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Solid breeder test blanket module design and analysis

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Abstract

This paper presents the design and analysis for the US ITER solid breeder blanket test articles. Objectives of solid breeder blanket testing during the first phase of the ITER operation focus on exploration of fusion break-in phenomena and configuration scoping. Specific emphasis is placed on first wall structural response, evaluation of neutronic parameters, assessment of thermo-mechanical behavior and characterization of tritium release. The tests will be conducted with three unit cell arrays/sub-modules. The development approach includes: (1) design the unit cell/sub-module for low temperature operations and (2) refer to a reactor blanket design and use engineering scaling to reproduce key parameters under ITER wall loading conditions, so that phenomena under investigation can be measured at a reactor-like level.

Keywords: Solid breeder blankets; TBM; ITER

1. Introduction

The ITER blanket test program will investigate various tritium breeding blanket design concepts proposed by the parties. Recognizing that a final selection between solid and liquid breeders cannot be made prior to fusion testing, the US has selected a helium-cooled solid breeder concept with ferritic steel structure and a beryllium neutron multiplier as one of the candidate breeder blankets for ITER TBM testing [1]. The concept is based on the use of lithium–ceramic pebbles as breeder material, whose complex thermomechanical interactions inside an integrated blanket system can only be addressed in a fusion environment. However, the US testing approach is to design unit cell/sub-module test articles, rather than testing a fully independent TBM [1,2]. The test program emphasizes international collaboration, including collaborative R&D, the sharing of common ancillary equipment, and possible co-development of TBMs. The design operating condi-

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tions of the main helium coolant for the proposed unit cell/sub-modules are similar to those of other neighboring modules, in which any special requests to the coolant operating conditions (such as temperatures) will be handled through a much smaller component, such as a helium coolant conditioner located in the port cell area. To maximize ITER testing, the tritium concentration and gas composition from each breeder purge gas line will be analyzed at the port cell area before merging with other purge gas lines for tritium extraction at the tritium building.

The unit cell/sub-module test article designs focus on particular technical issues of interest to all parties. A unit cell occupies a port area of about 19.5 cm × 21 cm and is housed behind another party's structural box, while a sub-module takes up a testing space of a quarter port (73 cm × 91 cm) and has its own structural box. Two distinct design approaches have been considered to fulfill these testing objectives: (1) design the unit cell/sub-module for low temperature operation, or a look-alike approach and (2) refer to a reactor blanket design and use engineering scaling to reproduce key parameters under ITER wall loading conditions, so that phenomena under investigation can be measured at their reactor-like level (an act-alike approach). The two approaches result in two different sets of operational parameters, the low temperature scenario being used for neutronics assessment and the high temperature scenario for thermomechanical performance evaluation.

2. General design description and performance analysis

Two configurations have served as the reference for designing the ITER test unit cell/sub-modules: (1) a layered configuration, where solid breeder and beryllium pebbles are placed parallel to the first wall (FW), and (2) an edge-on configuration, where both beryllium and breeder beds are placed perpendicular to the FW facing the plasma region. In the sub-module design, the breeding zones are housed behind a ferritic steel (FS) U-shaped FW structural box, as shown in Fig. 1. The overall FW thickness is 28 mm, including a coolant channel of 16 mm × 13 mm and a front wall thickness of 5 mm. The pitch between the coolant channels is 18.2 mm. The FW is designed to remove a total deposited heat of 0.307 MW, based on the contribution of the average surface heat flux of 0.3 MW/m^2, and nuclear heating deposition on the front and side walls of the FW structures with a neutron wall load of 0.78 MW/m^2. Because a relatively high velocity is needed to ensure an adequately high heat transfer coefficient for removing locally a surface heat load of 0.5 MW/m^2, the first wall design features a reduced coolant flow area by grouping five coolant flow channels in a series into one coolant flow path. The 8 MPa helium coolant enters the sub-module at a rate of 0.9 kg/s at a temperature of 300 °C (a typical value of helium-cooled solid breeder blanket designs) and is subsequently distributed into 10 first wall cooling paths for surface heat removal. The thermal–hydraulic and thermomechanical analysis of the FW has been previously presented [3], and shows that the temperature and stress magnitudes of the first wall are within the maximum allowable limits of the FS structure.

2.1. Neutronics analysis

Neutronics calculations have been performed to determine where the instruments should be placed in this design. The example shown in Fig. 1 is a proposed ITER test blanket sub-module developed for low temperature operations, with the aim of evaluating tritium breeding performance and validating neutronics code predictions. As shown, the ceramic breeder (Li_4SiO_4, 75% Li-6) and beryllium pebbles are packed into the layered and the edge-on configurations. The neutronics analysis includes the presences of the neighboring sub-module (in the example, the Japan's TBWG-13 sub-module [4] was considered) and the ITER frame structure [5]. An example result of the analysis presented in Fig. 2 is for the tritium production rate profiles. As shown, profiles of the tritium production rates revealed in the layered configuration are nearly flat over a reasonable distance in the toroidal direction: a necessary condition for local neutronics measurements. The steepness in the profiles near the end of the layers is due to the presence of the beryllium layer and to neutrons reflected by the structure contact in the vertical coolant panels. In the edge-on configuration, the situation is not as favorable as in the parallel sub-module, due to the presence of two types of gradients: one in the radial direction that shows large steepness near the FW and the other across the breeder beds in the toroidal direc-

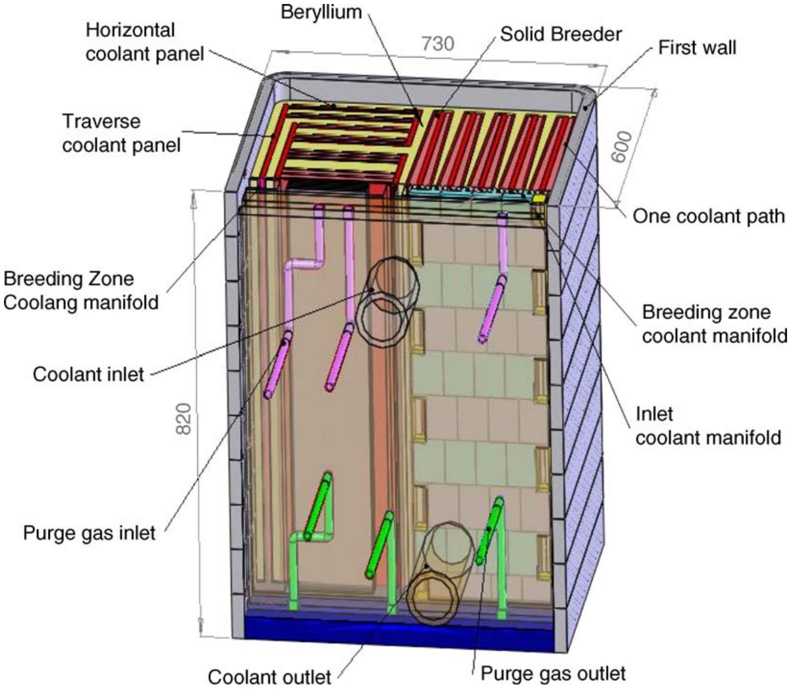

Fig. 1. Schematic view of the proposed sub-module for thermomechanics and tritium release tests.

tion, where extremely steep profiles are found across the 1-cm thick beds. This steepness decreases gradually towards the rear. Accordingly, it is recommended to perform neutronics measurements in the innermost beds at the rear of the sub-module, although the absolute values are a factor of 6 less than those at the front, which could have adverse effects on the statistics of the measurements. Details of this nuclear assessment can be found in a companion paper [5].

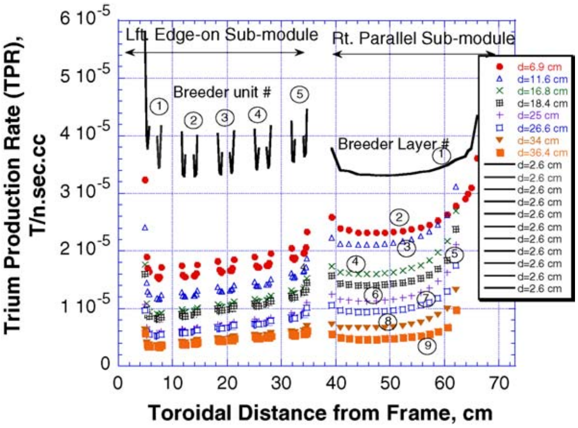

Fig. 2. Toroidal profile of tritium production rate in the two sub-configurations of the proposed sub-module at various distances *d* behind the first wall.

2.2. *Breeding zone thermal–hydraulics and thermal analysis*

The heating generation rates obtained from the neutronics calculation were used as inputs for subsequent thermal analysis and for the design of the heat removal system for the low and high temperature scenarios mentioned in Section 1. The total heat to be removed from this sub-module is 0.784 MW, including the heat deposited on the first wall from the surface heat flux of 0.3 MW/m^2. In the low temperature scenario, the 8 MPa helium coolant enters the sub-module at a rate of 0.755 kg/s and a temperature of 100 °C and is subsequently distributed into two paths to remove the heat generated in the breeder region, which amounts to 0.45 MW. In the low temperature operation design, the helium flows first into the breeder zone channels, then in the first wall, since the goal is to keep the breeding material at low temperature. With the proposed scheme, the exit temperature of the coolant from the breeder zones is 224 °C. The combination of a low coolant temperature and a much thinner breeding zone thickness results in the temperatures in the breeder zone falling below 350 °C. This ensures that tritium will not be released from the breeder material because of its low diffusion coefficient. The coolant then cools the first wall and leaves the first wall at about 300 °C. The resulting first wall maximum temperature is calculated to be 484 °C at the highest heat flux location of 0.5 MW/m^2. Since first wall cooling is not an issue for low temperature operation, the sub-module can be designed without using by-pass flow, and all the helium flowing in the breeder channels is routed into the first wall structure.

In the high temperature design the scheme is reversed, since the main challenge becomes the cooling of the first wall structure. In addition, it is designed for thermomechanics and tritium release tests; the thickness of the ceramic breeder material bed is increased in order to operate at temperature windows that are typical of power reactors. The 8 MPa helium coolant enters the sub-module at a rate of 0.9 kg/s, at a temperature of 300 °C and is subsequently distributed into 10 first wall cooling paths for surface heat removal. About 10% of this flow is by-passed away from the breeding zones to achieve a typical outlet temperature of 500 °C. The remaining coolant in the sub-module is divided into four paths for cooling upper and lower caps and two breeding configurations. 2D transient thermal analysis has been performed to study temperature characteristics under an ITER 400 s burn cycle. The analysis is based on effective properties of the pebble beds, which are treated as continuous materials. The effective thermal conductivity of the lithium orthosilicate material is treated as temperature dependent, with a typical value of 1 W/mK within 400–500 °C [6]. The beryllium pebble beds' effective thermal conductivities depend on the temperature and the stress/strain, and have a typical value of 3–4 W/mK in the same temperature range at a stress value of 0.5 MPa [6]. The analysis uses volumetric heat generation based on the nuclear heating rates from 2D nuclear analysis. As shown in Fig. 3, temperatures near the front, less than 5 cm behind the first wall, have reached equilibrium values, while temperatures near the back are about to reach equilibrium values.

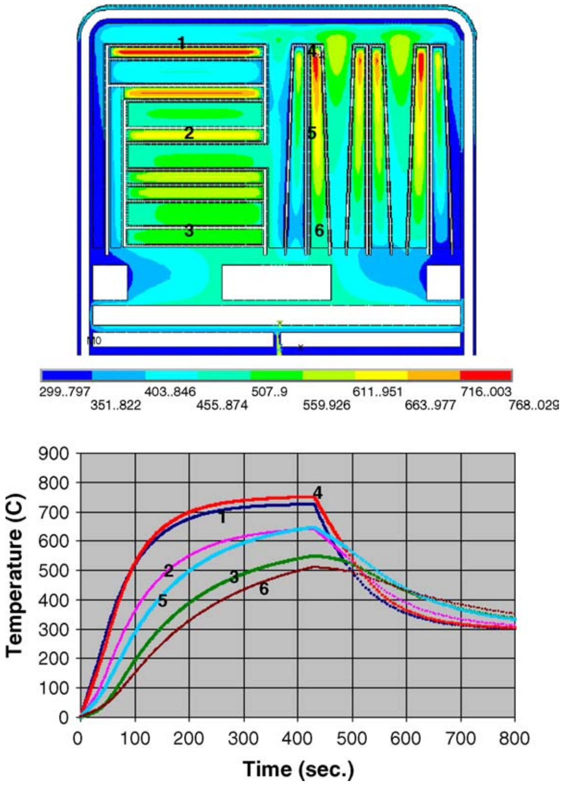

Fig. 3. 2D temperature profile at the end of a burn (top) and temperature histories during a burn cycle at several breeder locations (bottom).

2.3. Pebble bed thermomechanics analysis

The thermomechanical behavior of the lithium-based ceramic pebble bed at high temperature under pulsed operations is very complicated to simulate numerically. As a first approach, this behavior has been analyzed with the finite element code MARC [7], in which the pebble bed is treated as a continuous material with the same effective thermo-physical properties introduced for the thermal analysis. In addition, the elastic modulus and creep compaction of ceramic breeder (E_C and ε_C) and beryllium (E_B and ε_B) pebble beds are related to stress and temperature levels by the expression [6,8,9]:

$$E_C = 314 \times \sigma^{0.75} \quad \text{and} \quad E_B = 1772 \times \sigma^{0.83}\,\text{MPa} \tag{1}$$

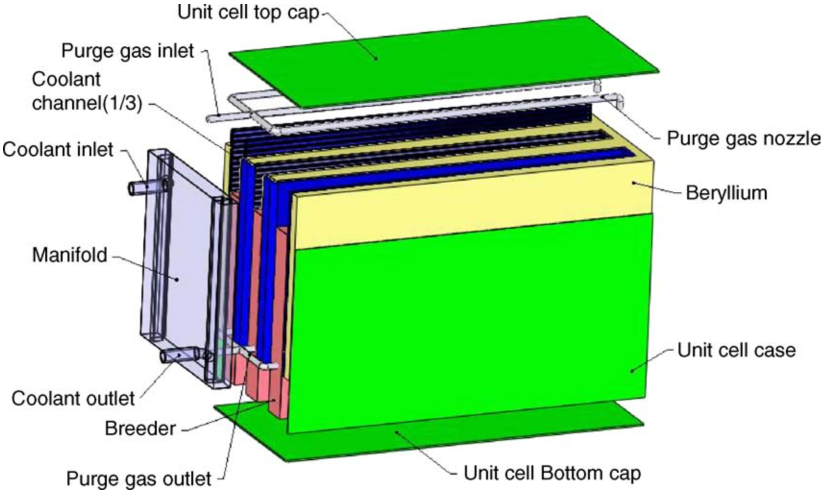

Fig. 4. Proposed solid breeder thermomechanical unit cell test blanket articles housed behind the EU structural box.

and

$$\varepsilon_{\mathrm{C}} = 1.6 \times 11.41 \times (\sigma)^{0.4} t^{0.2}\,\mathrm{e}^{-9741/T}$$
$$\text{and}\quad \varepsilon_{\mathrm{B}} = 6.40\varepsilon_{\mathrm{C}} \qquad (2)$$

where σ is the axial stress in MPa, T the temperature in °C, and t is the time in s.

The calculation has been performed for a breeder/beryllium unit representing a sub-unit found in the edge-on configuration as in the thermomechanics unit cell design (Fig. 4). As shown, the unit cell is to be inserted into the EU HCPB [10,11] structural box to address the issue associated with the pebble bed thermomechanical integrity. Without taking into account thermal creep effect, the calculated von Mises stress

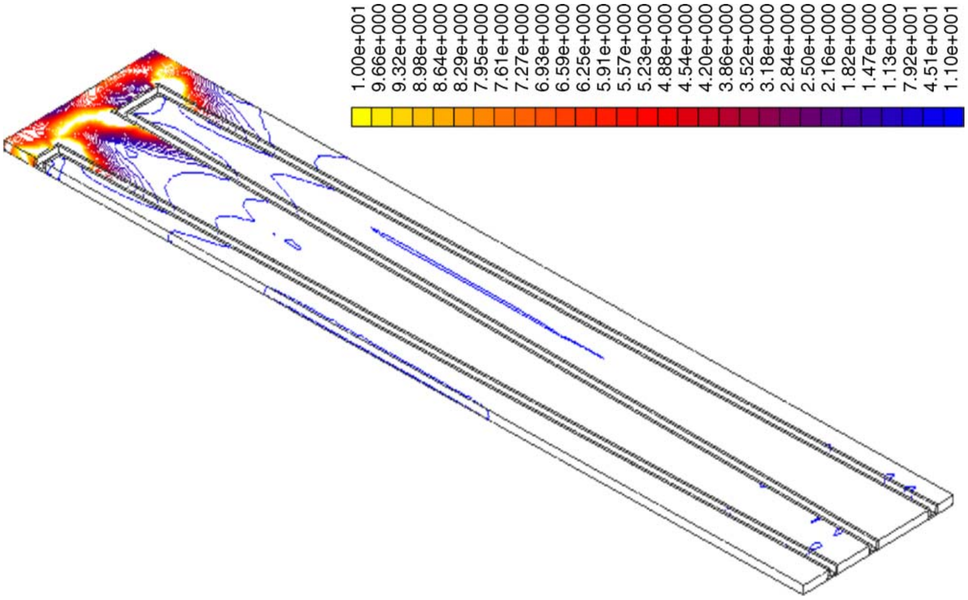

Fig. 5. Calculated *x*–*y* plane von Mises stress profiles in the breeder and beryllium pebble beds (stress ranges from 0 to 10 MPa).

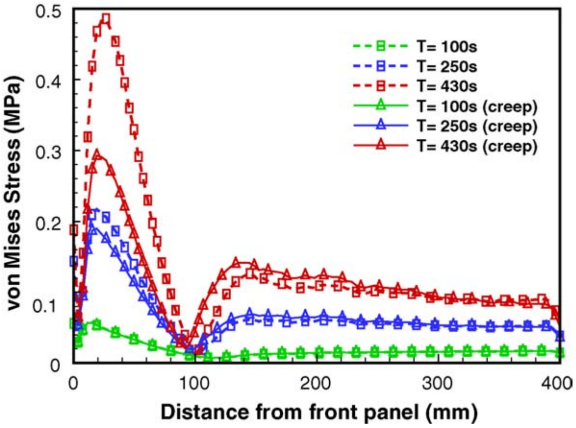

Fig. 6. Calculated stress histories along the centerline of the breeder pebble bed with and without thermal creep effect.

profile of this sub-unit, resulting from a combined effect of temperature gradient, differential thermal expansion and structural constraint, shows a maximum stress level of greater than 10 MPa located inside the beryllium pebble bed near the coolant plate (Fig. 5). Whether or not this high stress is accurately predicted is the subject of the current research effort. The maximum stress inside the breeder pebble bed of 1.0 MPa is found ∼6.5 cm away from the first wall. The stress profiles at the centerline of the breeder zone as a function of distance at different burn times are shown in Fig. 6 for analyses with creep and without creep. The peak stress levels drop to 0.5 MPa at the end of the ITER burn cycle when the thermal creep is coupled into the analysis.

3. Summary

The designs of the US ITER solid breeder blanket test articles have been presented. Two sets of design parameters have been introduced, relative to the low and high temperature operational scenarios that will be used for neutronics and thermomechanics tests, respectively. Tritium production and nuclear heating rates inside the sub-module have been calculated with a two-dimensional neutronics code which accounts for the presence of neighboring modules and frame structures surrounding the test article. The heat generation rates have then been used as input for a two-dimensional thermal analysis of the sub-module. The results showed that the desired power reactor operational temperature window for the lithium-based ceramic can be achieved with the high temperature sub-module design, and that sufficient cooling of the plasma facing first wall is contemporaneously ensured. The thermal analysis of the low temperature sub-module showed that it is possible to achieve conditions for which all the tritium generated in the ceramic breeder material will remain trapped inside the pebbles for out-of-pile measurements. Finally, the thermomechanical behaviors of the ceramic breeder beds have been simulated.

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