

Assessment of Tritium Self-Sufficiency with Realistic Blanket Designs

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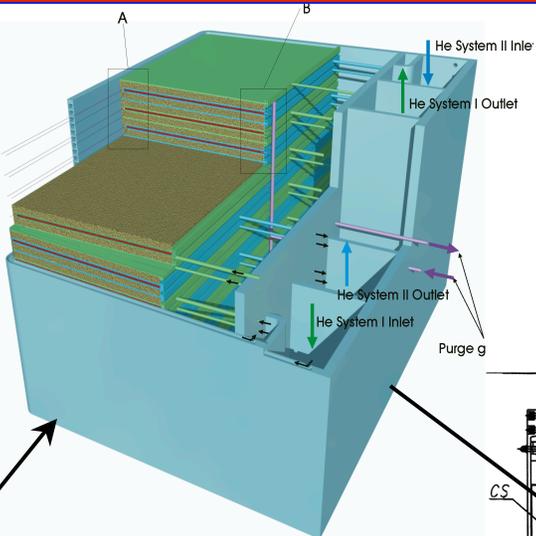
We need to demonstrate tritium self-sufficiency

- Adequate tritium supply is a central issue for the operation of ITER and the development of fusion energy
- There is no practical external source of tritium for fusion energy development beyond a few months of DT plasma operation in ITER
- All subsequent DT experimental devices, and the DEMO and power plants, will have to breed their own tritium
- ITER TBM program will be the first integrated experimental demonstration of the *principles* of tritium self-sufficiency

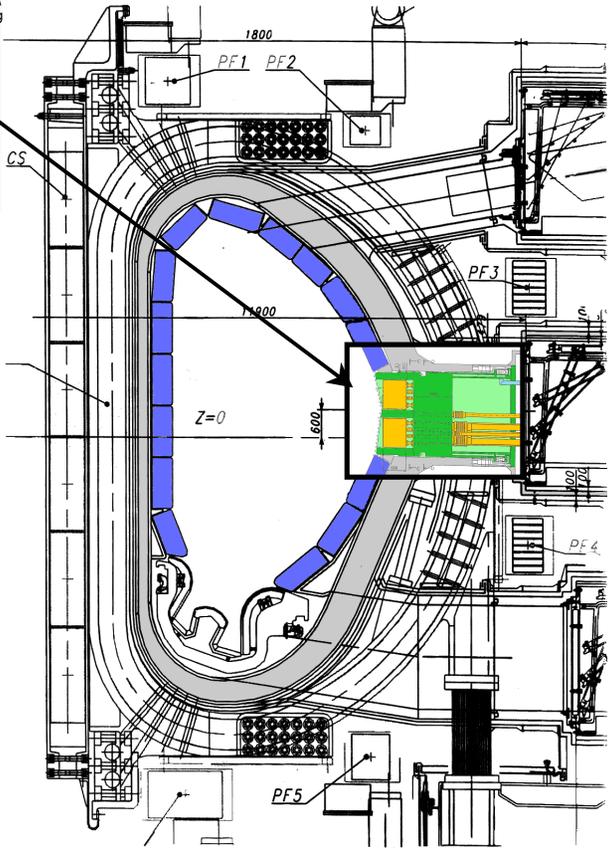


DEMO Blanket Testing in ITER

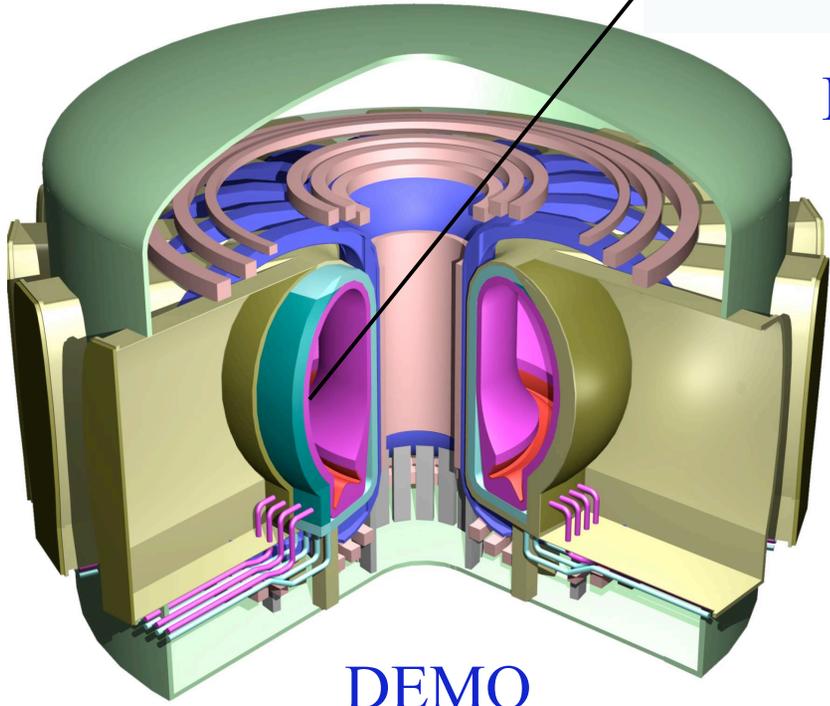
- 1. Detailed design of *realistic* DEMO Blanket
- 2. DEMO relevant TBM designed
- 3. TBM inserted for testing in ITER port



ITER



Blanket



DEMO

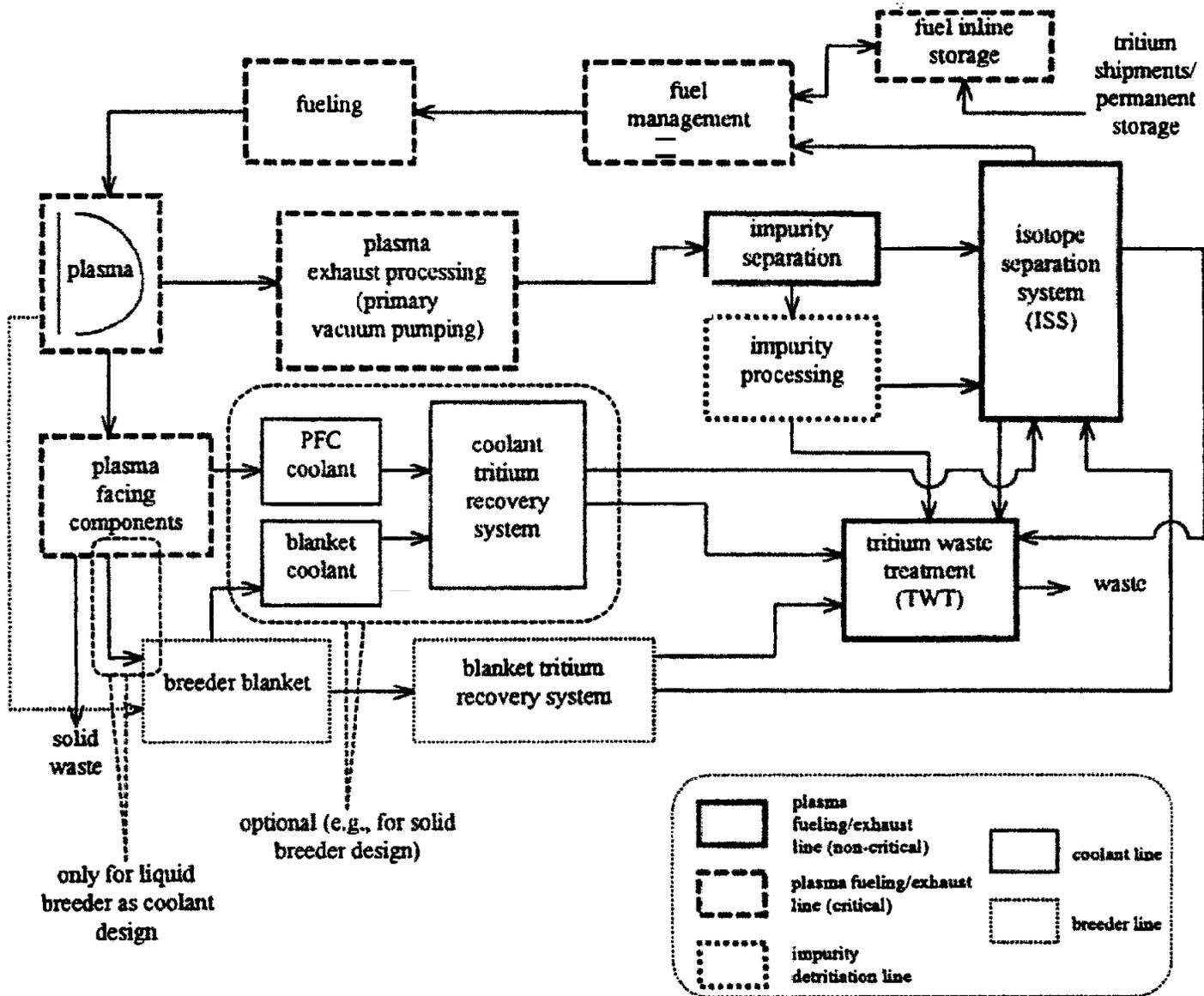


Achieving Tritium Self-Sufficiency

- To insure tritium self-sufficiency, the **calculated achievable TBR** should be **larger than the required TBR**
- The minimum **required TBR** should exceed unity by a margin that **accounts for tritium losses, radioactive decay, tritium inventory in plant components, and supplying inventory for startup of other plants**. The latter two have the largest impact.
- Analytic **dynamic models** were developed to describe the characteristic parameters of **elements of the tritium fuel cycle** as a **tool for evaluating the required TBR**
 - W. Kuan and M. Abdou, “A New Approach for Assessing the Required TBR and Startup Inventory in Future Fusion Reactors,” *Fusion Technology*, 35, 309 (1999)
 - Abdou, M.A., E.L. Vold, C.Y. Gung, M.Z. Youssef and K. Shin, “Deuterium-Tritium Fuel Self-Sufficiency in Fusion Reactors,” *Fusion Technol.*, 9, 250 (1986)
- The issue was also addressed extensively at **Snowmass in 1999**
- The required TBR ranges between **1.01 and 1.10** depending on the tritium inventory, required doubling time, tritium burnup fraction in plasma, required tritium fuel reserve, reliability of tritium processing system, losses and other system parameters



Fuel Cycle Schematic with Tritium Processing Lines



Uncertainties in Calculating the Achievable TBR

- Uncertainties in calculating the achievable TBR are due to
 1. System definition
 2. Modeling
 3. Nuclear data and calculation method

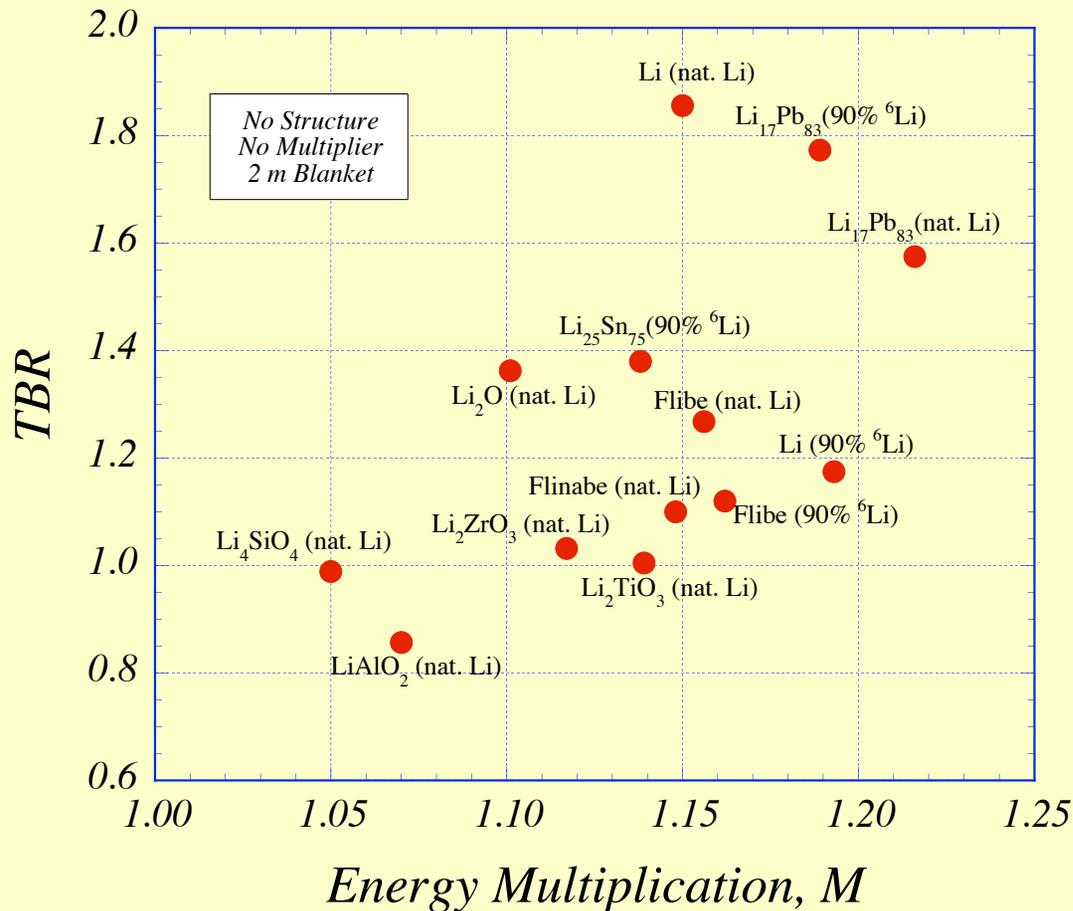


1) System Definition

- Uncertainties in defining several FW/blanket design details and many reactor features influence how accurate is the calculated achievable TBR
 - First wall thickness
 - Structure content in blanket
 - Stabilizing shell material, thickness, and location
 - PFC coating/tile material and thickness
 - Divertor material and geometry
 - Plasma heating and CD system
 - Penetrations for diagnostics and fueling
- Achievable TBR should be calculated for a realistic system
- Largest impact on TBR is due to definition of FW thickness, blanket structure content, and possible stabilizing shells and PFC coating
- Practical FW thickness and blanket structure content used should be based on detailed structural-mechanical and thermal-hydraulics analyses
- Using unrealistic design assumptions leads to significant error in predicted achievable TBR



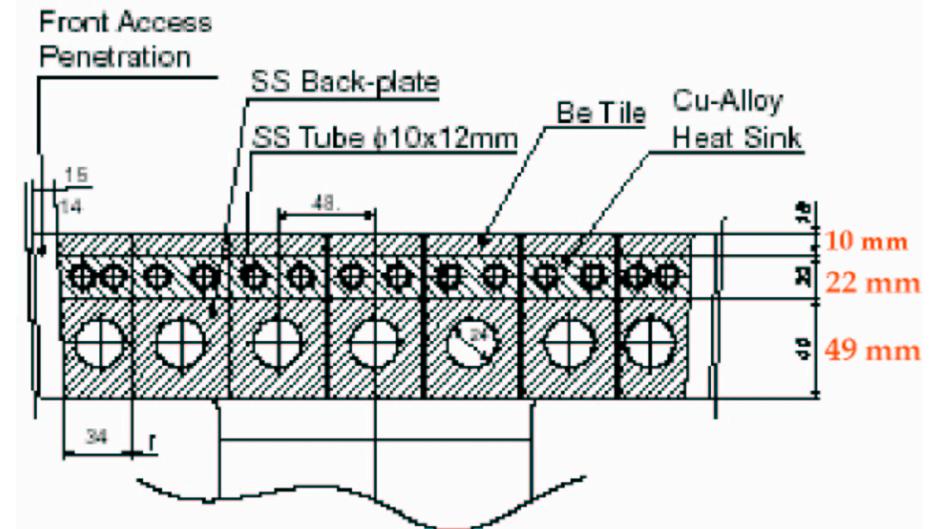
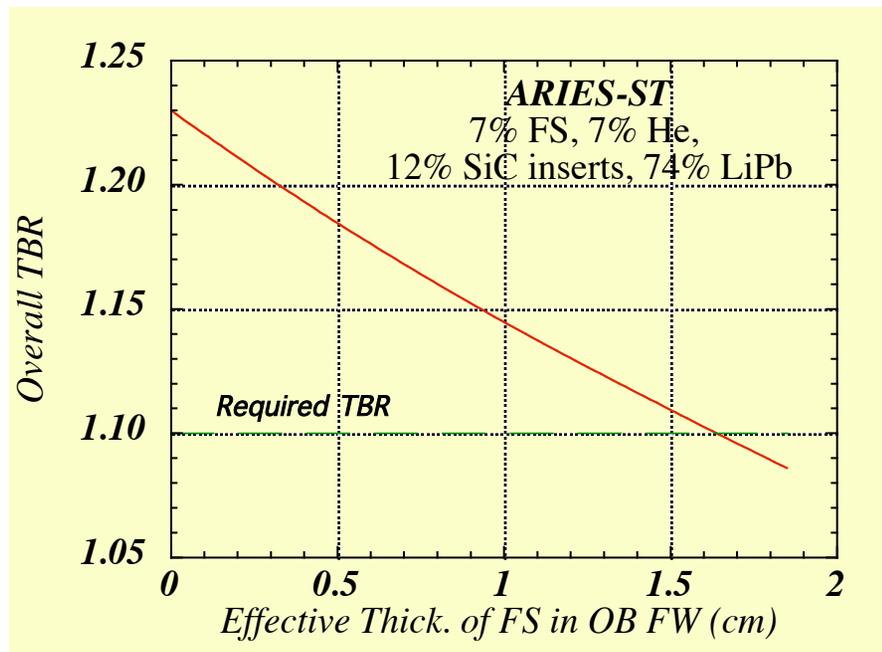
Tritium Breeding Potential of Candidate Breeders



- Li and LiPb have highest breeding potential
- Breeders with moderate breeding potential (Li₂O, Flibe, Flinabe, SnLi) require moderate amount of multiplier
- Ceramic breeders have poor breeding potential and require significant amount of multiplier and minimal structure content



Achievable TBR is Very Sensitive to FW Thickness



ITER FW Panel Cross Section

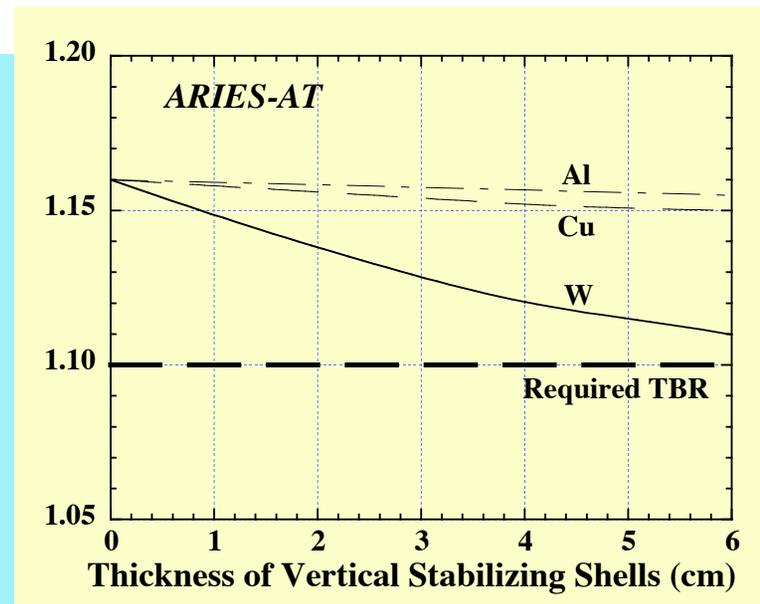
TBR drops by up to 15% with 2 cm thick FS FW

[L. El-Guebaly, Fusion Engr & Design, 2003]

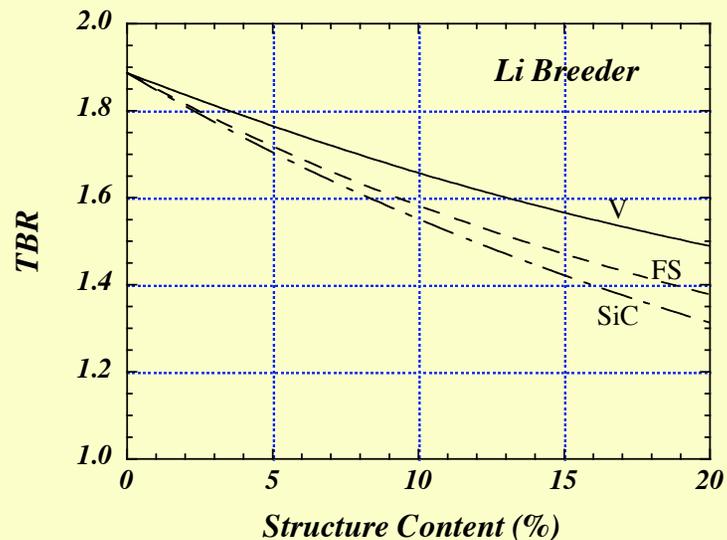
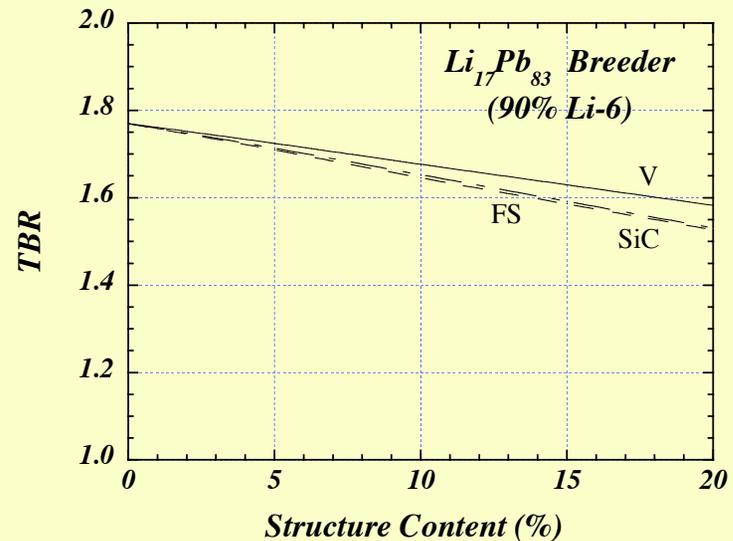
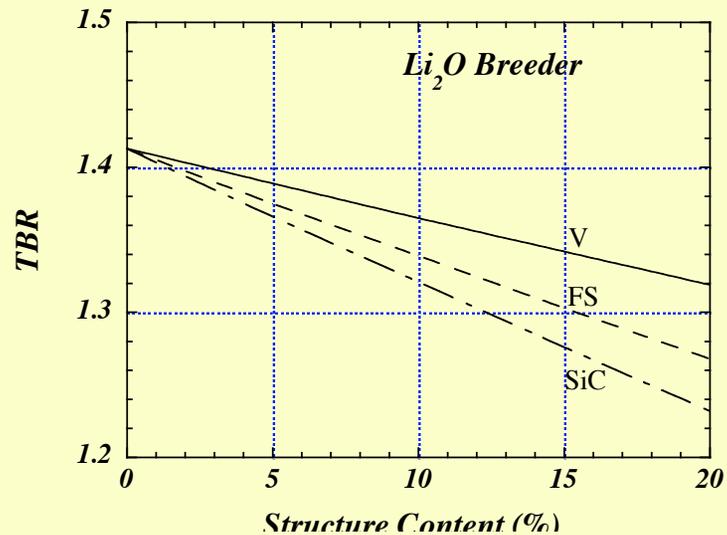


Impact of Stabilizing Shells on TBR

- Stabilizing shells should be located closer to plasma to have favorable impact on plasma performance
- Three candidate materials (W, Cu, Al) investigated in ARIES-AT
[L. El-Guebaly, et al., to be published in Fusion engineering & Design]
- Thickness of shell depends on type of conductor, operation temperature, and time constant
- Toroidally continuous OB stabilizing shells placed at upper/lower extremity of OB blanket
- Local TBR in OB blanket behind 4-cm W shells drops by ~40% but effect on overall TBR is only 4%
- Exact configuration of stabilizing shell is essential for accurate determination of TBR



TBR is Very Sensitive to Structure Content in Blanket



- Impact of structure content on TBR depends on breeder and structural material used
- V has the least impact on breeding
- Up to 30% reduction in TBR could result from using 20% structure in the blanket



2) Modeling

- 3D modeling is necessary
- Model should properly account for the Tokamak configuration with accurate source profile
- Heterogeneity in blanket components should be modeled accurately
- Model should account for side walls, support structure, and assembly gaps between modules
- Uncertainties due to modeling depend on degree of approximation used



3D Neutronics for US Breeder Blanket in ITER-CDA

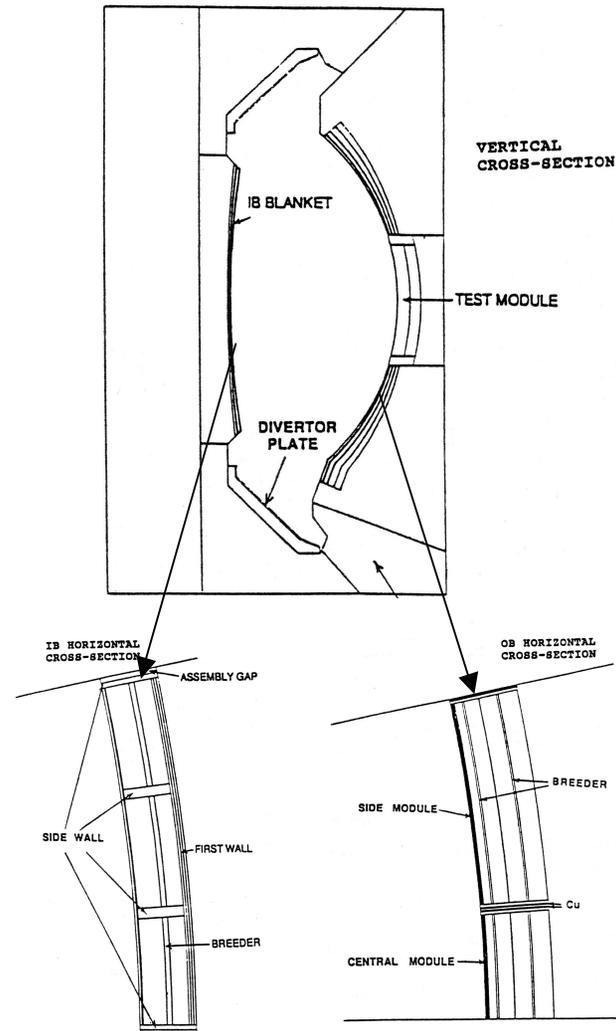
(Sawan et al., Fusion Technology, 1991)

$\text{Li}_2\text{O}/\text{Be}/\text{H}_2\text{O}/\text{SS}$
Breeding Blanket

Includes impact of test
modules and Cu
stabilizer loops

Model includes detailed
heterogeneity, layered
configuration, side walls, gaps

Overall TBR = 0.89

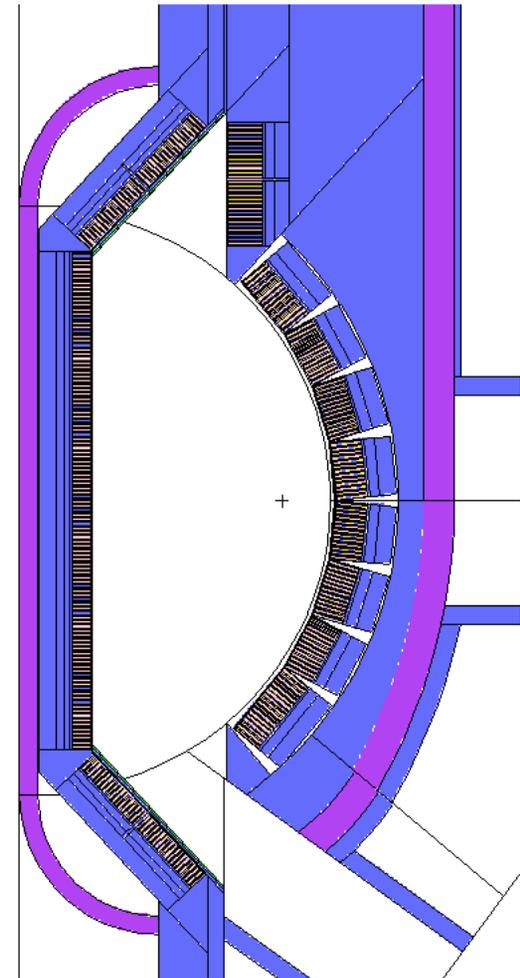


European DEMO Blanket Development

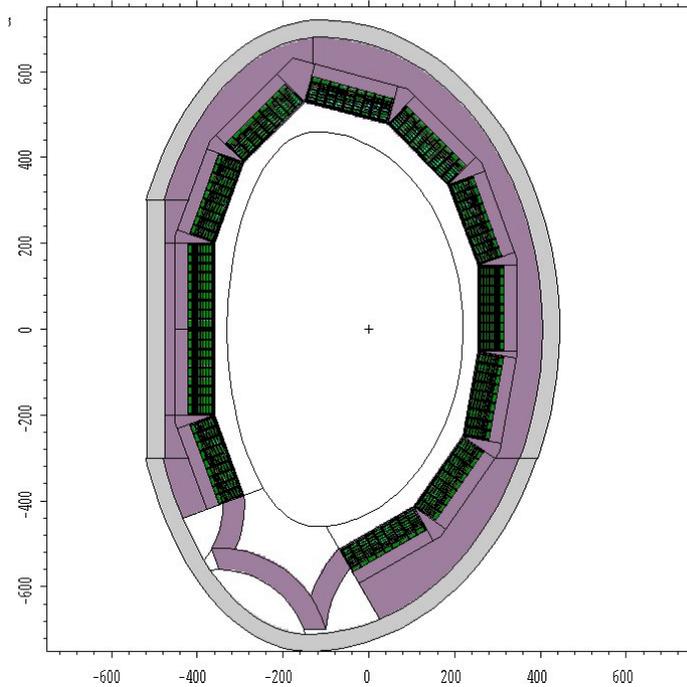
❑ *Detailed 3D analysis for the initial EU Demo Solid Breeder blanket given in KFK 5429 (M. Dalle Donne et al.) in 1994*

Input from U. Fischer

- 3D MCNP calculation
- Geometrical model for half a 22.5 degree torus sector of the DEMO-reactor (1/32 of the torus)
- Reflecting boundary conditions are applied at the lateral walls of the modeled torus sector
- Model includes the FW and blanket segments, the VV, top and bottom divertor as well as a bottom divertor exhaust chamber with a pumping duct entrance
- A heterogeneous array of He cooling plates, Be and ceramics pebble beds (Li_4SiO_4) integrated in blanket boxes according to their technical layout
- 25% ^6Li -enrichment
- *Total 3D TBR is 1.13 (0.79 OB, 0.25 IB, 0.09 divertor region)*
- The BOT blanket has evolved into the current HCPB

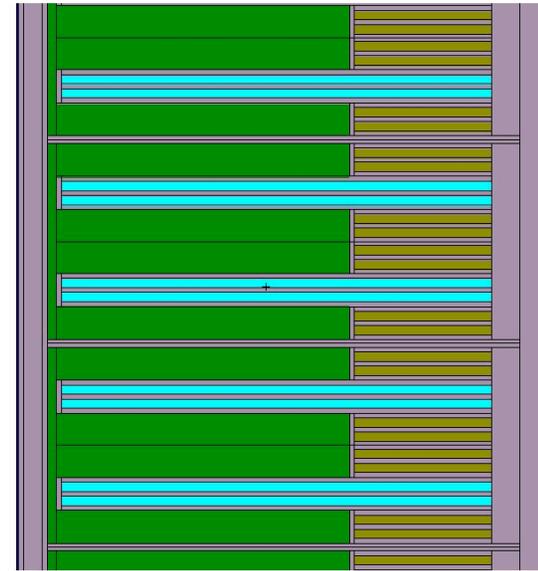


3D Modeling and Analysis of Helium Cooled Pebble Bed (HCPB) Blanket for DEMO (U. Fischer, FZK) FZKA-6763, 2003



PPCS model B (9° torus sector MCNP model)

plasma



*Detailed blanket model
(Li₄SiO₄/Be/FS/He)*

- Structural content and design configuration determined following structural-mechanical and thermal-hydraulics analyses
- 2 mm W protection layer
- 29 mm first wall thickness, 57% steel fraction
- 2 double containers per stiffening grid compartment
- 11mm thick stiffening plates
- Global TBR = 1.14



3) Nuclear Data and Calculation Method

- Uncertainties in predicting the achievable TBR due to uncertainties in nuclear data base have been **quantified for several blanket concepts** that have solid as well liquid breeder/coolants
 - M. Yousseff and M. Abdou, “Uncertainties in Prediction of Tritium Breeding in Candidate Blanket Designs due to Present Uncertainties in Nuclear Data Base,” Fusion Technology, 9. 286 (1986)
- This issue was discussed extensively at **Snowmass in 1999**
- Uncertainties in predicting the achievable TBR due to uncertainties in nuclear data base were found to be in the range of $\sim 2-6\%$
- Studies showed that $\sim 4\%$ uncertainty in the TBR could be attributed to processing of various multi-group data whereas the corresponding uncertainty arising from processing point-wise data for Monte Carlo calculation is less ($\sim 2\%$).
- The uncertainty in the TBR calculation due to the transport calculation itself using state-of-the-art Monte Carlo codes is small. Uncertainty of $\sim 1\%$ results from the statistical nature of the Monte Carlo method. Uncertainties in discrete ordinates calculations are larger and could be in the range of 2-3%
- Assuming that above listed uncertainties are uncorrelated, the uncertainty in the TBR **due to data, and calculation method uncertainties is $\sim 5-9\%$** for multi-group discrete ordinates calculations and $\sim 3-6\%$ for 3-D continuous energy Monte Carlo calculations



3) Nuclear Data and Calculation

Method (Continued)

- Recommendations from Snowmass working group addressing the potential for achieving tritium self-sufficiency:
 - An aggressive effort is required to reduce the uncertainty due to nuclear data and calculation method to <3%
 - Use existing 14 MeV neutron source facilities and code development to improve the ability to predict tritium breeding
- Nuclear data for fusion applications have been under continuous improvement. The effort was culminated by issuing the International Fusion Evaluated Nuclear Data Library (FENDL-2) in 1998. The data has been extensively benchmarked and tested in integral experiments
- Neutronics R&D activities need to be enhanced to improve the accuracy of data and predictive capabilities



TBM testing in ITER is a significant step on road to assess feasibility of tritium self-sufficiency

- Conditions in ITER are different from those in DEMO or commercial reactor (e.g., SS/H₂O shielding blanket, Be tiles on FW, disruptions, ports, etc) and measured TBR will be different from that expected if the same concept is used in DEMO or commercial reactor
- Testing in ITER with TBM having its own integrated loops and systems for tritium breeding, tritium processing, heat extraction, etc will provide information (e.g., tritium mean residence time, tritium inventory, reliability and efficiency of tritium processing system, etc) that allow better determination of the minimum required TBR
- Testing in ITER will provide information that help better definition of practical blanket design parameters (e.g., FW thickness, structure content). Subsequent calculations of TBR in DEMO conditions with accurate modeling of realistic blanket design parameters based on testing results will allow accurate estimation of achievable TBR.
- Help validate predictive capabilities for tritium transport
- Comparing tritium production in TBM as calculated with exact modeling of ITER basic machine and TBM details to the measured tritium production will identify error bar to be used with calculated achievable TBR in DEMO or commercial reactor. *How accurate can we measure tritium production in ITER TBM?*



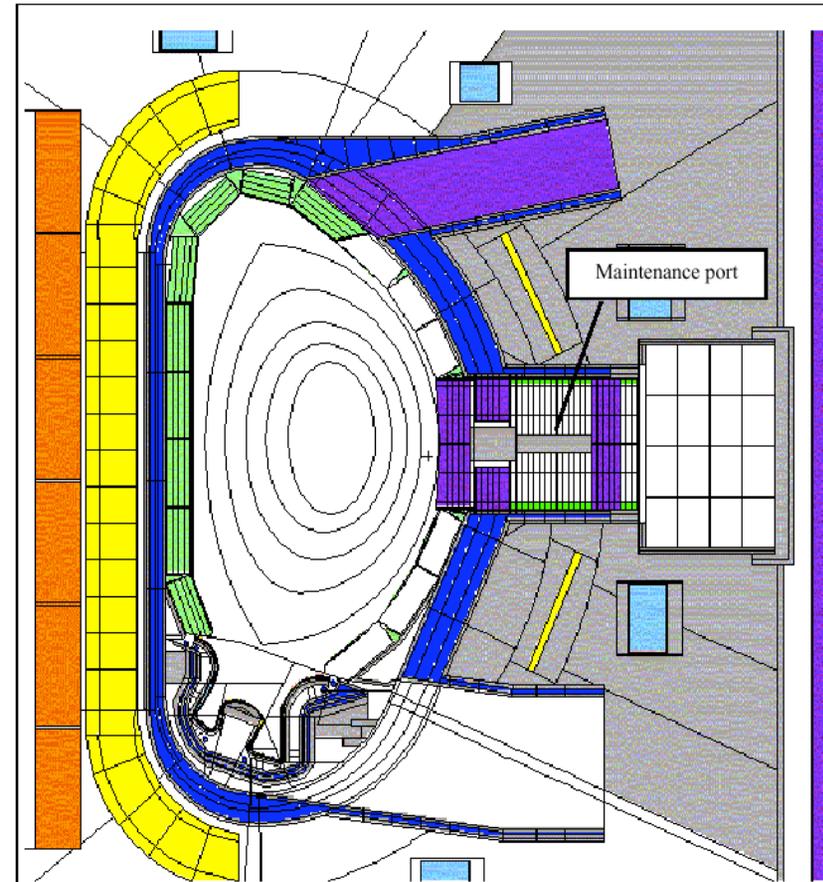
Roadmap to Demonstrate Tritium Self-Sufficiency

1. Evaluating **tritium breeding potential** is an important part of the **evaluation study** to select two blanket concepts for US ITER TBM. Close coordination between mechanical, structural, thermal-hydraulics, safety, materials, neutronics,... analysis is essential to evaluate concepts based on realistic design parameters
2. **Preliminary assessment of tritium breeding potential** of evaluated concepts will be based on **accurate modeling of the design details in the DEMO environment**. Existing predictive tools (codes, data) to be used.
3. DEMO relevant **TBM**s for testing in ITER are designed. Some **design modifications** will be necessary to accommodate ITER operating conditions and environment (e.g., disruptions, low wall loading, pulsed operation, etc)
4. **TBM** design configuration is to be **modeled for 3D neutronics** calculations with **all design details** included. The TBM 3D model **integrated** in the complete basic **ITER machine 3D model**



Detailed 3D TBM model can be integrated into existing complete ITER 3D MCNP model

- Existing ITER model includes details of shielding blanket modules, divertor cassettes, vacuum vessel with ports, TF coils, PF coils, CS coil
- Result of collaborative effort between home teams and JCT (several PMYs). US HT contributed divertor model and source subroutine modification to MCNP to sample from actual distributed neutron source in plasma
- Special geometrical features in MCNP (Universe, Fill) allow integrating components modeled separately in one integrated model
- Detailed modeling of the TBM can be done separately and integrated into the existing complete ITER model



- Codes are being developed at FZK and UW to convert CAD files to MCNP geometry input. Could be utilized?

Roadmap to Demonstrate Tritium Self-Sufficiency

(Continued)

5. Perform 3D neutronics calculations using the integrated model and most recent nuclear data (FENDL-2). Exact ITER conditions (e.g., exact modeling of neutron source profile in plasma) should be used
6. Comparing calculated tritium production in the TBM to the measured tritium production will identify error bar (primarily due to data and calculation method with accurate modeling) to be used with calculated achievable TBR. Question: *How accurate can we measure tritium production?* Depends on concept, temperature, etc. Can we have dedicated small TBM sub-modules operating at a very low temperature?
7. Neutronics calculations will also provide important nuclear environment parameters (e.g., radiation damage, transmutations and nuclear heating profiles in the TBM) that help in analyzing TBM testing results
8. Testing in ITER with TBM having its own integrated loops and systems for tritium breeding, tritium processing, heat extraction, etc will provide information that allow better determination of the minimum required TBR
9. Testing in ITER will provide information that help better definition of realistic practical blanket design parameters (e.g., FW thickness, structure content)



Roadmap to Demonstrate Tritium Self-Sufficiency

(Continued)

10. Detailed blanket design for the DEMO with realistic design parameters will be based on the results of TBM testing in ITER
11. Using the dynamic models of the fuel cycle and input from ITER testing results the minimum required TBR in the DEMO is calculated
12. 3D neutronics calculations for the DEMO with detailed modeling of the realistic blanket design will yield the achievable TBR. Uncertainties in calculation based on tritium production measurement in the TBM should be factored in
13. DEMO blanket design might go through several iterations to ensure that the calculated achievable TBR is larger than the required TBR. This enhances the potential of demonstrating tritium self-sufficiency in the DEMO when built

