Engineering Scaling Requirements for Solid Breeder Blanket Testing

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An engineering scaling process is applied to the solid breeder ITER TBM designs in accordance with the testing objectives of validating the design tools and the database, and evaluating blanket performance under prototypical operating conditions. The goal of scaling is to ensure that changes in structural response and performance caused by changes in size and operating conditions do not reduce the usefulness of the tests. Initially, constitutive equations are applied to lay out the basic operating and design parameters that dominate blanket phenomena. The suitability of these similarity criteria for the TBM design is then confirmed by comparing finite element predictions of prototype and scale model responses. The TBM design also takes into account the need to check the codes and data for future design use. Specifically, predictability of tritium production and nuclear heating rates in a complex geometry, tritium release and permeation characteristics under fusion environments belong to this category. We conclude that this engineering scaling design process has maximized the value of ITER testing.

I. INTRODUCTION

It is clear that a true prototype blanket performance can never be correctly simulated under ITER reduced neutron wall load combined with a non-uniform surface heat flux distribution. Moreover, the TBM will be subjected to cyclic effects from pulsed operations and a number of disruptive loads, which can make interpretation of test results complicated or even impossible. Nevertheless, it is beneficial to apply engineering scaling laws to test blanket module design and to provide an adequate model that correctly scales the primary features of the problem such as a thermal stress, with secondary influences such as primary stress allowed to deviate. In addition, scale model test results can be used as calibration benchmarks for analytical methods, or to make quantitative predictions of the prototype response. For such applications it is necessary to have a set of "scaling relations" that relate the observed model and predicted prototype behavior.

The goal of the scaling analysis is to ensure that the test results of the reduced-scale conditions can be meaningfully extrapolated to prototype conditions. It investigates the required designs that a scaled model must comply with in order that it respond in a manner similar to that of the prototype. In general, the scale modeling approach starts with the identification of the primary modes of system response, followed by the establishment of the variables that contribute to these modes of system response. Scaling relations are derived and used to compute scale model parameters for the variables of interest. The key ITER parameters, which have been used as the basis for the solid breeder submodule designs, include surface heat flux magnitude and distribution and neutron wall load.[1] Other transient and abnormal operating parameters, such as pulsed operations and disruptions, introduce non-prototype behavior and can only distort the simulations. Under such conditions, true prototype behavior can not be fully simulated. However, it can be argued that an adequate model which correctly scales the primary features of the problem, with secondary influences allowed to deviate, is obtainable.

Reproducing prototype operating temperature is a key to ITER solid breeder test module design, since it has a crucial influence on both blanket thermomechanical and tritium release performances. Furthermore, since the coolant temperature determines the minimum operating temperature encountered in the blanket elements, reproducing coolant operating temperatures serves as a starting point for the engineering scaling process. This implies that typical inlet and outlet temperatures of 300^{o} and 500^{o}C for blanket designs with ferritic steel as the structural material are preserved in the test blanket module design. Moreover, the ITER test blanket module receives a higher ratio of surface heat to neutron wall load and a non-uniform surface heat load. This creates a challenge in preserving prototype temperature distributions in the blanket module. A higher ratio of surface heat load to neutron wall load implies that a higher flow rate is needed to remove the first wall surface heat load in order to satisfy first wall temperature criteria. However, such a high flow rate becomes excessive for blanket internal cooling and leads to a lower outlet temperature and an overall lower temperature magnitude in the blanket region. Consequently, the submodule design allows for the fact that the exit temperature reproduces typical prototype helium outlet temperatures of 500°C by reducing breeder element flow rate through a by-pass flow control. The other challenge comes from the reduced geometric size of the module as compared to the size of a typical prototype module. A lower mass flow needed for the scale model due to reduced geometrical and operating parameters results in a lower velocity or equivalently, a lower heat transfer coefficient. To overcome this, less coolant paths per flow manifold are considered in order to reduce the overall coolant flow area and increase the coolant velocity. A set of example scaling relations is presented in Table 1 to illustrate various aspects of thermal-hydraulic simulation, while design parameters of helium coolant are listed in Table 2.

Scaling Relation	Remarks
1) $\Delta T_s = \Delta T_p$ $\Delta T_s = \frac{Q_s}{m_s Cp} = \frac{n_s A_s^{FW}}{m_s Cp}$ $\Delta T_p = \frac{Q_p}{m_p Cp} = \frac{n_p A_p^{FW}}{m_p Cp}$ $\frac{m_s}{m_p} = \frac{n_p A_p^{FW}}{n_s A_s^{FW}}$	*S: scale model;* *p: Prototype* *ΔT:He temperature rise* *n: Neutron wall load* A^{FW} *: First wall area* *m: He mass flow rate* *Cp: heat capacity* n_s*= 0.78 MW/m*^{2}*(ITER)* n_p*= 4.8 MW/m*^{2} *(ARIES-AT)*
2) $h_s \approx h_p$ $h_s \propto v_s \propto \frac{m_s}{A_s^f}$ $h_p \propto v_p \propto \frac{m_p}{A_p^f}$	*h: heat transfer coefficient* *v: velocity* A^f *: coolant flow area* $\frac{A_s^f}{A_p^f} = \frac{n_p A_p^{FW}}{n_s A_s^{FW}}$
3) $\frac{\phi_s}{n_s} vs \frac{\phi_p}{n_p}$ $\left(\frac{0.5}{0.78}\right)_s vs \left(\frac{0.6}{4.8}\right)_p$	ϕ *: surface heat load* ϕ_s = 50% 0.5 MW/m^2 and 50% 0.25 MW/m^2 ϕ_p = 0.6 MW/m^2*

Table 1 Scaling relations applied for helium thermal-hydraulic design

Parameter	Value
Power from surface heat flux	0.249 MW
Power from breeding zone with 1.2 multiplication factor)	0.622 MW
Helium inlet/outlet temperature	300/500°C
Mass flow rate to first wall	0.9 kg/s
Mass flow rate to breeding zone	0.82 kg/s
Mass flow rate -bypass	0.08 kg/s
Coolant ΔT first wall	53.5°C
Coolant ΔT breeding zone	146.5°C

Table 2 Thermalhydraulic design parameters for ITER scale model

II. MODEL FOR PEBBLE BED THERMO-MECHANICAL INTERACTION SIMULATIONS

In addition to evaluate primary modes of system response in the scale model, the approach incorporates testing objectives of performance exploration and concept evaluation concurrently being addressed by built-in flexibility. This scheme leads to two breeder design configurations housed in one submodule, as illustrated in Figure 1. In one configuration, both beryllium and breeder beds are placed perpendicular to the FW facing the plasma region. In configuration two, a parallel configuration is considered. The latter option resembles the blanket concept considered in the US ARIES-CS and HAPL designs.[2] In addition, it worth noting that each configuration includes several units, which provides multiple test data and allows statistical significance on test results to be analyzed simultaneously. Despite their impact on neutronics performance, the breeder pebble bed configurations display distinct thermomechanical performances due to dissimilar temperature profiles across the units. The effect of thermomechanical interactions on the integrity of the breeder unit is the primary response that the scale model is designed for.

Appropriate scaling factors for pebble bed thermomechanical interactions may be directly obtained by examining the constitutive equations that govern the performance. In the present TBM submodule design approach, the packing density and material properties are specified to be identical to those of the prototype, which leaves stress, elastic moduli and creep scaling factors to be established.

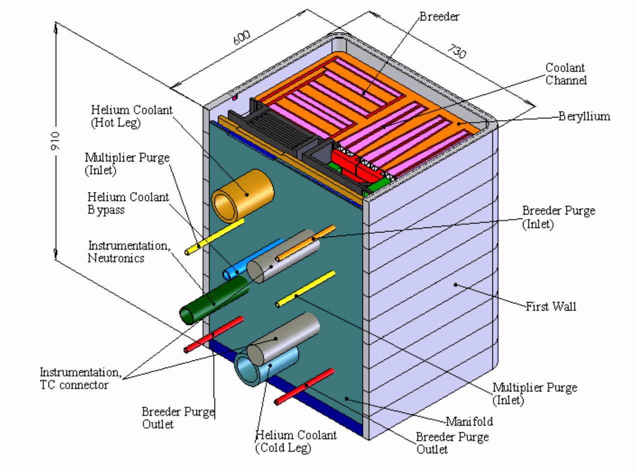

Fig. 1 Schematic view of a ITER solid breeder submodule

The elastic modulus and creep compaction of a ceramic breeder pebble bed is related to stress and temperature levels by the expression:[3-5]

$$E = 130x\sigma^{0.47} \qquad (1)$$

and

$$\varepsilon^{c} = 12.12x(\sigma)^{0.65}t^{0.2}e^{\frac{-10,220}{T}} \qquad (2)$$

where σ is the axial stress in MPa, T temperature in ^{o}C and t time in second.

These constitutive equations indicate that in order to reproduce prototype thermomechanical behavior, the scale model should be operated at the same stress and temperature levels as those of prototype. Since ITER neutron wall load (0.78 MW/m^2) is much smaller than that of a prototype fusion power reactor (i.e. 3 MW/m^2), attention must be paid to correctly modeling the temperatures because of the much lower nuclear heating rates generated in the scale model. Replicating prototype temperature levels requires scaling up the breeder unit dimension by a factor of roughly the square root of the ratio of the neutron wall load between the scale and prototype models. To further evaluate whether structural wall/ceramic breeder pebble bed thermo-mechanical interaction has been correctly simulated in the scale model, the aforementioned constitutive equations were incorporated into a finite element code,[6] where stresses generated due to temperature gradient and differential thermal expansion were calculated. In addition, the breeder/coolant interface is modeled by the contact elements in order to simulate any separation that may be caused by any differential deformation. As shown in Figure 2, the von Mises stresses calculated for the ITER scale model pebble bed show a similar range of magnitudes to that of the prototype (for which dimensions and operating parameters are taken from the EU Demo HCPB design[7]), although the scale model shows a slightly higher maximum stress (2.25 MPa as compared to 1.75 MPa found in the prototype model) and a more gradual fall off in stresses near the back region. This is because a tapered configuration is considered for the ITER scale model (as compared to that of a uniform toroidal width in the prototype model) in order to achieve a more uniform temperature profile such that the toroidal dimension increases as it moves toward the rear region. In addition, the scale model adopts a shorter radial dimension (35 cm as compared to 47 cm). These differences applied in the scale model design results in that the scale coolant channel plate deforms less than that of the prototype coolant channel plate as shown in the same figure, in which analysis shows about a 0.41 mm gap formed at 20.6 cm away from the front wall as compared to that of a 0.18 mm gap at 15.2 cm under the same mechanical boundary conditions. This gap produces an additional heat transfer resistance at the interface and causes increases in local temperatures. The impact of this temperature increase on closing the gap due to further increase in bed deformation can not be estimated using the existing FEM model. On the other hand, the deformation found in the prototype model can be reduced by installing a reinforced grid inside the breeder unit, the design of which should be explored later. Similar calculations have been performed for scale model and prototype layer configurations. In this configuration, the von Mises stress exerted on the pebble bed due to a combined effect of differential thermal expansion and mechanical constraint is about 3.0 MPa for both models as shown in Figure 3. This magnitude is slightly higher than that found in the edge-on configuration (about 1.75 MPa) due to its larger temperature gradient across the bed. The location of the maximum stress is closer to the side wall in the scale model case. Both cases adopt fixed

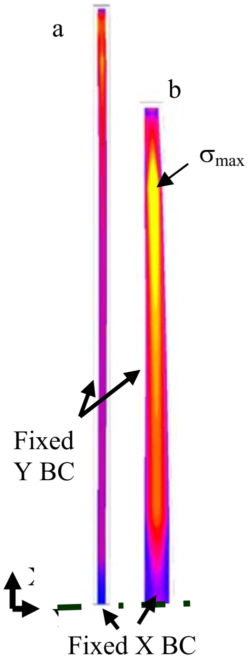

Fig. 2 Pebble bed stress distribution. (a: EU-HCPB like prototype model b: ITER scale model)

boundary conditions at the side wall and symmetric boundary condition at the center of the computational model since only half of the model is simulated.

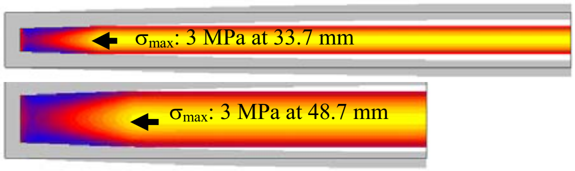

Figure 3 Stress and deformation profiles for prototype and scale models (top: ARIES-CS like model having 47 cm in the toroidal direction and 9 mm bed width; bottom: ITER scale model with 32 cm in the toroidal direction and a 18 mm bed width)

Theses stresses exerted on the pebble bed are transmitted to the particle/particle contacts, which initiate thermal creep at regions where temperatures are high (above 650°C). The creep evolutions at the center point of a breeder unit in layer configurations are shown in Figure 4. In the case of the prototype, the creep stops at about 100 hours of operation indicating a complete stress relaxation at this point, as shown in the stress evolution curve of Figure 4. The stress relaxation evolution characteristic at the mid-plane of the edge-on breeder unit as illustrated in Figure 5 shows that the stress near the first wall region relaxes as time proceeds, but it remains near the same at the back, where temperatures are low.

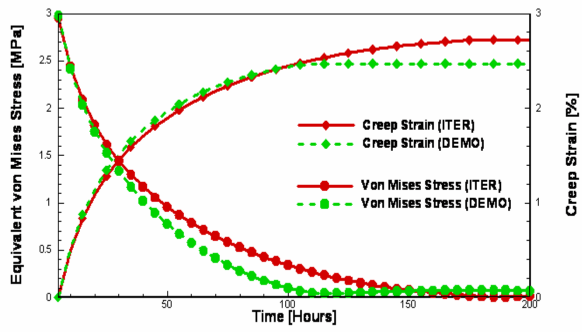

Figure 4 Creep and stress relaxation evolutions have been preserved under steady state operations

III. SCALING CRITERION APPLICABLE TO FIRST WALL STRUCTURAL BOX DESIGN

The use of small physical scale models to study large scale geological structures has an immediate impact on performance parameters such as displacement, which generally scales with dimension. However, experiments with small scale models have had an important influence on the development of the understanding of an integrated structural response under fusion complex loadings and of predicting methods for first wall thermo-mechanical behavior. The key parameters that the scale model attempts to simulate are temperature and stress magnitudes. Since there is no simple analytical scheme that can be applied, brute-force computational FEM approaches are utilized to recapture key Demo parameters under a reduced neutron wall load in ITER.

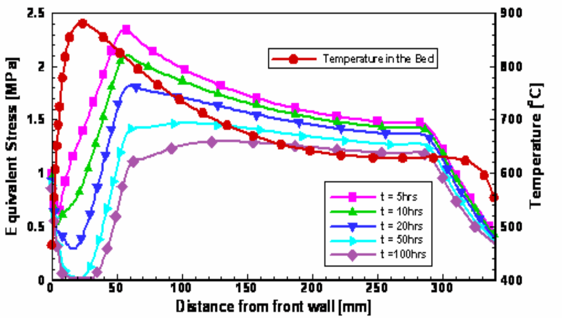

Figure 5 Stress evolutions along the mid-plane of ITER scale-model (edge-on configuration)

The model created for this simulation is a subset of the full blanket module. It represents one full pass of fluid through the unit and contains five channels. For increased accuracy and to facilitate the eventual transient analysis of the first wall heating process, the unit is modeled with ten quadrilateral elements across the first wall. This cross section is constant around the outer perimeter of the model. The section in the center is solid and also meshed with solid quadrilateral elements. The model is held in place by a "sliding" condition on the back face of the model. The model is fixed across the back face from movement in the perpendicular direction. A single node in the center is also constrained from motion in the X and Y directions. This holds the model without over-constraining and introducing unnecessary stress concentrations. The computational model employs 280,570 elements. The material used for this analysis is F82H Steel and the properties were taken from Tavassoli et al.[8] A summary of the properties is as follows:

Density: 7.871E-006 g/mm^3
Young's Modulus: 217.2605 GPa at 20 °C
177.5899 GPa at 600 °C
Specific Heat: 470 J/g-K at 20 °C
810 J/g-K at 700 °C
Thermal Expansion: 1.04e-5 ppm/Cat 20 °C
1.24e-5 ppm/C at 700 °C
Thermal Conductivity: .033 W/mm-K

The analysis is done in two phases. First a thermal analysis is performed by applying a heat flux of .0.5 MW/m^2 to one half of the front wall and a heat flux of .0.25 MW/m^2. to the other half (assumed for

ITER first wall design). To simulate the coolant flowing through the five channels, a convection condition is applied to the internal walls of the channels. The convection coefficient for the faces directly opposite of the first wall is given as 5890 W/m^{2}K and on the other walls as 3700 W/m^{2}K. Following the thermal analysis a structural analysis was performed using the output nodal temperatures as an applied thermal load for expansion calculations. In addition to this applied thermal loading a pressure of 8 MPa was applied to the inside of the five channels.

The result of the thermal analysis shows a maximum temperature of 522.8°C (Figure 6), which is below the maximum allowable temperature of 550°C. The calculated temperature profile in the first wall reflects combined features of the cooling scheme and a non-uniform heat flux distribution, in which first wall temperature gradually increases as the helium moves from the first coolant channel to the last (the fifth) channel and is hotter on the high heat flux side. The results of the structural analysis show the maximum stresses lie in the large radius at the top of the model. The peak stresses shown in Figure 7 are around 268 MPa. This maximum stress is similar to the maximum stress magnitude reported for JA's Demo design, which is below the yield strength at 550°C of 380 MPa. For simplification this model was created with square channels, which induced certain stress concentrations in the corners. A round corner design will be considered in later analysis. The maximum displacement was in the hot side of the unit and was calculated to be 3.51 mm, as shown in Figure 8.

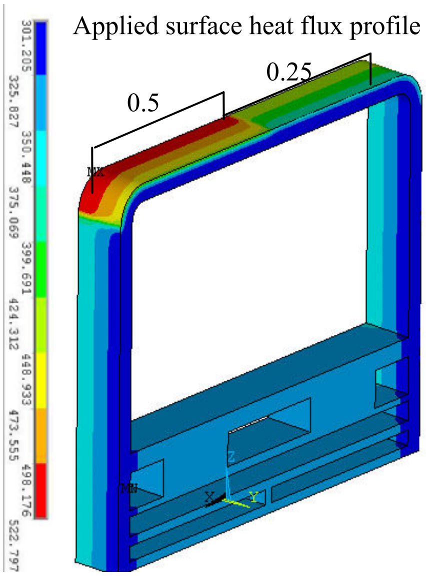

Figure 6 Temperature profile of one flow path

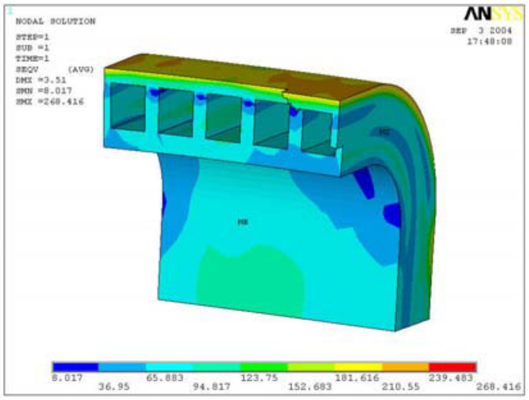

Figure 7 Stress distributions near the hot side of the unit (maximum stress of 268 MPa is found at the corner of the inner wall). The total thickness: 28 mm (including 5 mm front and 7 mm back). The coolant channel dimension is 16 x 13 mm^2 with a pitch of 18.2 mm.

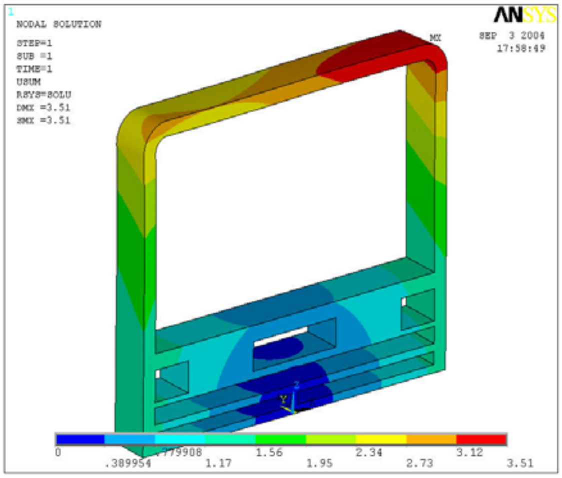

Figure 8 Displacement profile of the 5 coolant-channels unit. The non-uniform characteristics of the displacement shown in present analysis due to a non-uniform ITER surface heat flux profile may not be prototypical. The maximum displacement is 3.51 mm.

IV. DESIGN CONSIDERATION FOR SOLID BREEDER NEUTRONIC SUBMODULE

In addition to modeling qualitative interpretation of system response, scale model test results can be used to benchmark/calibrate any numerical codes or analytical methods, or to make quantitative predictions of the prototype response. A schematic view of a neutronic submodule design that complied with this purpose is shown in Figure 9, in which its design criterion is determined by the geometrical size requirements to maintain a high spatial resolution for any specific measurement and allow complexity to maximize code validation. The submodule incorporates two layer design configurations behind the first wall structural containment: one features prototype look-alike and the other prototype act-alike. The neutronic performance of this submodule including the presences of neighboring submoulde and frame structure was modeled as shown in Figure 10.

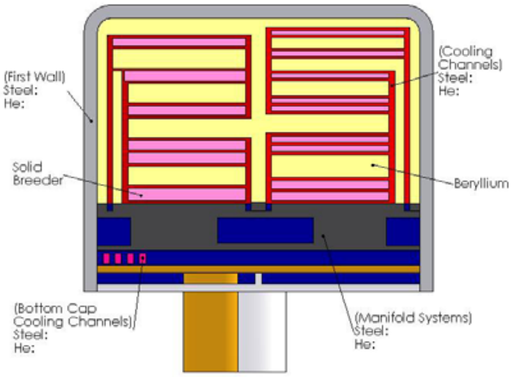

Figure 9 Example neutronic submodule for nuclear code and data verification tests

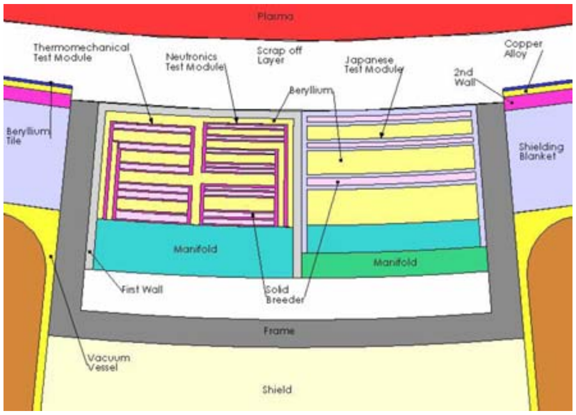

Figure 10 Top view of the 2-D nuclear model (The model includes neutronic submodule and its neighboring submodule, frame structure and vacuum vessel)

Key results of the analysis are presented in Figures 11 and 12, in which Figure 11 focuses on the tritium production characteristics and Figure 12 on the heating rate profiles. As shown, profiles of the tritium production rates are nearly flat over a reasonable distance in the toroidal direction where measurements can be performed (10-16 cm in the left configuration and 10-20 cm in the right configuration). The steepness in the profiles near the ends of layers is due to presence of the beryllium layer and to neutrons reflected by the structure contact in the vertical coolant panels (VCP). This is more pronounced at the outer VCP. The tritium production rate values are larger at these locations by a factor of 1.4-1.5.

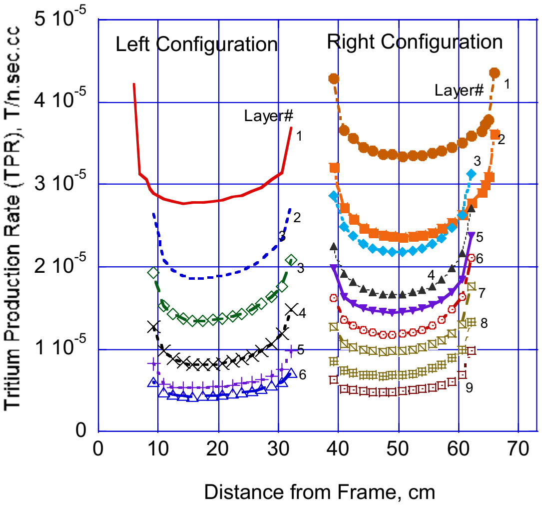

Figure 11 Toroidal Profile of Tritium Production Rate (TPR) in each Breeder Layer of the Two Test Blanket Configurations

As shown in Figure 11, the heating rate in the breeder layer of the left configuration is a factor of ~4 larger than in the Be layer of the right configuration, and is flat over ~10 cm. It peaks near the vertical coolant panels. Heating profile in beryllium is flat over the entire layer. This feature is applicable to other beryllium layers (not shown). The features shown indicate the heterogeneity effect which cannot be produced with a 1-D model. However, the adequate flat portion found in the heating rate shows that good measurements on heating rates can be performed. Details of this nuclear assessment can be found in a companion paper.[9]

V. SUMMARY

Engineering scaling analysis and process have been successfully applied to ITER solid breeder TBM designs. Primary parameters such as temperature magnitudes, stress and strain levels have been preserved in the scale model. First wall design has reproduced prototype maximum temperature and stress levels by using a 5 channel per flow path design. In addition, 2-D nuclear analysis shows that flat tritium production and nuclear heating profiles can be obtained in a quarter port submodule with two design configurations. This ensures that a high spatial resolution for any specific measurement can be achieved in the scale model.

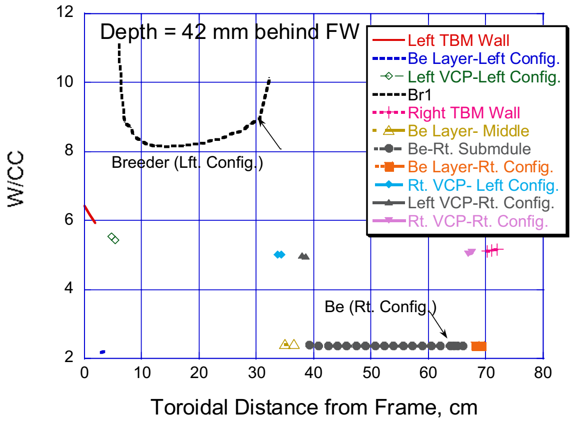

Figure 12 Nuclear heating across the proposed two blanket design configurations in the toroidal direction at depth 42 mm behind the FW

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