Prototypical DEMO Test Module First Wall Design

In order to reproduce DEMO first wall thermal stress, a thicker wall is needed for the ITER test module design to accommodate ITER lower surface heat flux. However, incorporating a thicker first wall could reduce the nuclear heating rate and tritium production rate in the breeding region. Therefore, it might be necessary to decoupe such a testing function by using another test article. The ITER test module first wall dimensions were chosen such that the total (primary plus secondary) stress experienced by the test module first wall are at the same level of that of DEMO blanket first wall. For the surface heat flux at the level expected, the stress state of the first wall is mainly determined by the thermal stress. This allows the same coolant diameter to be used in the ITER test article such that the hydraulic parameters of the coolant (e.g., heat transfer coefficient) can be preserved.

The first wall stress distribution was first estimated for DEMO conditions using ANSYS model as shown in Figure 7-a. The model incorporating the first wall and associated coolant channels, side wall, and blanket coolant panels is subjected to the DEMO surface heat flux and nuclear heatings. In order to observe how the thermal expansion of the beds affecting the first wall behavior, the model included part of the breeding zone in which its thermal mechanical properties were calculated from the solid material properties scaled with the bed packing density. The boundary conditions included symmetry at the central plane, fixed at the back of the ribs and zero heat fluxes at the calculation boundary of the breeding zone. The analysis indicated that the stress state of the first wall is significantly affected by the thermomechanical properties of the bed, in particular bed effective thermal expansion coefficient. Moreover, the back wall is subjected to an extremely high stress if the design does not release the bed thermal expansion.

Similar calculations were performed for different ITER test modules (see Figure 7-b and 7-c based on lower values of thermal expansion coefficients): a full toroidal scale module with thick walls and a half toroidal scle module with thick walls. The catch was to see whether the DEMO first wall thermomechanical performance can be reproduced in a full scale ITER test article (relative to DEMO toroidal dimension) and further to see whether similar behavior can be seen in a half-scale ITER test article. These results suggested that it seems feasible to use a small scale test article to reproduce the DEMO 2-D stress distribution if thicker walls are used in the design. The test module first wall dimensions as shown include a 13 mm front wall, a 9 mm back wall and an overall wall thickness of 36 mm as compared to DEMO of 5 mm, 6 mm, and 25 mm respectively. The calculated neutronics parameters under a DEMO-act alike test article first wall differ slightly from those of DEMO-look alike test article (about 4%, see Figure 5 Conf. 3).

5.0 Conclusion

Reproducing DEMO operating conditions is found feasible under ITER redued operating conditions if engineering scaling rules are applied to the ITER test module design. The amount of increase in the ITER test module first wall thickness necessary to reproduce stress distribution might not lead to significant changes in the tritium production and nuclear heating rates for the design considered. Thus, it is possible to evaluate the performance parameters of the first wall and the breeding zone together in an integrated test module. The final test module first wall dimensions include 13 mm front wall, 9 mm back wall and an overall wall thickness of 36 mm as compared to DEMO of 5 mm, 6 mm, and 25 mm respectively. Analysis using "linear scale" thermal mechanical properties (such as packed bed effective Young's modules and thermal expansion coefficient) show that the thermal expansion of the ceramic breeder and Be beds behind the first wall might exert too much stress on the first wall. It is therefore necessary to evaluate and quantify those properties experimentally to ensure a sound design.

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Figure 1 ITER Test Port Elevation View