Ceramic Breeder Blanket Conceptual Design for ARIES-CS

UC San Diego

Presented by Xueren Wang

Contributors: S. Malang, A.R. Raffray, and
L. El-Guebaly

ARIES Meeting
University of Wisconsin, Madison
June 16-17, 2004

Outline

- Introduction
- Layout of He-cooled ceramic breeder blanket

  -*Box design*

  -*Helium flow schemes*

  -*Access tubes to the blanket module*

  -*Mechanical attachment to the blanket module*
- Thermal-hydraulic analysis
- Pressure stress analysis
- Summary

Introduction

- The first phase of the ARIES-CS study has focused on scoping out maintenance schemes and blanket designs best suited for a compact stellarator configuration.
- Three possible maintenance schemes were considered over past years:

  (1) Maintenance approach based on field-period units.

  (2) Maintenance approach through a small number of designated ports.

  (3) Maintenance approach through ports arranged between each pair of adjacent modular coils.

- Several blanket conceptual designs compatible with three possible maintenance schemes have been investigated:

  -Dual coolant blanket with helium cooled FW/structure and self-cooled Li breeding zone for the first maintenance scheme (Done).

  -Self-cooled Flibe blanket or Pb-17Li/SiC blanket for the second maintenance scheme(Done).

  -He-cooled ceramic breeder blanket for the third maintenance scheme(Current study).

- The most attractive integrated the configuration with blanket concept and maintenance scheme will be selected for detailed study.

Layout of the Helium-Cooled Ceramic Breeder Blanket

Blanket Design Considerations

- Blanket module design pressure impacts the amount of structure required in the module design, and, thus, and the module weight &size, the design complexity and the TBR.
- Cooling channels in FW and BZ would be designed to accommodate the coolant high pressure ~8 MPa. The module itself under normal operation would only need to accommodate the low purge gas pressure(order of 0.1 MPa).
- Packing factor for both types of pebble beds is assumed to be ~62%, and Lithium ortho-silicate (Li_4SiO_4) is selected as ceramic breeder.
- Brayton power cycle is assumed to be used in CB design to avoid the safety issue linked with using a Rankine cycle.
  - Maximize He coolant outlet temperature and optimized blanket parameters (for given thermo-mechanical and pressure drop constraints) for maximum cycle efficiency:

    @ blanket inlet ~400 °C, blanket outlet ~610 °C.

    @ divertor structure: inlet 400 °C, outlet ~600 °C ; divertor target plate: inlet 600 °C , outlet 800 °C.

    @ helium exit temperature to the power conversion system: 650 °C

A.R. Raffray, "Some of the Major Considerations in Designing a Ceramic Breeder Blanket for ARIES-CS" Presented in ARIES Meeting, March 8, 2004.

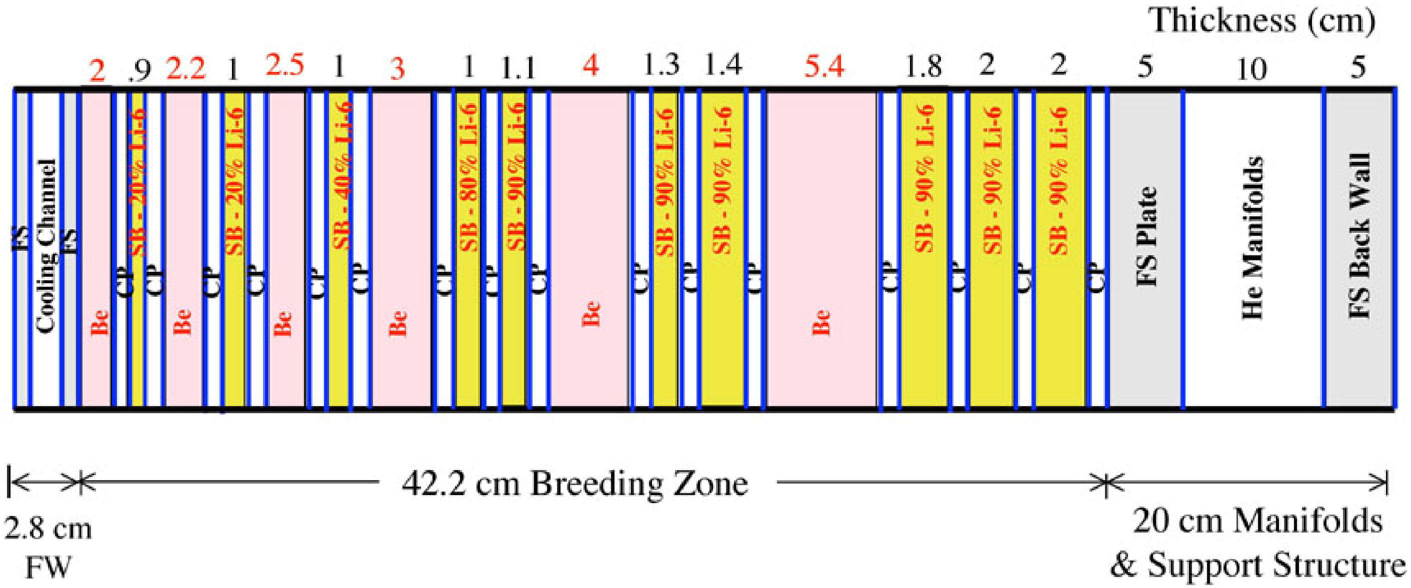
Optimization of the Radial Build Based on TBR and Bed Temperature Limits (from Laila)

UC San Diego

THE UNIVERSITY of WISCONSIN MADISON

Schematic of 65 cm Blanket

(4.5 MW/m² peak)



0.6 cm Thick Cooling Plates (CP)

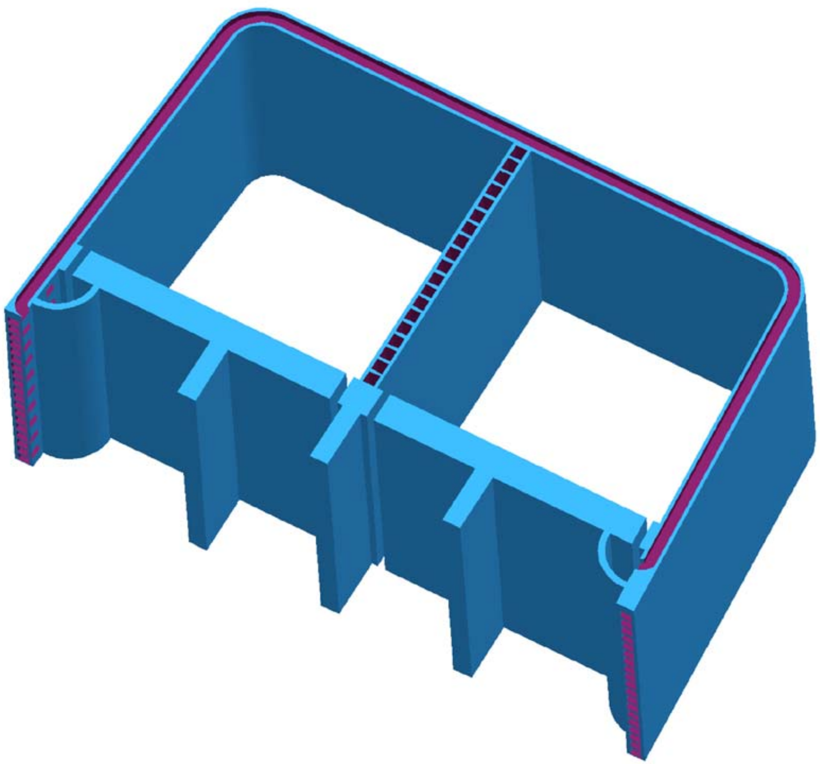
65 cm Blanket:
28 cm He
37 cm solid materials

$T_{max,Be} < 750°C$; $T_{max,CB} < 950°C$; $\delta_{CB\ region} > 0.8$ cm

Low-Pressure Requirement on Module Leads to Simpler Design

UC San Diego

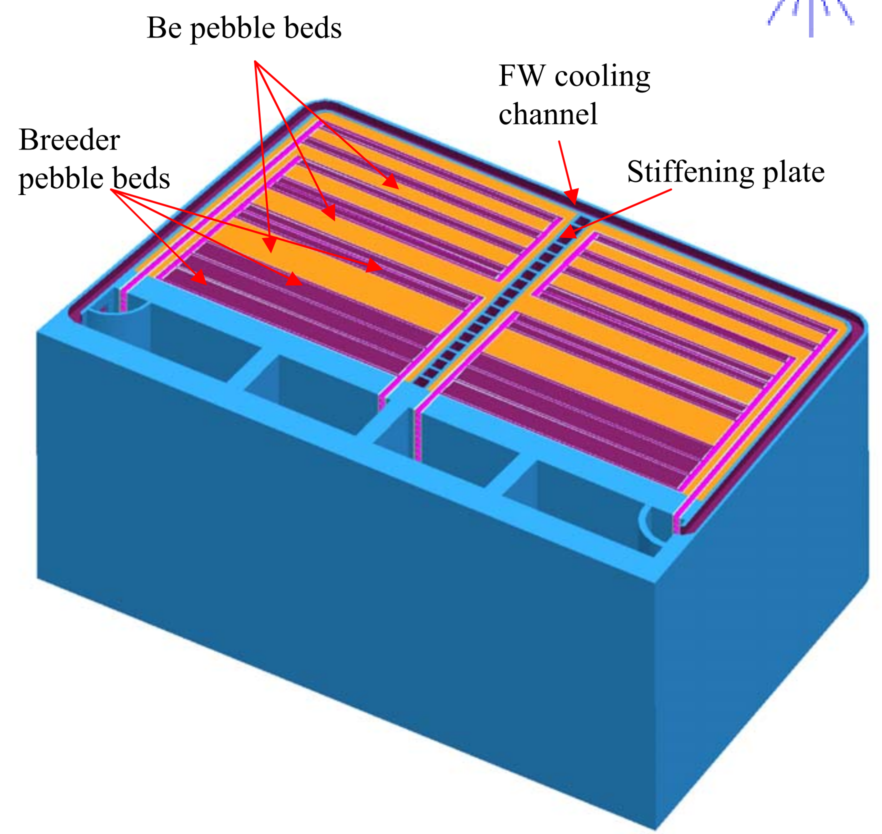
- Maximum pressure in the blanket box caused by LOCA is limited to 1 MPa. This allows a simpler lay-out of blanket box.
- The blanket box would have dimensions of up to 1.0 x 0.65 x 4.0 m^3 (toroidal x radial x poloidal) with a stiffening plate arranged only in one direction (perpendicular to the FW).
- Blanket box and inlet manifold are build of RAFS with a maximum allowable temperature of 550 °C. The FW can be plated with a layer of ODS FS with a maximum allowable temperature of 700 °C.



Isometric view of the U-shape blanket box

Arrangement of the Breeder and Beryllium Pebble Beds

- Breeder and beryllium pebble beds are arranged in parallel to the FW.
- The height of the pebble beds is adjusted to the local volumetric heat generation rate, resulting in an increase of height from the front to the back.
- Ratio between breeder and multiplier can be adjusted to maximize tritium breeding and shielding, and it can be varied from the front to the back.
- The Li-6 enrichment in the breeder beds increases from the front (natural Li) to the back.

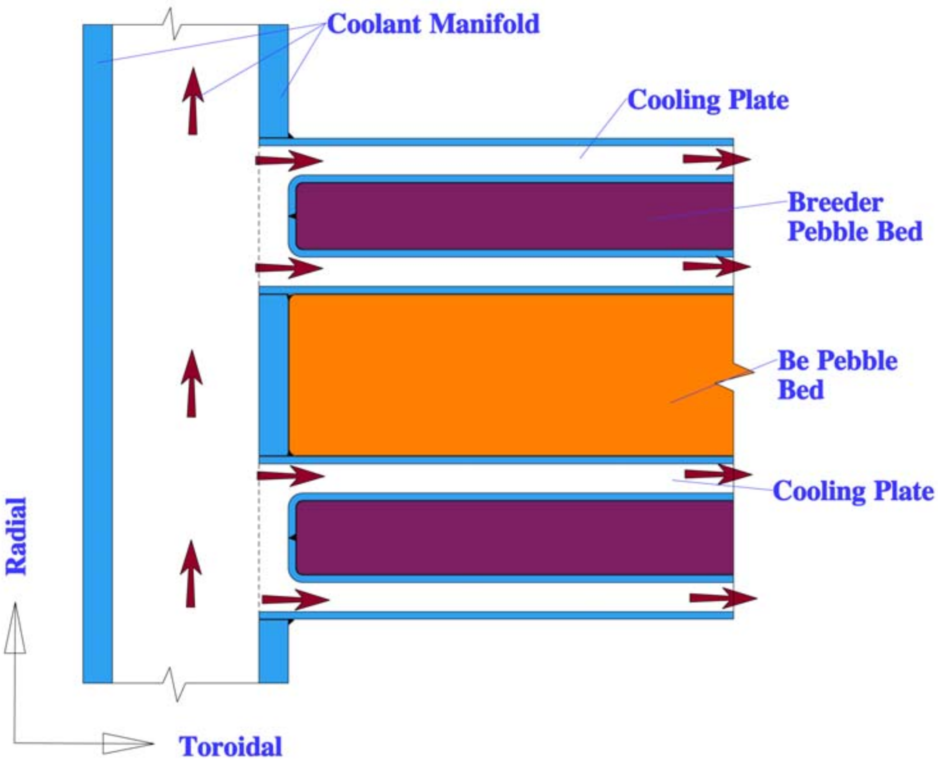


Isometric view of the ceramic breeder blanket

Arrangement of the Breeder and Beryllium Pebble Beds(Cont.)

UC San Diego

- Inside the breeding zone, each breeder bed is enclosed by two cooling plates.
- This assembly is filled outside the blanket box with ceramic pebbles, and closed.
- All the cooling plates are welded to larger manifold plates before inserting the breeding zone into the blanket box.
- Beryllium pebbles are filled into any empty space inside the box, and compacted by suitable vibrating the module.

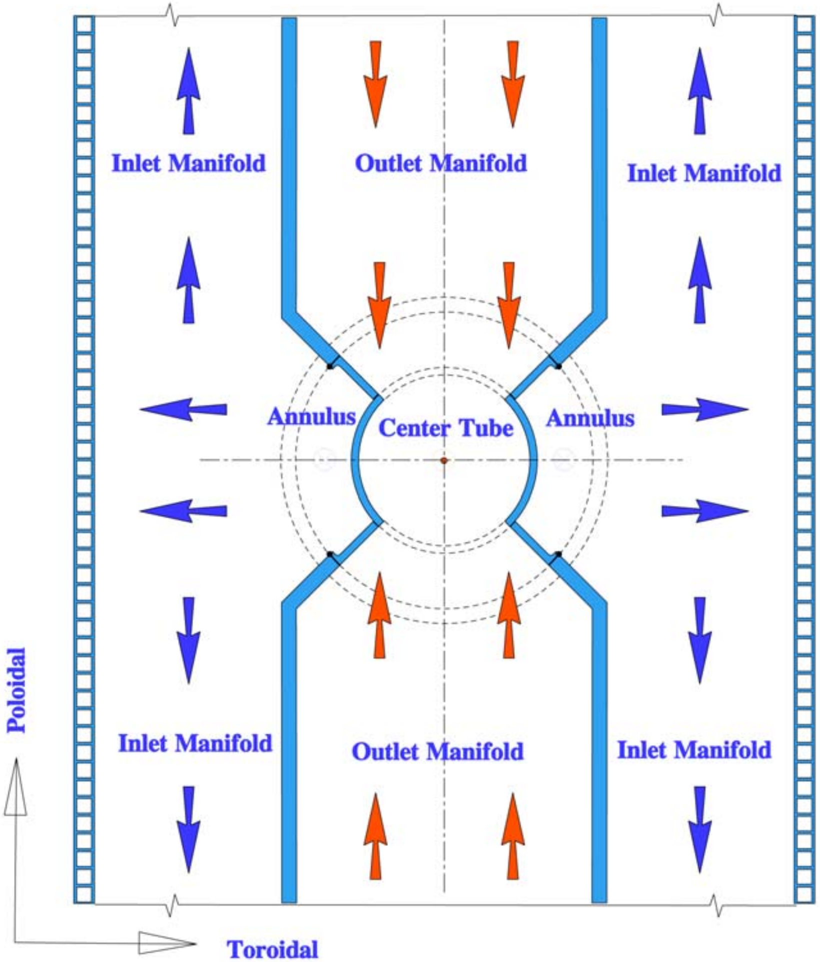


To weld the Cooling Plate(ODS steel) to the manifold(ODS steel) is a major issue because there are no methods known to get high strength welds on ODS steel.

Helium Coolant Flow Scheme in Manifolds

UC San Diego

➢The helium enters the module box from the back side, flows in poloidal manifolds arranged in the back of the module, from where is diverted into radial->toroidal->radial direction to cool side walls and first wall.

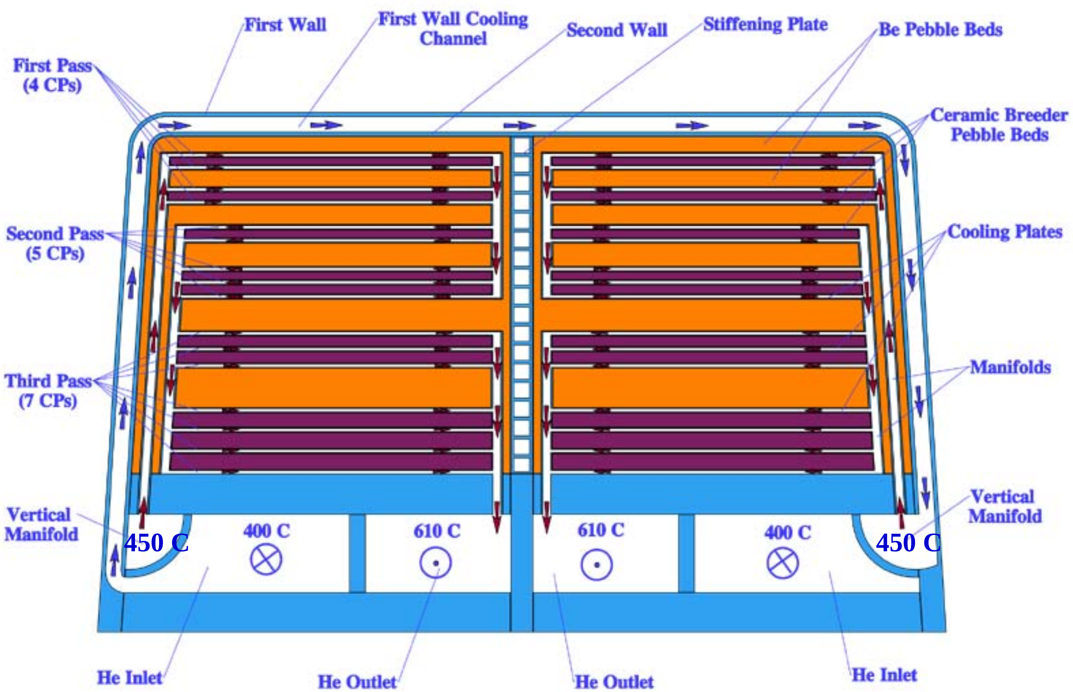


Cross-section cut through manifolds

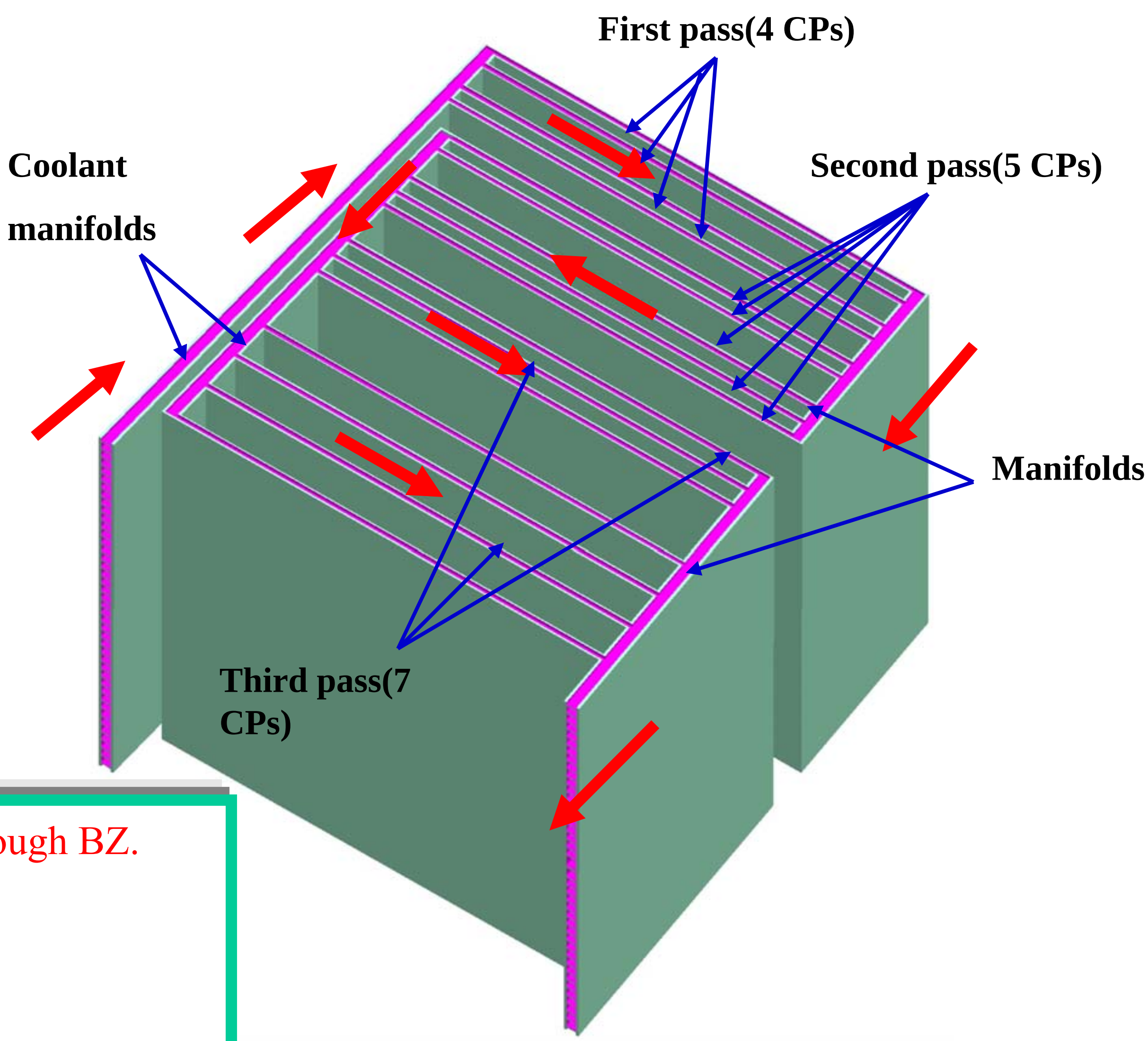
Helium Coolant Flow Scheme in FW and BZ

UC San Diego

- Blanket box and breeding region are cooled in series.
- The helium flows in the FW cooling channels in toroidal direction, alternating from one to the next channel from left to right and right to left, resulting in a symmetric temperature field.
- Temperature rise in FW pass is in the order of 50 °C.
- The helium coolant flows in the breeding zone meander-like from the front to the back, and is heated up to ~ 610 °C

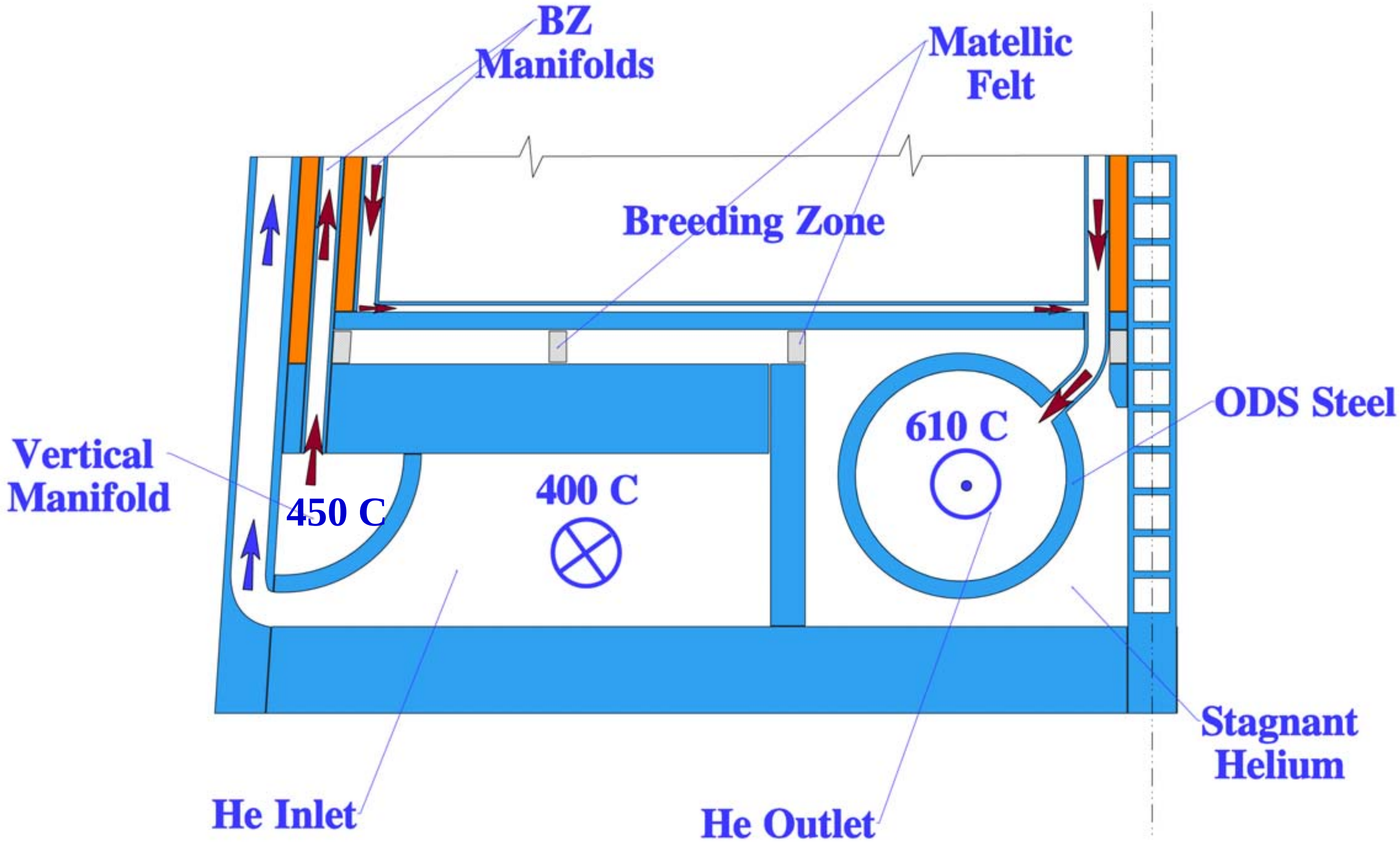


Details of the Coolant Channels in Form a Meander in the BZ



- 3 cooling passes through BZ.
- 6 Be beds.
- 10 CB beds.
- 16 cooling plates.

Possible Design of the Outlet Manifold for High Helium Temperature



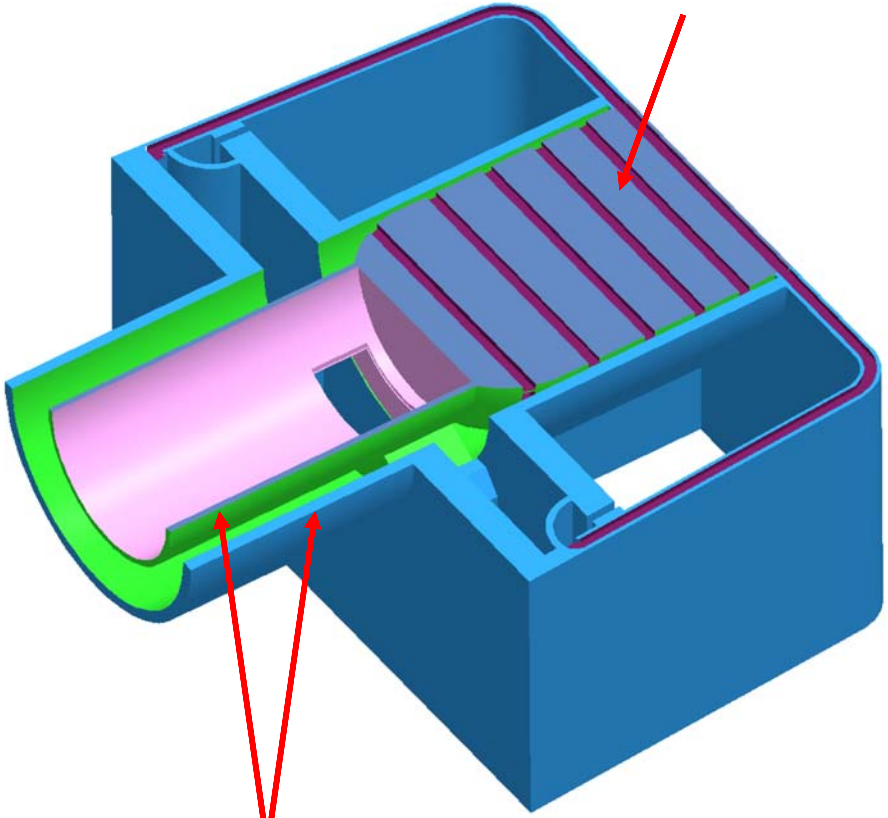
Arrangement of Coolant Access Tubes to the Blanket Module

UC San Diego

- The arrangement of one access tube in the center of the module facilitates blanket replacement, and enables a symmetric design of the module, with poloidal manifolds on both sides of the module, running from the middle to top and bottom of the module.

- The intention is to have the module installed/replaced by working from the plasma region with an articulated boom.

- The FW will have a large opening allowing to access to the concentric coolant access pipes located at the rear side of the blanket module after removing a closing/shielding plug.

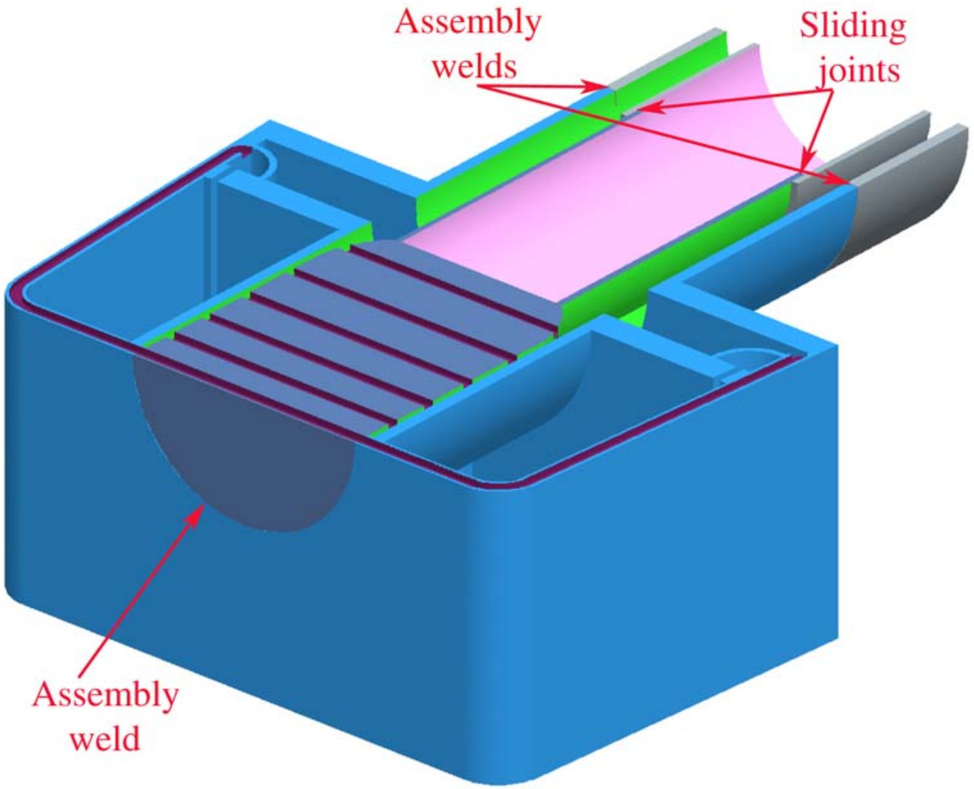


Arrangement of Sliding Seals at the Inner Tube

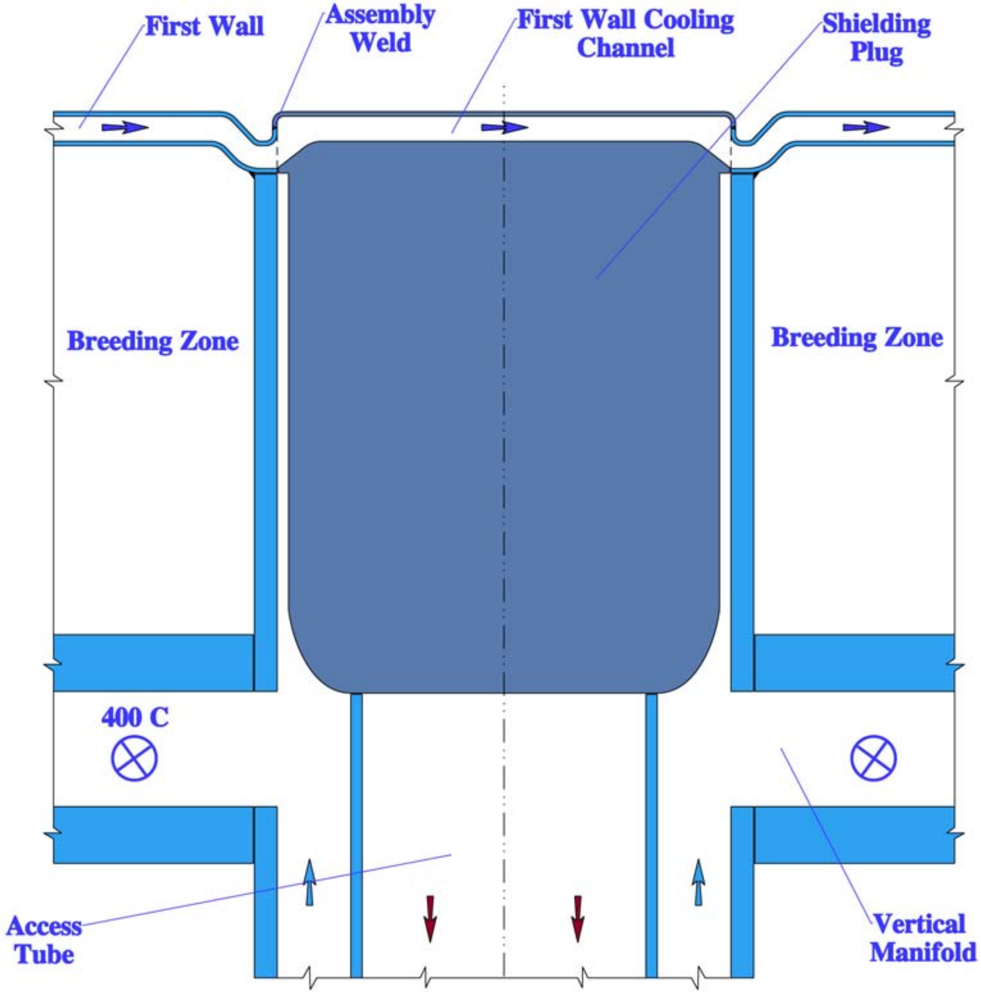
- There is a sliding seal at the inner tube separating the hot exit flow in the central tube from the “cold” inlet flow in the annulus. Therefore *only the outer tube has to be cut/re-welded for a module replacement.*

- This weld is located behind the permanent shielding zone, limiting the He-generation in the steel to a value allowing re-weldability up to the end of the plant life.

- There is a second weld to be cut/re-welded, arranged at the FW, but in this case both parts will be replaced with a blanket exchange.



How Can the Closing Disk be Reliably Welded at the FW?

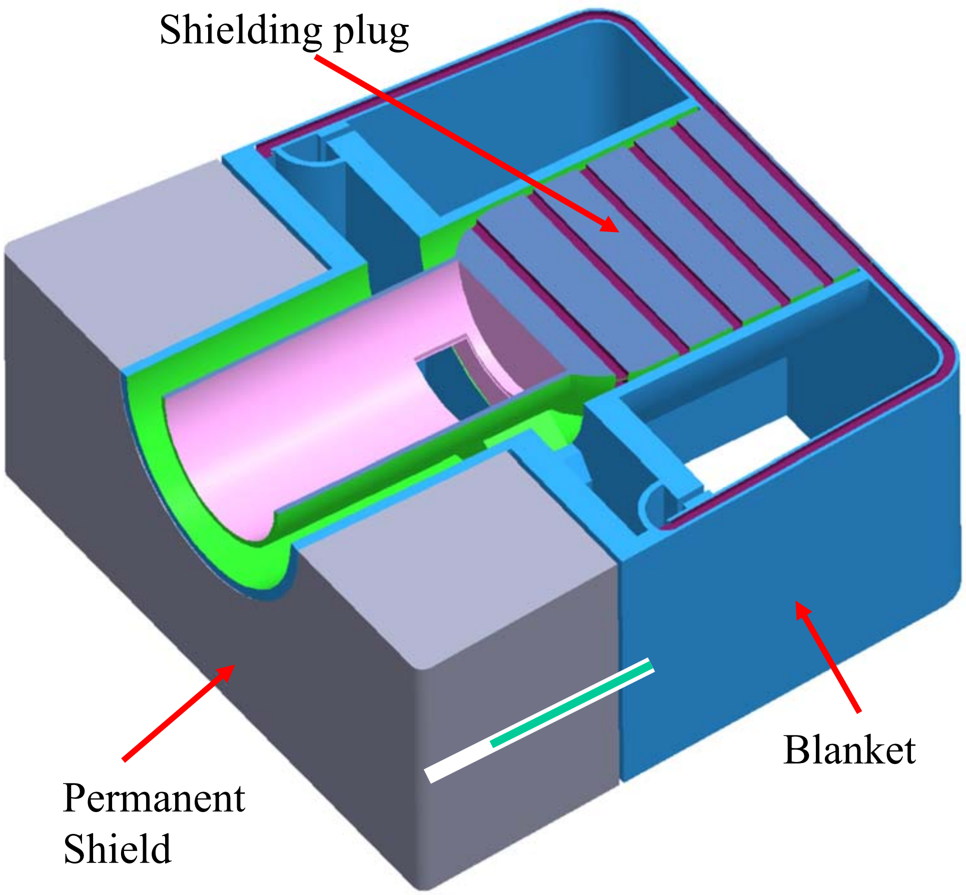


Mechanical Attachment of the Blanket Module

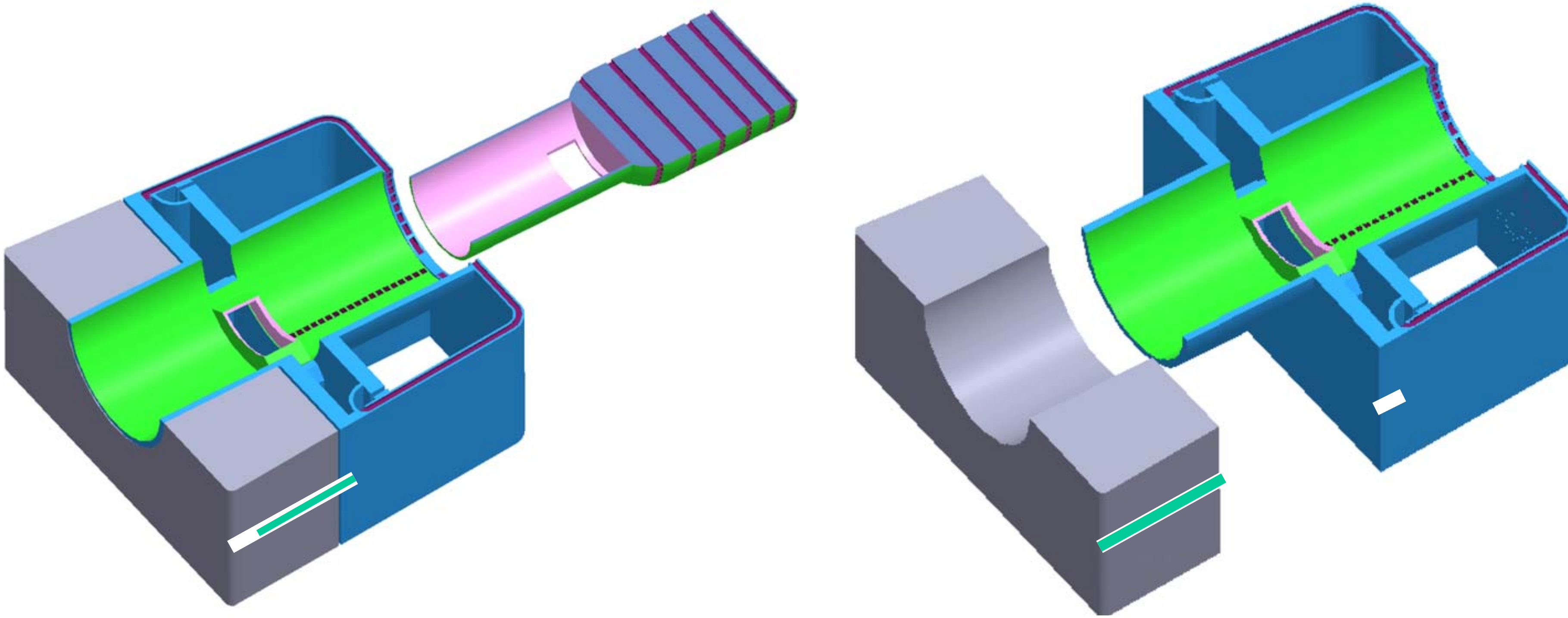
- The concentric coolant access tubes are arranged in the middle of the module, allowing free differential expansion of the module in all directions.

- The outer coolant access tube with about 400 mm diameter and a wall thickness of ~ 20 mm can serve as mechanical attachment.

- Additional mechanical attachments are required at both ends of the modules. For this purpose bolts are arranged outside the shielding zone in the gaps between neighboring modules, allowing to insert a tool for turning the nuts.



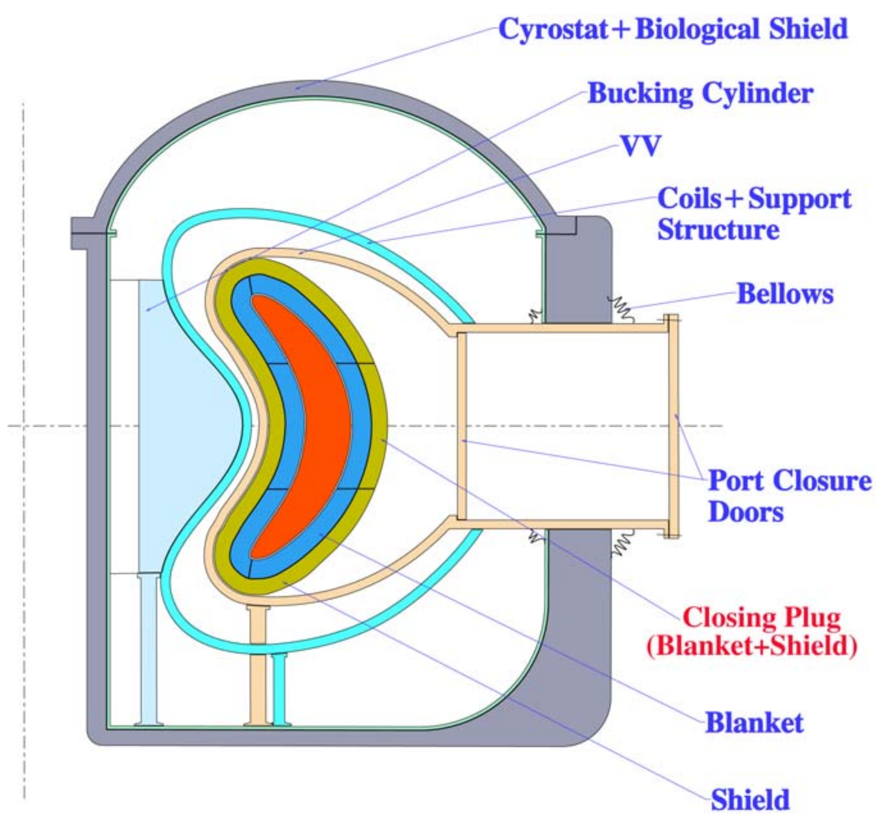
Steps of Removing the Access Tube



- Cut the assembly weld in the front disk at the FW first.
- Pull out the shielding plug with inner tube.
- Cut the outer tube weld located behind the permanent shield.
- Open/Remove the attachment bolts.
- Pull out the blanket box.

Schematic Layout of Coils System, Supporting Structure, Vacuum Vessel and Maintenance Ports

UC San Diego



The optimum locations for these ports are the 0°, 120°, and 240° cross-sections, available space ~2.5m x 10m for three field-period configuration.

	R=8.3 m (3 field-periods)	R=8 m (2 field-periods)	R=6.62 m (2 field-periods)
Port #1	2.5 x 11.0	3.9 x 10.0	3.2 x 8.2
Port #2	1.6 x 10.2	4.1 x 8.9	3.3 x 7.3
Port #3	1.2 x 5.0	4.2 x 5.3	3.5 x 4.4
Port #4	2 x 3.03	3.8 x 4.6	2.4 x 3.8
Port #5	3.5 x 3.6	4.7 x 5.0	3.9 x 4.1
Port #6	2.1 x 10.5	3.9 x 7.8	3.2 x 6.5
Port #7		3.9 x 10.0	3.2 x 8.2
Port #8		4.7 x 10.9	3.8 x 9.0

***A.R. Rene, "Maintenance Studies for 3-field Period and 2-field Period Configuration" presented at ARIES Meeting, Dec. 2003.**

Steps to be Performed for an Exchange of Ceramic Breeder Blankets

UC San Diego

@ Pull out first the Closing Plugs from access port

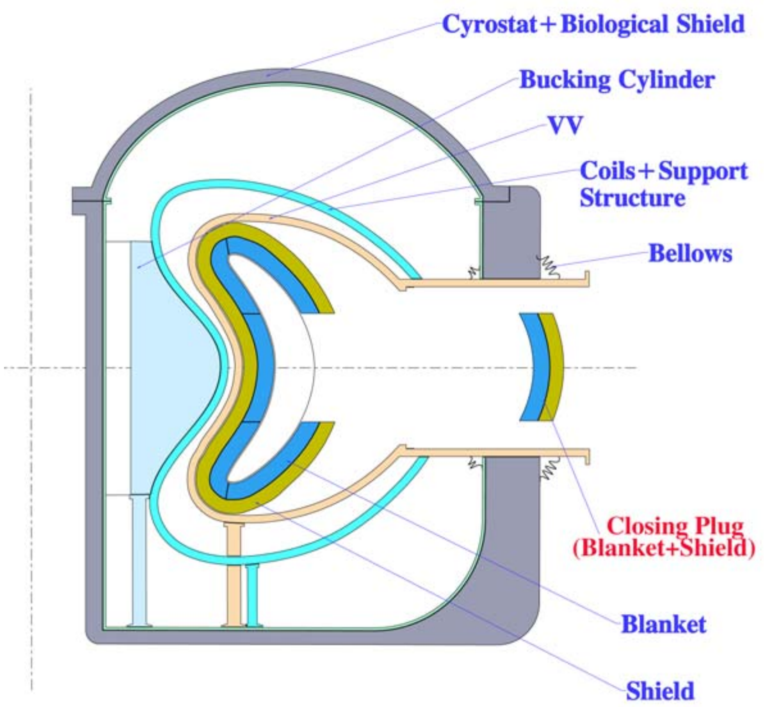
- Open and remove the first and second doors.
- Cut the coolant access tubes from back.
- Pull out the closing plug and insert the articulated boom into the plasma region.

The boom has to be equipped with two classes of tools:

> ***@ tools for opening attachment bolts, inserted from the plasma region through radial gaps between the modules.***
>
> ***@ tools for cutting/re-welding the front disk at the FW as well as the coolant access tubes at the back of blanket module.***

@ Remove other blanket modules

- There are ~17 modules to be served with the boom working from the plasma region(assuming there are ~3 rows, and 6 modules/row).
- Cut the weld in the front disk at the FW and take it out.
- Cut the weld of the coolant access tubes at the back of blanket.
- Open the attachment bolts.



Thermal Hydraulic Analysis

Material Properties and Design Constraints

Lithium Ortho-silicate Pebble Bed	
Thermal conductivity, W/m-K	1.0-1.2
Max. allowable temperature, °C	<950
Beryllium Pebble Bed	
Thermal conductivity, W/m-K	8.0
Max. allowable temperature, °C	<750
ODS -Steel	
Thermal conductivity, W/m-k	33.0
Max. allowable temperature, °C	<700
Ratio of the Pumping Power to Thermal Power	<5%

Initial Thermal Hydraulic Parameters

Blanket module(toroidal x radial x poloidal), m^3	1 x 0.65 x 4
Maximum neutron wall loading, MW/m^2	4.5
Blanket energy multiplication factor	1.3
FW surface heat flux, MW/m^2	0.5
Total thermal power of one blanket module, MW	25.4
Coolant inlet pressure, MPa	8
Coolant inlet temperature, °C	400
Coolant outlet temperature, °C	610
Total flow rate of one blanket module, m^3/s	4.65
<u>Geometry:</u>	
FW cooling channel(radial x poloidal), mm^2	20 x 20
FW front and back thickness, mm	4
Cooling channel in breeding zone(radial x poloidal), mm^2	4 x 4
Cooling channel front and back thickness, mm	1
Coolant manifolds in breeding zone(radial x poloidal) mm^2	15 x 15

Initial Thermal Hydraulic Results

	Parameter based on original radial build
Tin, °C	400
Tout, °C	610
Max. FW Temp, °C	652
Max. Be bed Temp, °C	747
Max. Ceramic bed Temp, °C	939
Max. CP's Temp, °C	631
$\Delta P/P_{th}$	3.35%

***Optimization of thermal hydraulics parameters coupled with Brayton cycle to be presented by R. Raffray**

Pressure Stress Analysis

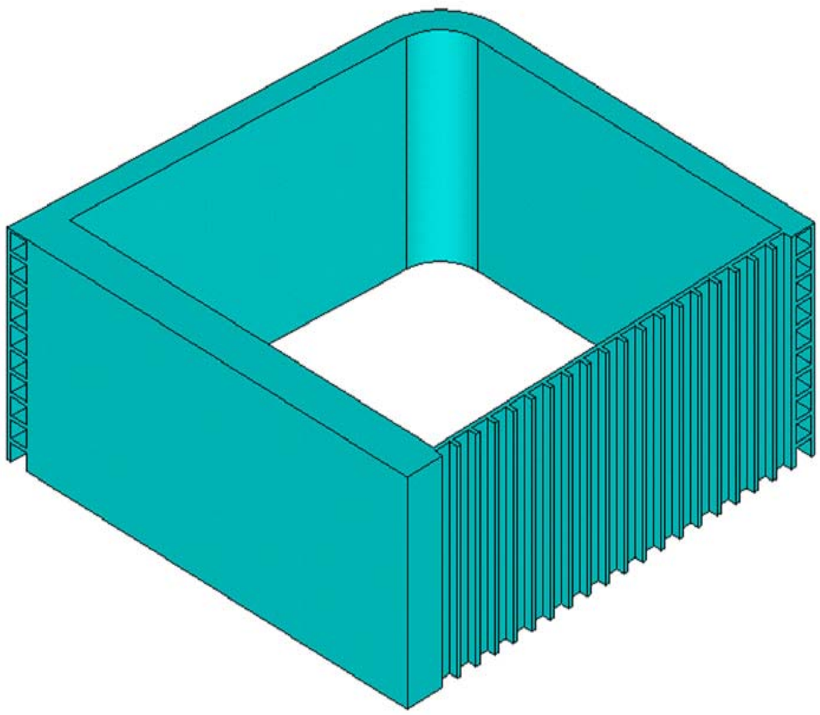
UC San Diego

- Only a half corner blanket box including stiffening plate was simulated using the finite element code ANSYS.
- The stress analysis is limited to the accident scenario (LOCA) that the pressure is less than 1 MPa.
- The average primary membrane stress (P_m) is limited to

$$P_m \ll S_m$$

- The allowable design stress intensity (S_m) at the FW-averaged temperature of 615 °C is

$$S_m < 115 \text{ MPa (F82H)}$$

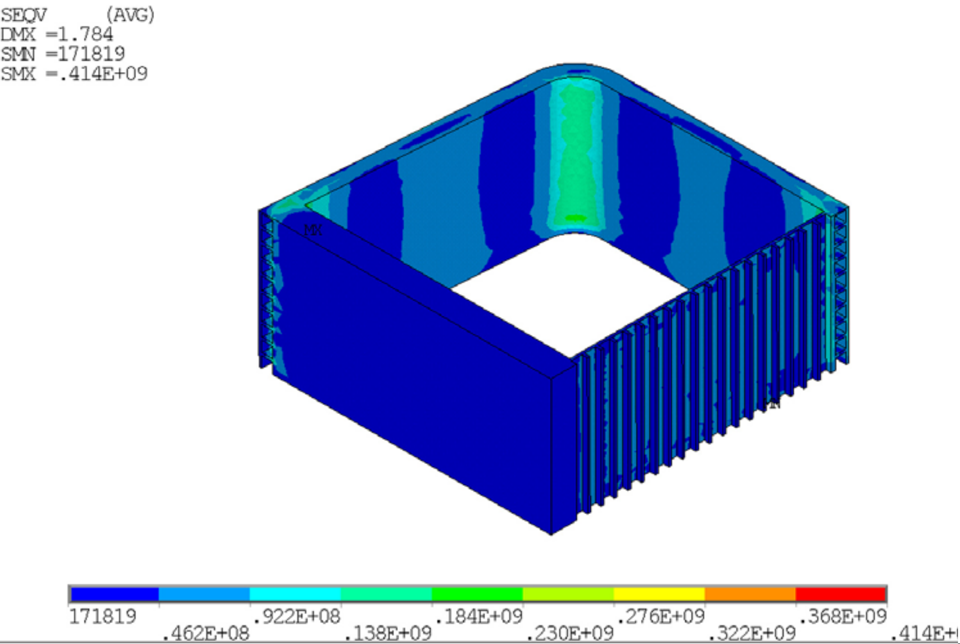


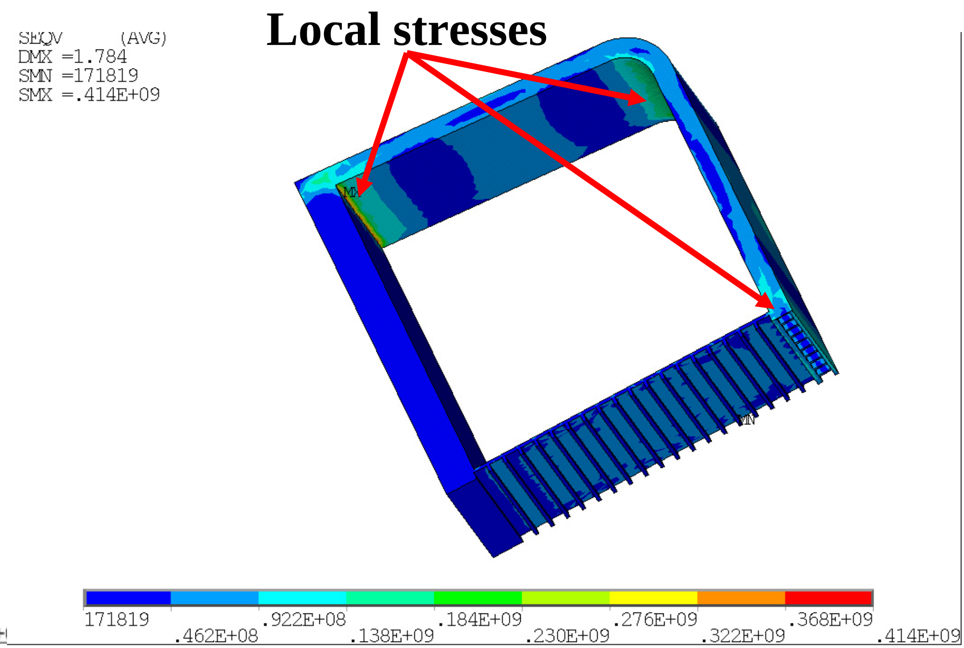
Geometry for FEA Modeling

***S.J. Zinkle, et. all, "Thermophysical and Mechanical Properties for Fe-(8-9)%Cr Reduced Activation Steels"**

http://aries.ucsd.edu/LIB/PROPS/FS/FS.html

Primary Membrane Stress Intensity Under 1 MPa Pressure of LOCA





- Maximum stresses locate in three channel corners.
- The local stresses can be got rid of by design.
- Higher stresses can be allowed under accidental conditions than at operational conditions.
- Allowable bending stresses are 50 % higher than membrane stresses.

Summary

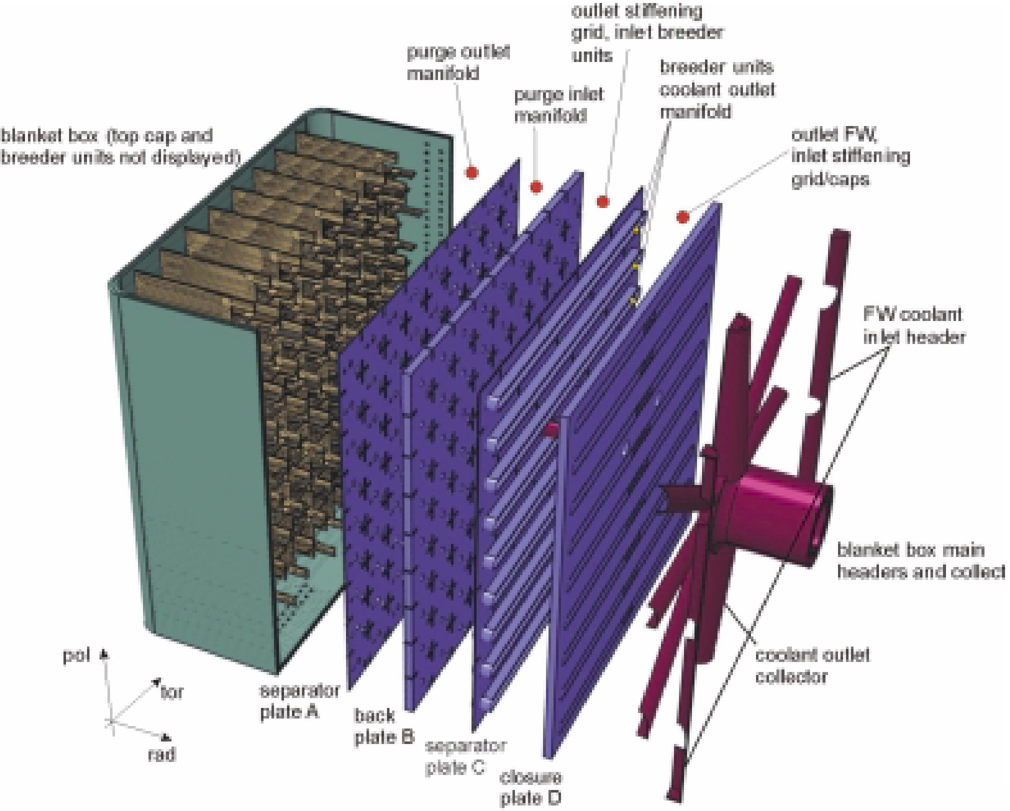
UC San Diego

- **Low-pressure requirement on module leads to a simpler blanket box design with meandering coolant channels.**
- **Modular blanket design would be suited for compact stellarator application**

  -module geometry may accommodate the irregular first wall geometry.

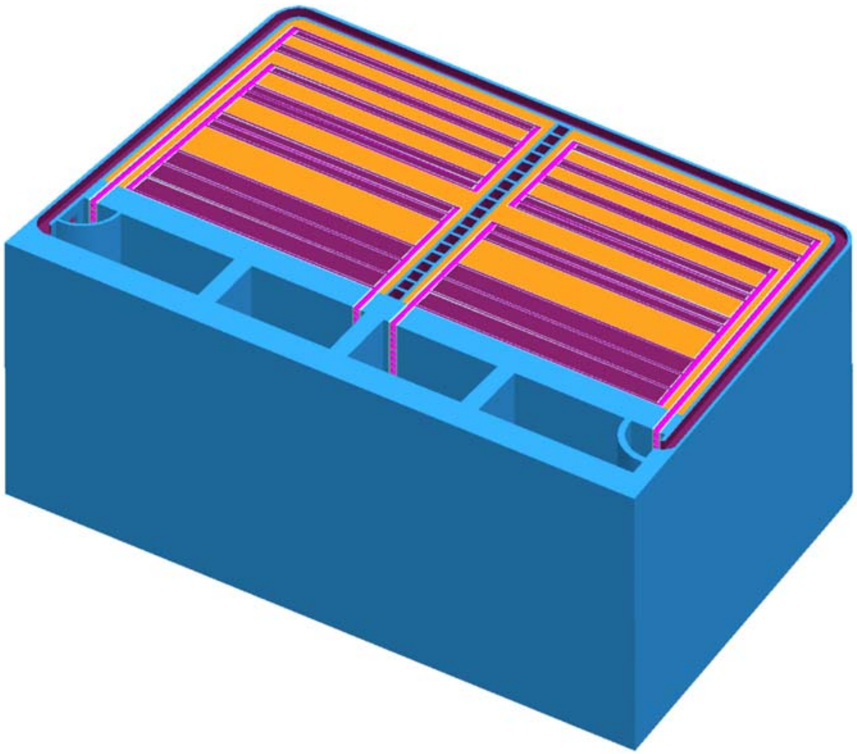
  -module size can differ from different port location to accommodate port size.
- **The initial thermal hydraulic results indicate that the ratio of the pumping power to thermal power is ~3.35%, and the maximum temperature of the FW, Be pebble beds and ceramic breeder pebble beds are under design limits. (not optimised)**
- **Optimization of thermal hydraulics parameters coupled with Brayton cycle will be presented by R. Raffray**

Extra Viewgraph



Blanket box with stiffening grid and exploded back wall

EU HCPB Concept



ARIES He-cooled Ceramic Breeder Blanket