

CERAMIC BREEDER BLANKET FOR ARIES-CS

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Outline

- **Summary of ARIES-CS engineering plan of action**
- **Ceramic breeder modular design layout**
- **Power cycle selection: Brayton cycle**
- **Optimization studies**
- **Conclusions**



Engineering Activities During Phase I of ARIES-CS Study

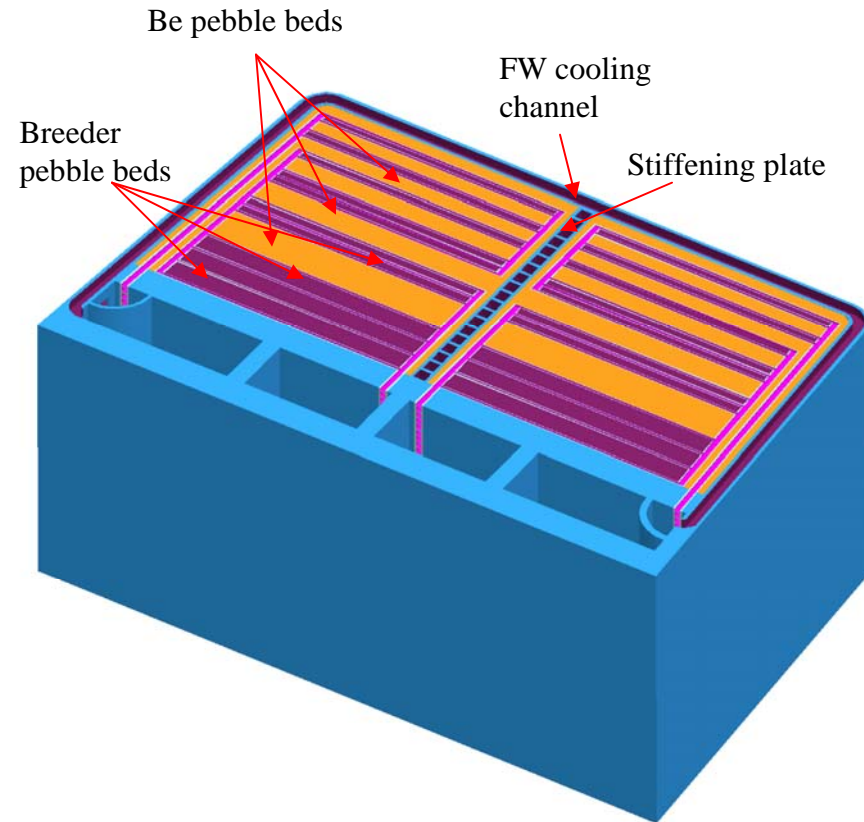
- **Perform Scoping Assessment of Different Maintenance Schemes and Blanket Concepts for Down Selection to a Couple of Combinations for Detailed Studies During Phase II**
 - **Three Possible Maintenance Schemes:**
 1. **Field-period based replacement including disassembly of modular coil system (e.g. SPPS, ASRA-6C)**
 2. **Replacement of blanket modules through small number of designated maintenance ports (using articulated boom)**
 3. **Replacement of blanket modules through maintenance ports arranged between each pair of adjacent modular coils (e.g. HSR)**
 - **Different Blanket Configurations**
 1. **Self-cooled flibe blanket with advanced ferritic steel**
 2. **Self-cooled Pb-17Li blanket with SiC_f/SiC composite as structural material**
 3. **Dual-Coolant blanket concept with He-cooled steel structure and self-cooled liquid metal (Li or Pb-17Li)**
 4. **Helium cooled ceramic breeder blanket with ferritic steel structure**



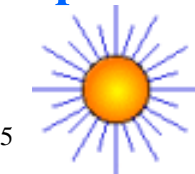
Considerations on Choice of Module Design and Power Cycle for a Ceramic Breeder Concept

- The blanket module design pressure impacts the amount of structure required, and, thus, the module weight & size, the design complexity and the TBR.
- For a He-cooled CB blanket, the high-pressure He will be routed through tubes in the module designed to accommodate the coolant pressure. The module itself under normal operation will only need to accommodate the low purge gas pressure (~ 1-10 bar).
- The key question is whether there are accident scenarios that would require the module to accommodate higher loads. If coupled to a Rankine Cycle, the answer is yes (EU study):
 - Failure of blanket cooling tube + subsequent failure of steam generator tube can lead to Be/steam interaction and safety-impacting consequences.
 - Not clear whether it is a design basis ($<10^{-6}$) or beyond design basis accident (passive means ok).
- To avoid this and provide possibility of simpler module and better breeding, we investigated the possibility of coupling the blanket to a Brayton Cycle.

Low-Pressure Requirement on Module Leads to “Simpler” Design

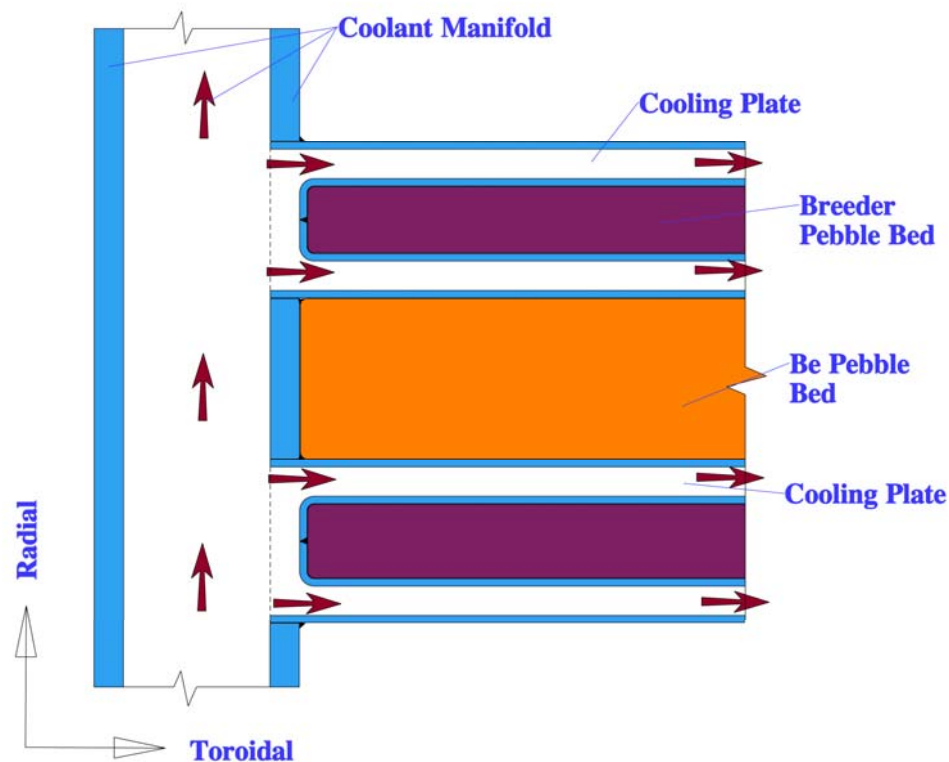


- **Modular box design with coolant flowing through the FW and then through the blanket**
 - 4 m (poloidally) x 1 m (toroidally) module
 - Be and CB packed bed regions aligned parallel to FW
 - Li_4SiO_4 or Li_2TiO_3 as possible CB
- **In general modular design well suited for CS application**
 - accommodation of irregular first wall geometry
 - module size can differ for different port location to accommodate port size



Arrangement of the Breeder and Beryllium Pebble Beds

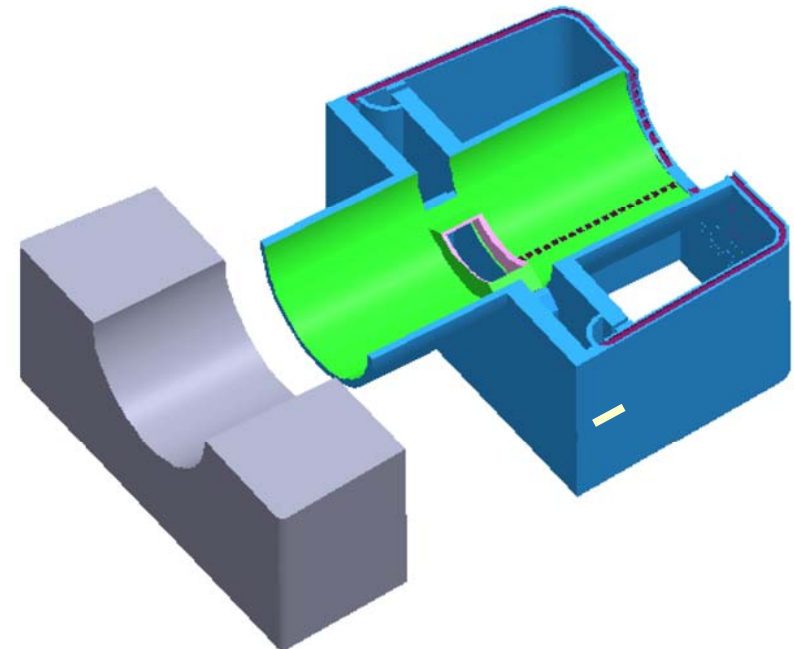
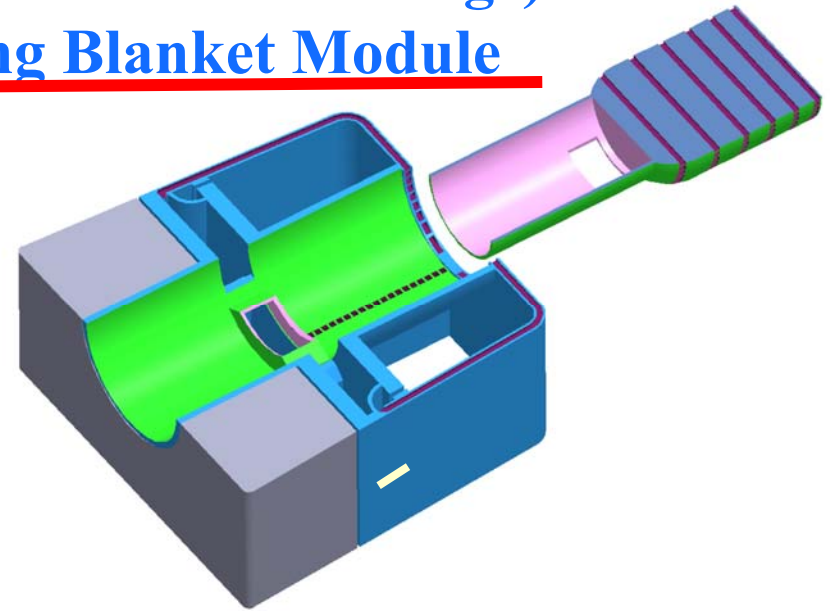
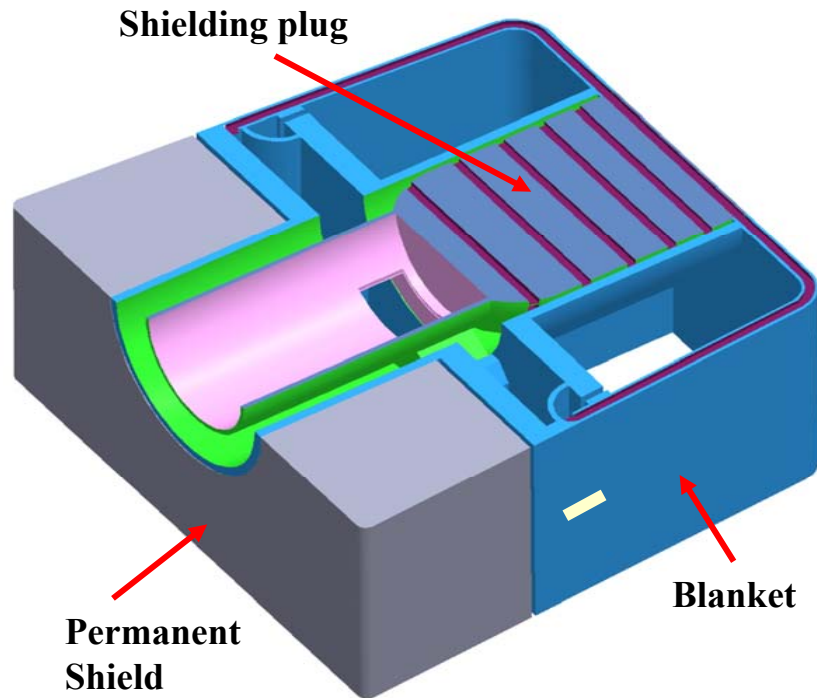
- Inside the breeding zone, each breeder bed is enclosed by two cooling plates.
- This assembly is filled outside the blanket box with ceramic pebbles, and closed.
- All the cooling plates are welded to larger manifold plates before inserting the breeding zone into the blanket box.
- Beryllium pebbles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



- Use of ODS FS in high temperature location would allow for higher temperature and cycle efficiency.
- Joining is a key issue because of difficulty of producing high strength welds with ODS FS.



Access Tube + Shielding Plug (~3% fractional coverage) for Cutting Tube Prior to Removing Blanket Module



- 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 module.

Steps to be Performed for an Exchange of Ceramic Breeder Blankets*

Pull out first the Closing Plugs from access port

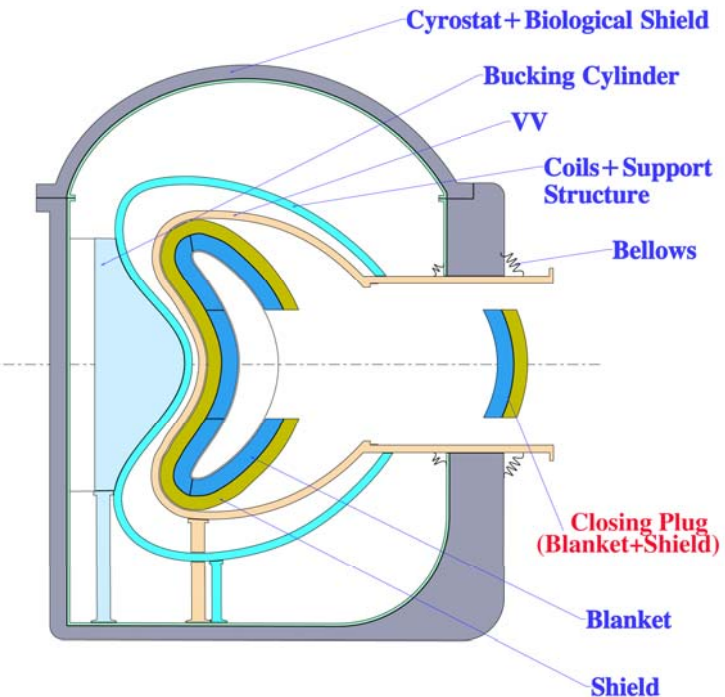
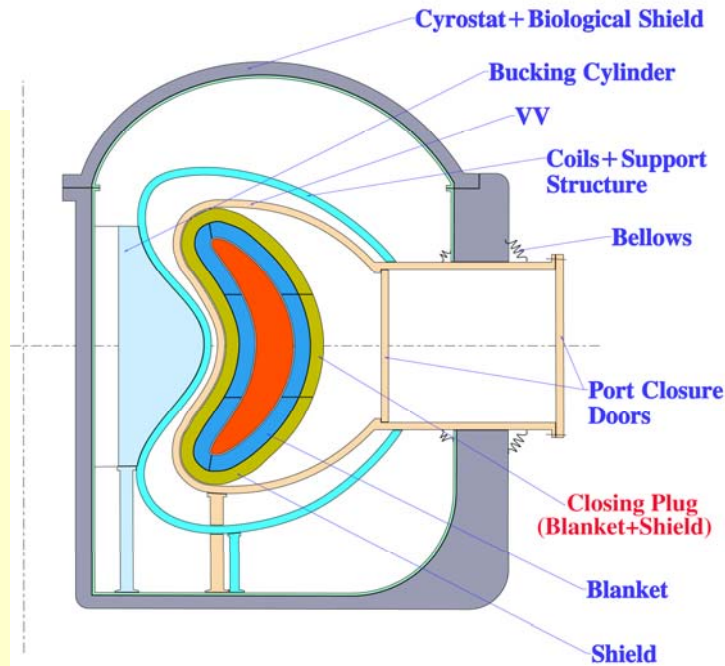
- Open and remove the first and second doors.
- Cut the coolant access tubes from back.
- Pull out the closing plug and insert the articulated boom into the plasma region.

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

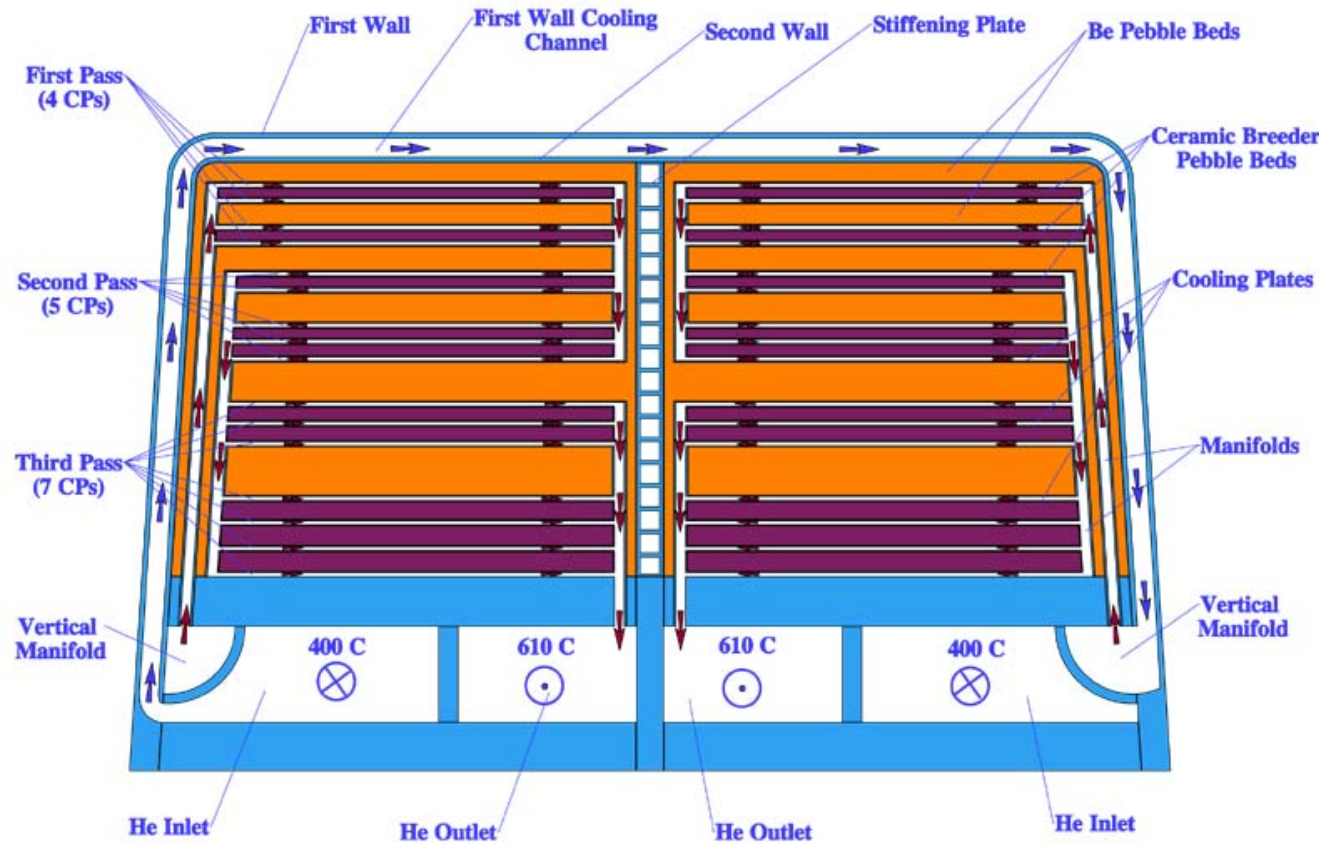
- Cut the weld in the front disk at the module FW and remove module shielding plug.
- Cut the weld of the coolant access tubes at the back of blanket.
- Remove the attachment bolts.



* See X.R. WANG, S. MALANG, A.R. RAFFRAY and the ARIES Team, "Maintenance Approaches for ARIES-CS Power Core," 16th TOFE

Ceramic Breeder Blanket Module Configuration

- He flows through the FW cooling tubes in alternating direction and then through 3-passes in the blanket



- Number and thicknesses of Be and CB regions optimized for tritium breeding ($TBR \geq 1.1$) and high cycle efficiency for given wall load based on:

- $T_{\max, \text{Be}} < 750^\circ\text{C}$
- $T_{\max, \text{CB}} < 950^\circ\text{C}$
- $T_{\max, \text{FS}} < 550^\circ\text{C}$
($< 700^\circ\text{C}$ for ODS)
- $k_{\text{Be}} = 8 \text{ W/m-K}$
- $k_{\text{CB}} = 1.2 \text{ W/m-K}$
- $\delta_{\text{CB region}} > 0.8 \text{ cm}$

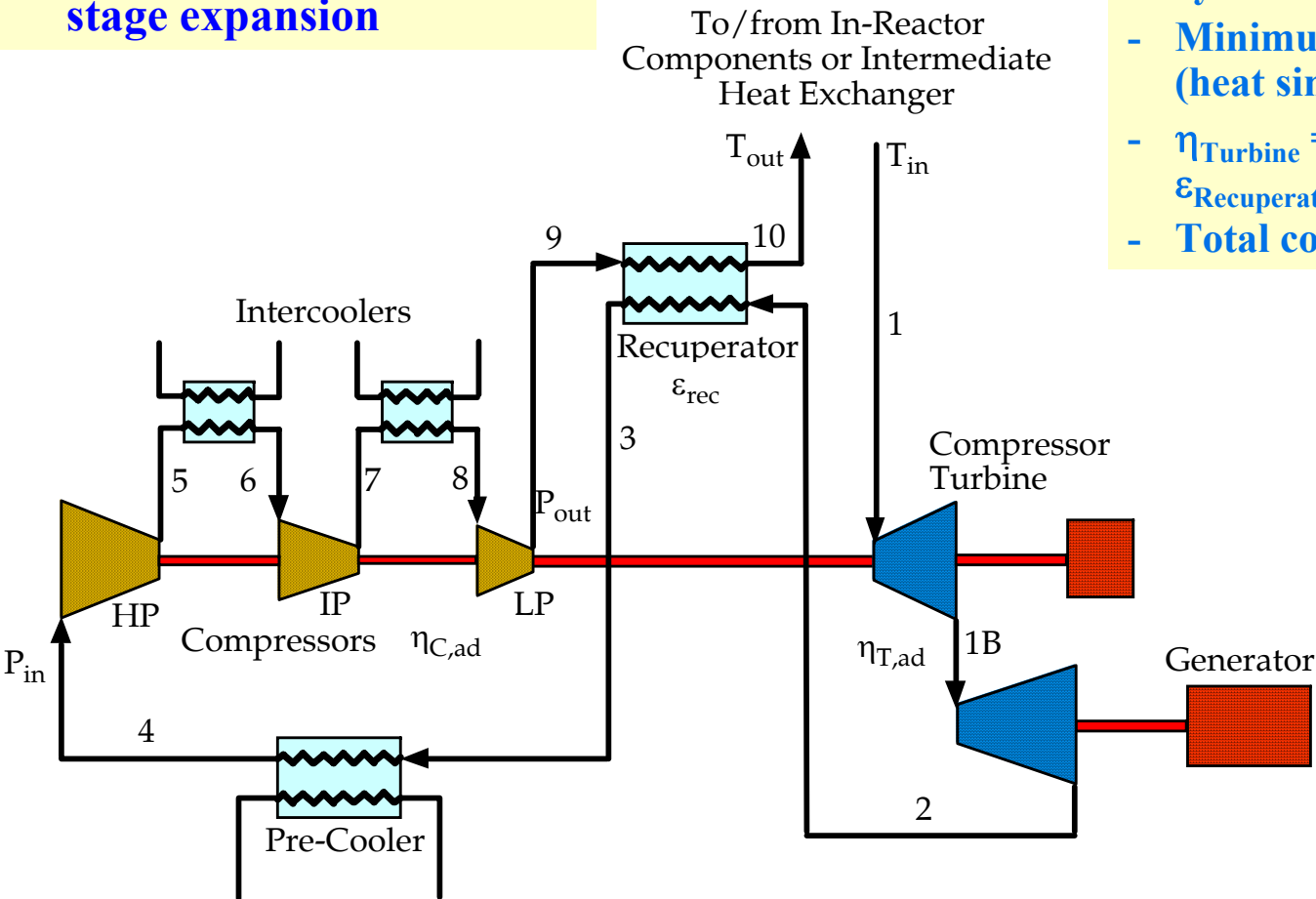
- 6 Be regions + 10 CB regions for a total module radial thickness of 0.65 m*

* See L. EL-GUEBALY, et al., and the ARIES Team, "Benefits of Radial Build Minimization and Requirements imposed on ARIES Compact Stellarator Design," 16th TOFE

Two Example Brayton Cycle Configurations Considered

Brayton I:

- A more conventional configuration with 3-stage compression + 2 inter-coolers and a single stage expansion



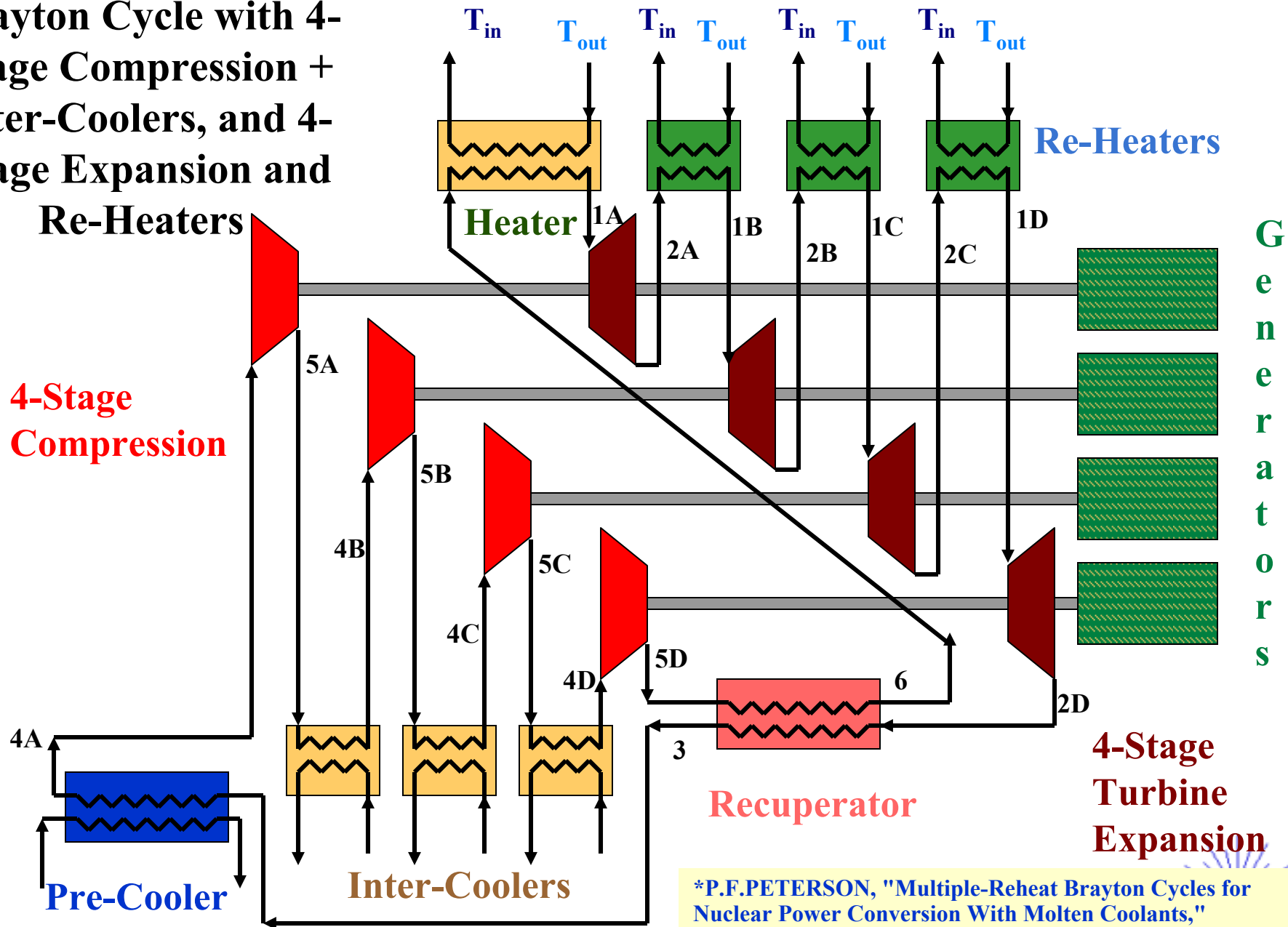
- Blanket outlet He is mixed with divertor outlet He (assumed at $\sim 750^\circ\text{C}$ and carrying $\sim 15\%$ of total thermal power) and then flown through HX to transfer power to the cycle He with $\Delta T_{HX} = 30^\circ\text{C}$
- Minimum He temperature in cycle (heat sink) = 35°C
- $\eta_{Turbine} = 0.93$; $\eta_{Compressor} = 0.89$; $\epsilon_{Recuperator} = 0.95$
- Total compression ratio < 2.87



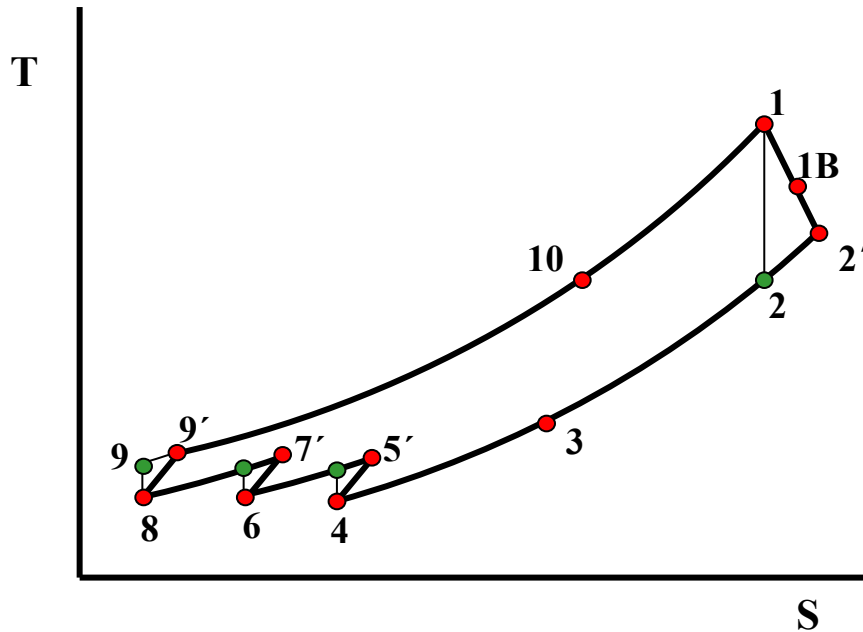
Brayton II*

Brayton Cycle with 4-Stage Compression + Inter-Coolers, and 4-Stage Expansion and Re-Heaters

He Blanket Coolant

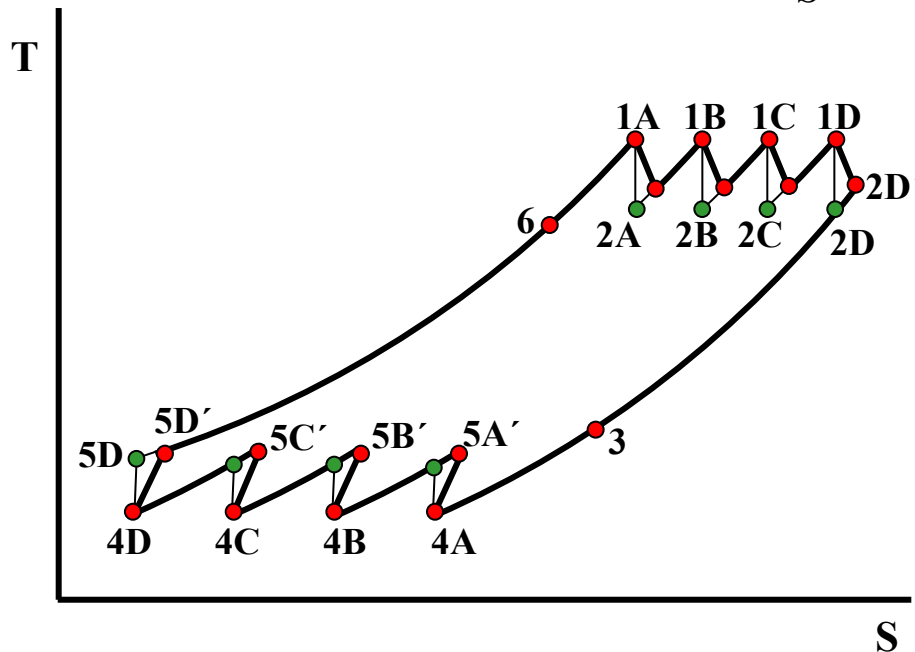


Comparison of T-S Diagrams of Brayton I and Brayton II



Brayton I:

- 3-stage compression + 2 inter-coolers and a single stage expansion



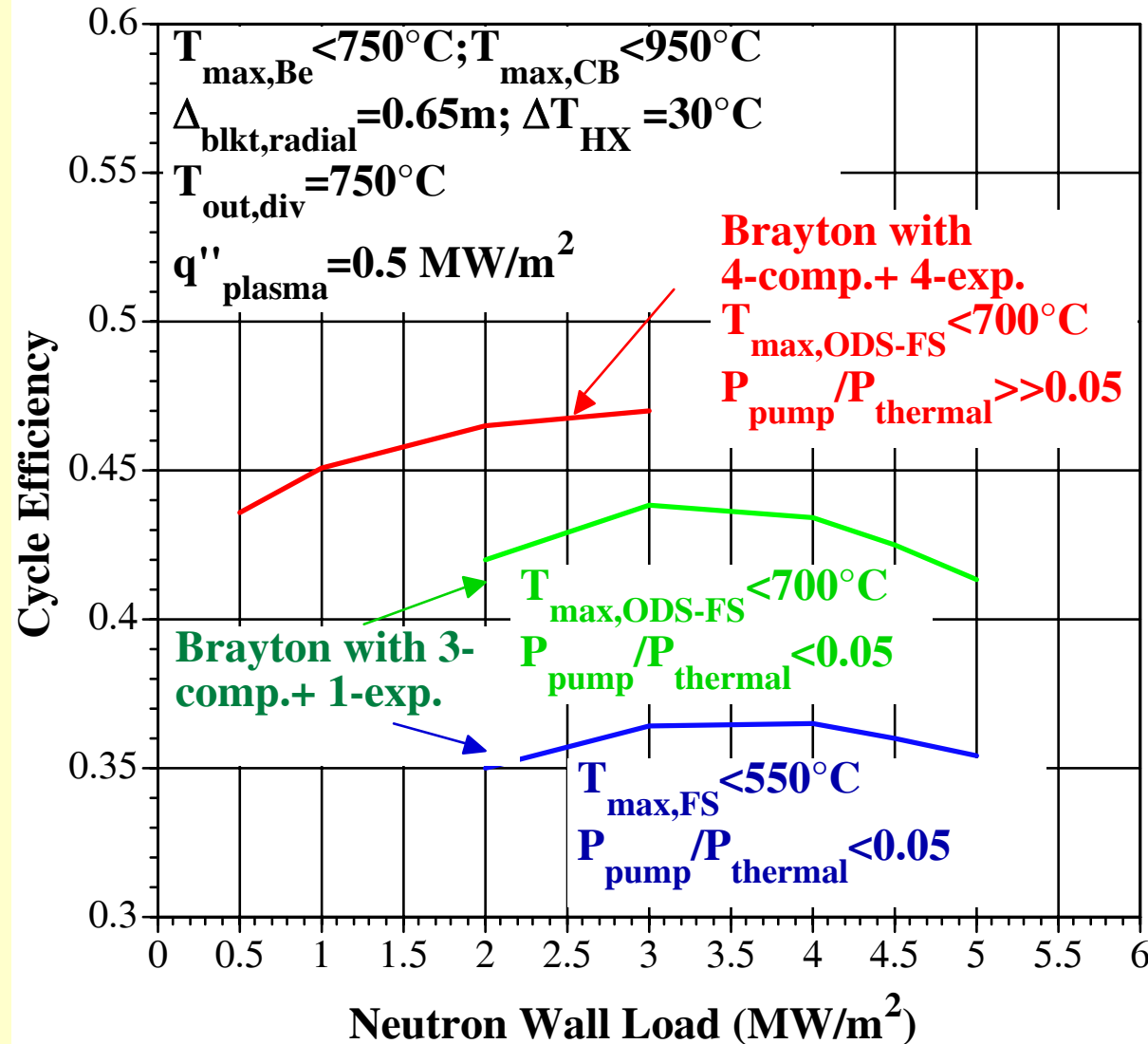
Brayton II:

- 4-stage compression + 3 inter-coolers and 4-stage expansion + 3 re-heaters
- More severe constraint on temperature rise of blanket coolant



Example Optimization Study of CB Blanket and Brayton Cycle

- Cycle Efficiency (η) as a function of neutron wall load (Γ) under given constraints
- For a fixed blanket thickness ($\Delta_{\text{blkt,radial}}$) of 0.65 m (required for breeding), a maximum Γ of 5 MW/m² can be accommodated with:
 - $T_{\text{max,FS}} < 550^\circ\text{C}$; $\eta \sim 35\%$
 - $T_{\text{max,FS}} < 700^\circ\text{C}$; $\eta \sim 42\%$
- The max. η corresponds to $\Gamma \sim 3$ MW/m²:
 - $T_{\text{max,FS}} < 550^\circ\text{C}$; $\eta \sim 36.5\%$
 - $T_{\text{max,FS}} < 700^\circ\text{C}$; $\eta \sim 44\%$
- The max. $\eta \sim 47\%$ for $\Gamma \sim 3$ MW/m² for Brayton II.
- However, as will be shown, $P_{\text{pump}}/P_{\text{thermal}}$ is unacceptably high in this Brayton II case.

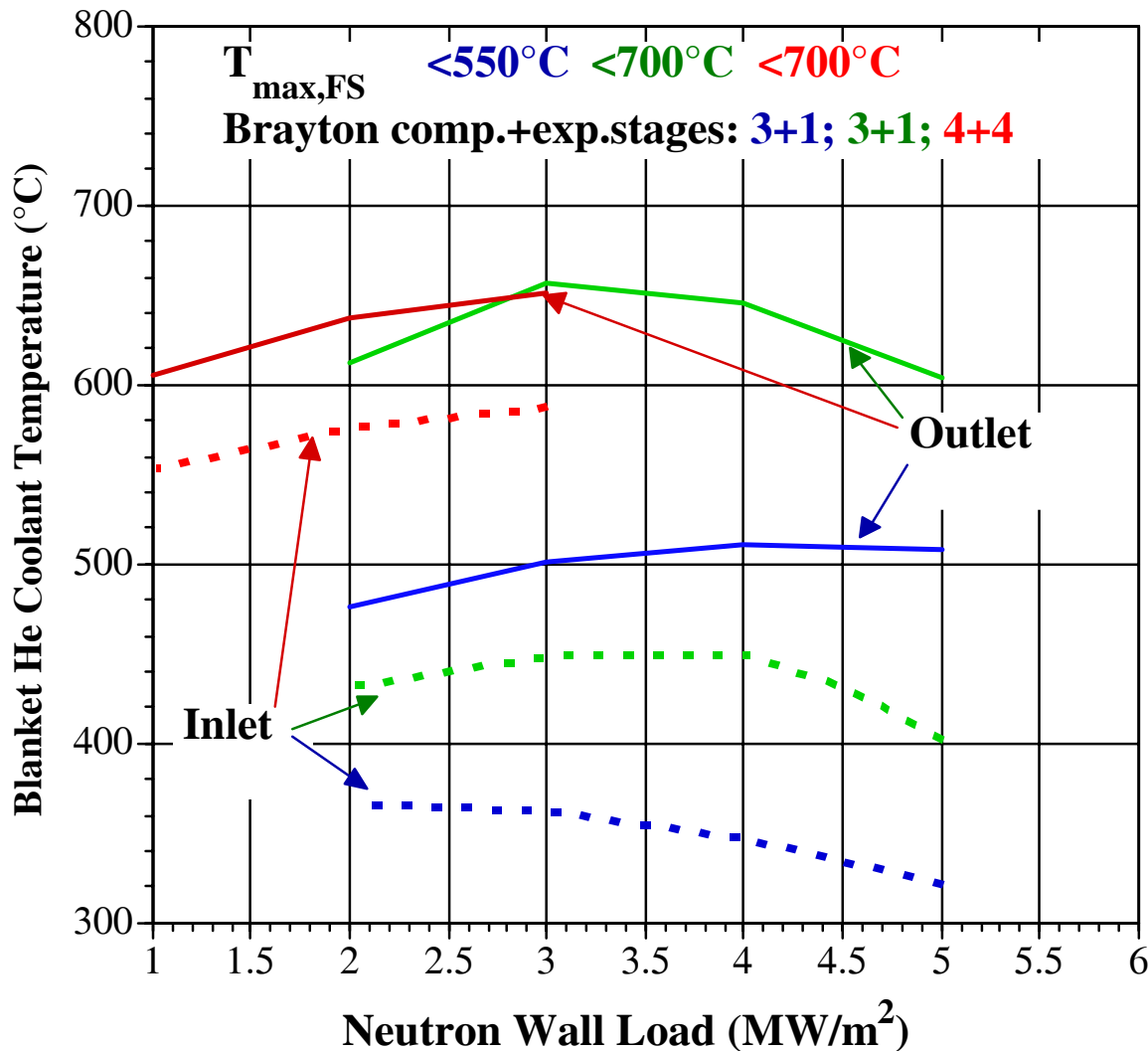


Corresponding He Coolant Inlet and Outlet Temperatures

$$T_{\max, \text{Be}} < 750^{\circ}\text{C}; T_{\max, \text{CB}} < 950^{\circ}\text{C}; \Delta T_{\text{HX}} = 30^{\circ}\text{C}$$

$$P_{\text{pump}}/P_{\text{thermal}} < 0.05; q''_{\text{plasma}} = 0.5 \text{ MW/m}^2; \Delta_{\text{blkt, radial}} = 0.65\text{m}$$

$T_{\max, \text{FS}} < 550^{\circ}\text{C}$ $< 700^{\circ}\text{C}$ $< 700^{\circ}\text{C}$
 Brayton comp.+exp.stages: 3+1; 3+1; 4+4



- Difference in blanket He inlet and outlet temperatures much smaller for Brayton II because of reheat HX constraint

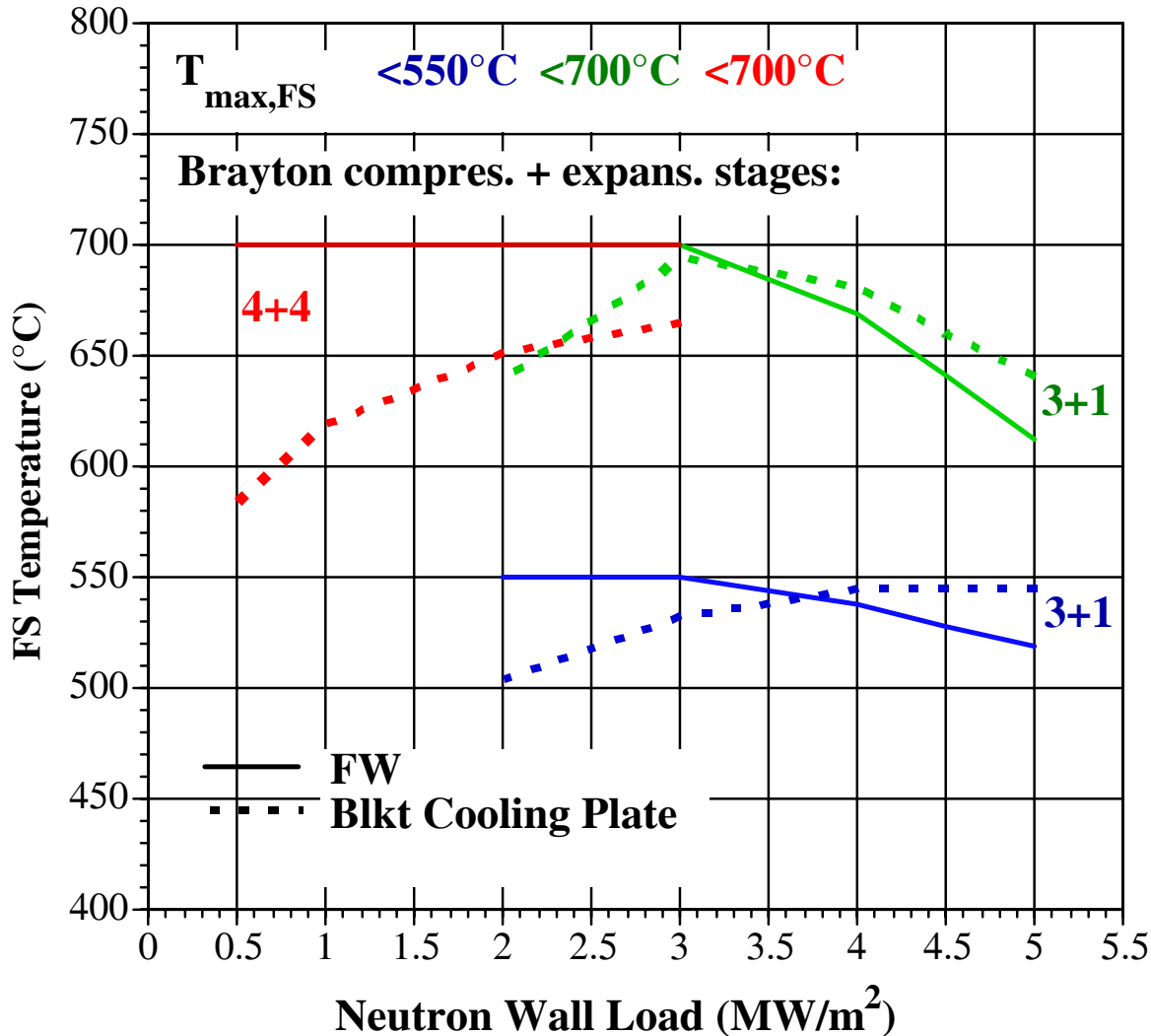
- Major constraint on accommodating temperature and pressure drop limits



Corresponding Maximum FS Temperature

$$T_{\max, \text{Be}} < 750^\circ\text{C}; T_{\max, \text{CB}} < 950^\circ\text{C}; \Delta T_{\text{HX}} = 30^\circ\text{C}$$

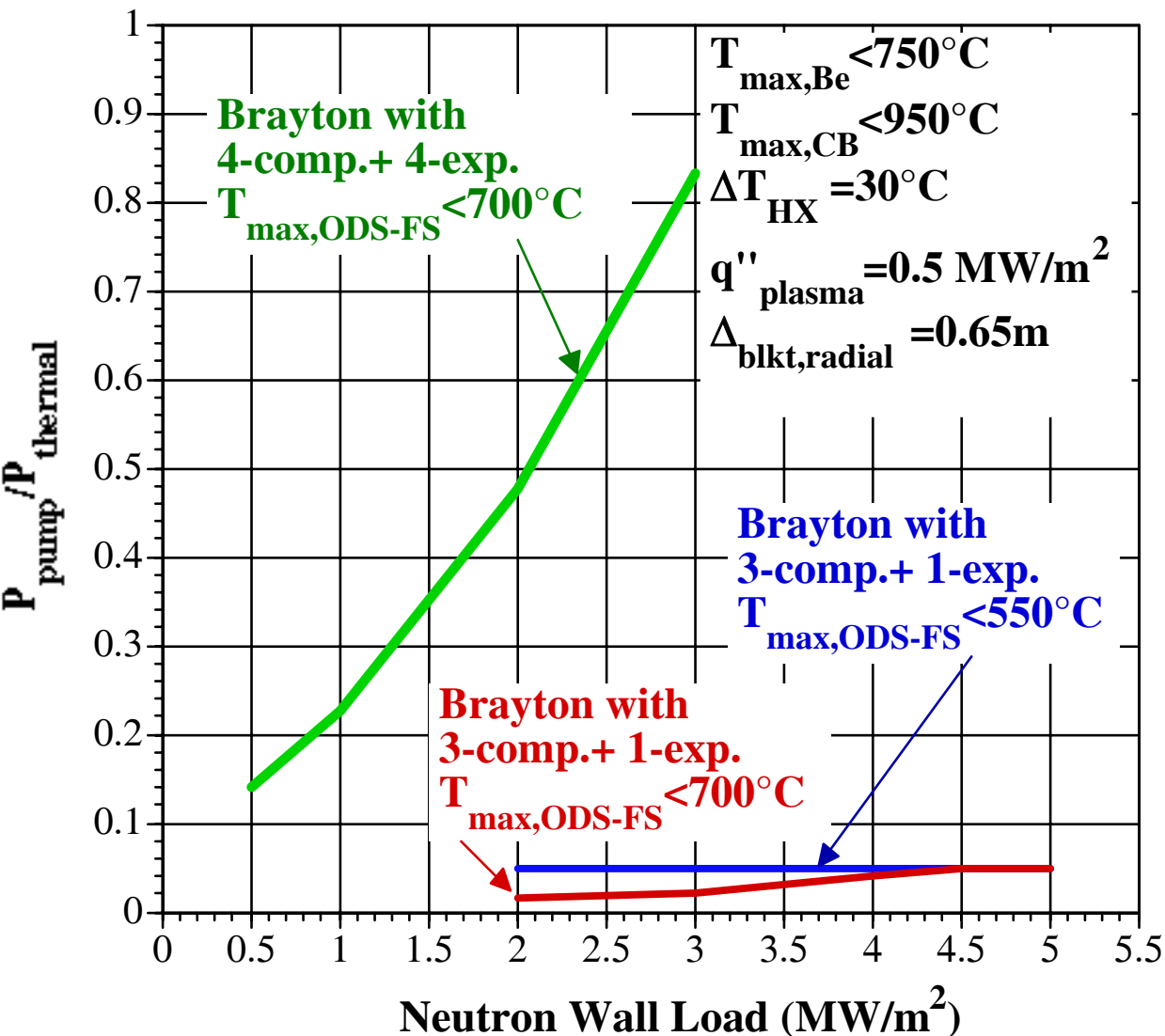
$$P_{\text{pump}}/P_{\text{thermal}} < 0.05; q''_{\text{plasma}} = 0.5 \text{ MW/m}^2; \Delta_{\text{blkt, radial}} = 0.65\text{m}$$



- For lower Γ ($< \sim 3 \text{ MW/m}^2$), $T_{\max, \text{FS}}$ limits the combination of blanket outlet and inlet He coolant temperatures
- For higher Γ ($> \sim 3 \text{ MW/m}^2$), $T_{\max, \text{CB}}$ and $T_{\max, \text{Be}}$ limit the combination of blanket outlet and inlet He coolant temperatures



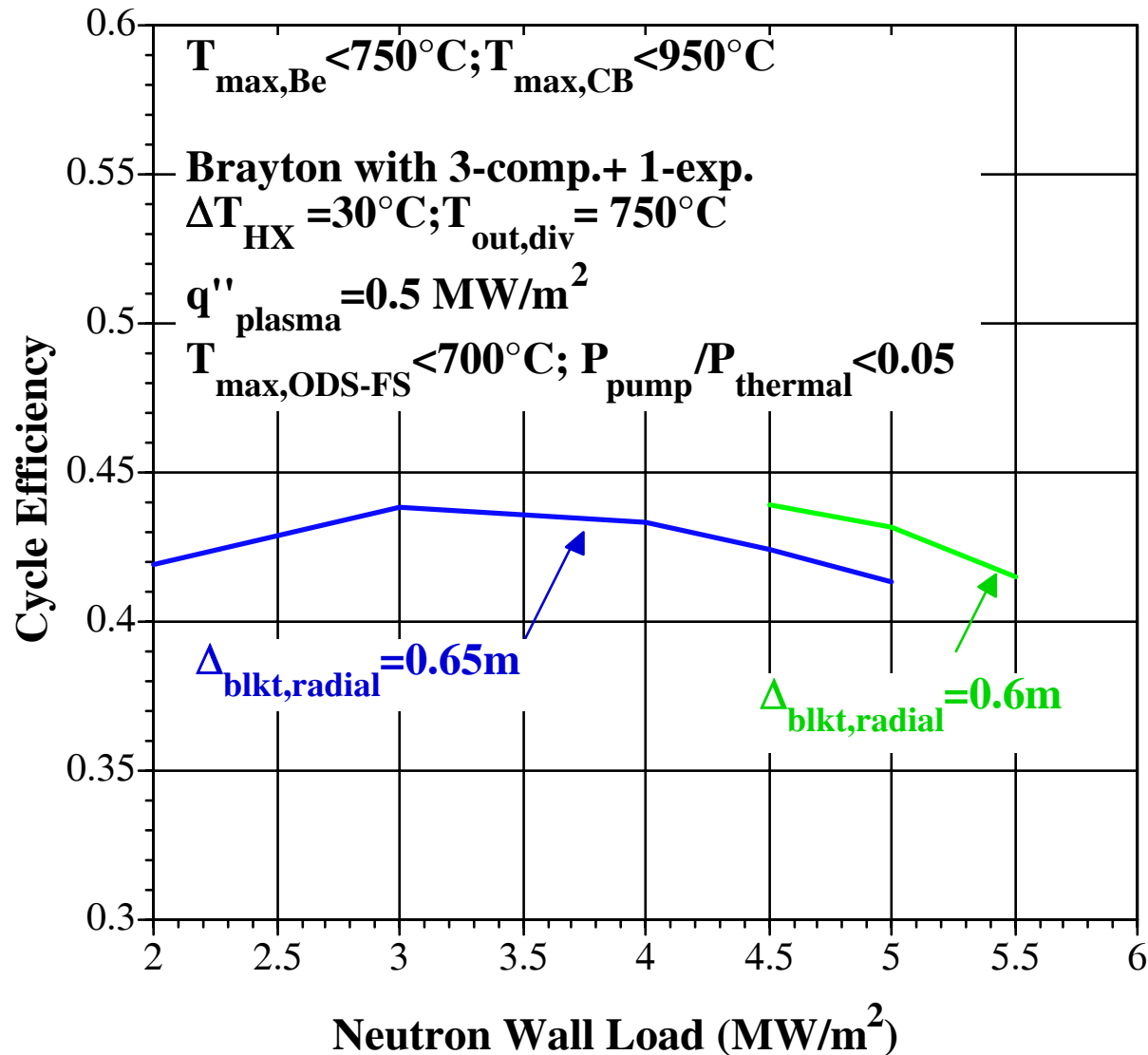
Corresponding Ratio of Pumping to Thermal Power for Blanket He Coolant



- An assumed limit of $P_{\text{pump}}/P_{\text{thermal}} < 0.05$ can be accommodated with Brayton I.
- With Brayton II the smaller coolant temperature rise requires higher flow rate (also for better convection) and $P_{\text{pump}}/P_{\text{thermal}}$ is much higher particularly for higher wall loads
- On this basis, Brayton II does not seem suited for this type of blanket as the economic penalty associated with pumping power is too large



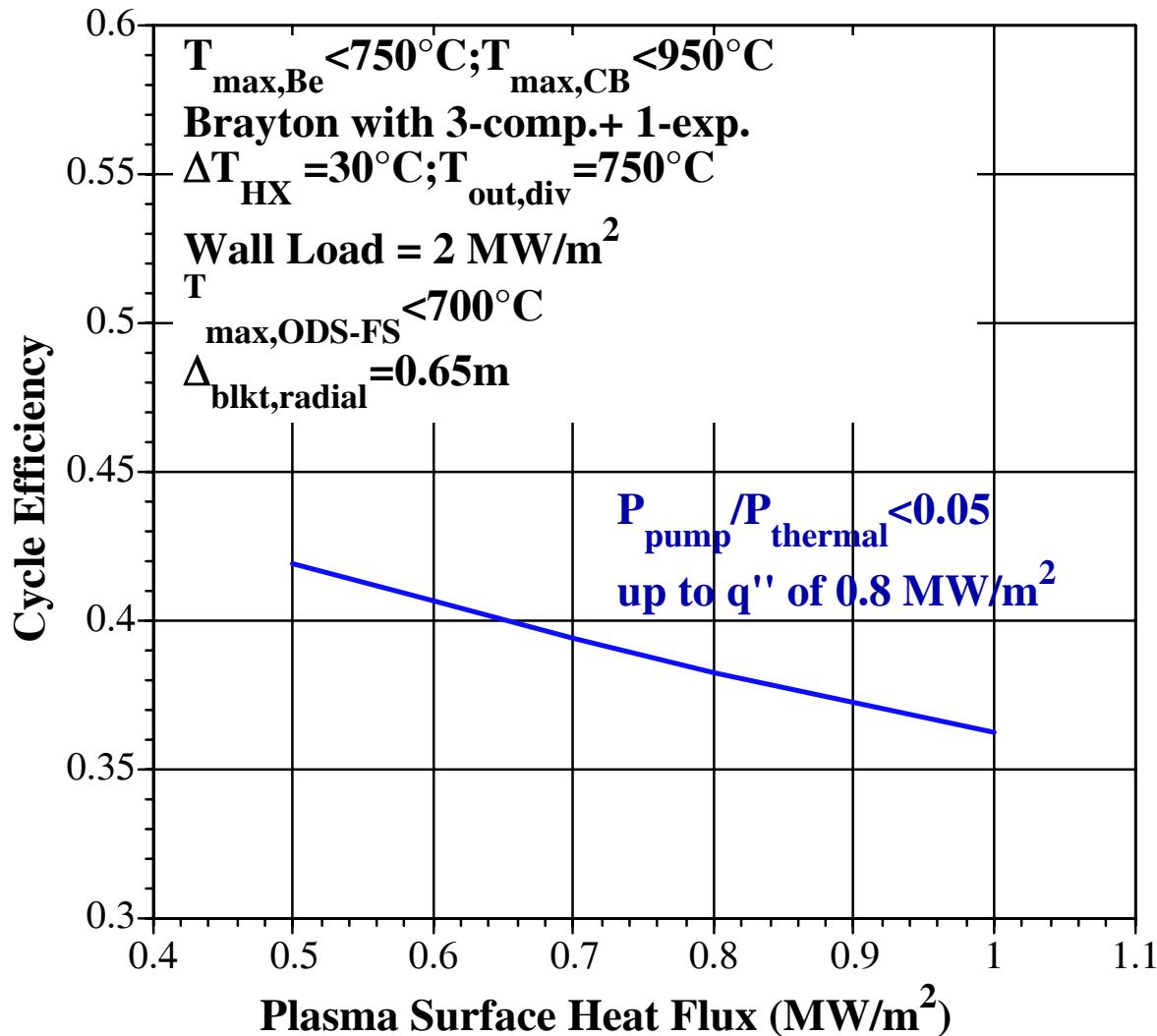
Effect of Changing Blanket Thickness on Brayton Cycle Efficiency



- Decreasing the total blanket thickness to from 0.65 m to 0.6 m allows for accommodation of slightly higher wall load, $\sim 5.5 \text{ MW/m}^2$ and allows for a gain of 1-2 points in cycle efficiency at a given neutron wall load
- But is it acceptable based on tritium breeding?



Effect of Changing the Plasma Surface Heat Flux on Brayton I Cycle Efficiency



- The efficiency decreases significantly with increasing plasma surface heat flux.
- This is directly linked with the decrease in He coolant temperatures to accommodate max. FS temp. limit in the FW (700°C).
- Challenging to accommodate this design with a Brayton cycle for plasma heat flux much higher than 0.5 MW/m^2 .



Conclusions

- **A He-cooled CB concept has been evolved in combination with a Brayton power cycle**
 - This avoids the potential safety problem associated with steam generator failure in the case of a Rankine cycle.
- **Reduced activation FS is used as structural material in regions where the temperature is $<550^{\circ}\text{C}$ and ODS FS in regions where the temperature is higher (but $<700^{\circ}\text{C}$)**
 - A key issue which must be addressed is the joining of ODS FS.
- **A TBR of 1.1 is achievable for a total blanket thickness of 0.65 m.**
- **The design can accommodate a neutron wall load of up to $5\text{-}5.5\text{ MW/m}^2$ and a surface heat flux of 0.5 MW/m^2 with corresponding cycle efficiencies of up to 42% for a Brayton cycle with 3-stage compression and one-stage expansion.**
 - The maximum FS temperature limit in the FW makes it very challenging to accommodate higher surface heat fluxes.
 - The cycle efficiency can be increased to $\sim 47\%$ for a more advanced 4-stage compression, 4-stage expansion Brayton cycle.
 - However, the pumping power requirement is unacceptably large, effectively ruling out such a cycle for this application.
- **Credible fabrication and assembly processes have been evolved for a port-based maintenance scenario.**
- **This study provides the information required for the ARIES-CS Phase I design assessment and down-selection to a couple of concepts for the more detailed studies planned for Phase-II.**

Results of ARIES-CS Phase I Effort Presented at 16th TOFE

Invited Oral Papers for ARIES Special Session

1. F. Najmabadi and the ARIES Team, “Overview of ARIES-CS Compact Stellarator Study”
2. P. Garabedian, L. P. Ku, and the ARIES Team, “Reactors with Stellarator Stability and Tokamak Transport”
3. J.F. Lyon, L. P. Ku, P. Garabedian and the ARIES Team, “Optimization of Stellarator Reactor Parameters”
4. A. R. Raffray, L. El-Guebaly, S. Malang, X. Wang and the ARIES Team, “Attractive Design Approaches for Compact Stellarator”
5. L. El-Guebaly, R. Raffray, S. Malang, J. Lyon, L.P. Ku and the ARIES Team, "Benefits of Radial Build Minimization and Requirements Imposed on ARIES-CS Stellarator Design"

Contributed Papers

6. L. El-Guebaly, P. Wilson, D. Paige and the ARIES Team, "Initial Activation Assessment for ARIES-CS Stellarator Power Plant"
7. L. El-Guebaly, P. Wilson, D. Paige and the ARIES Team "Views on Clearance Issues Facing Radwaste Management of Fusion Power Plants"
8. S. Abdel-Khalik, S. Shin, M. Yoda, and the ARIES Team, "Design Constraints for Liquid-Protected Divertors"
9. X. Wang, S. Malang, A. R. Raffray and the ARIES Team, “Maintenance Approaches for ARIES-CS Power”
10. A. R. Raffray, S. Malang, L. El-Guebaly, X. Wang and the ARIES Team, “Ceramic Breeder Blanket for ARIES-CS”

