Thermal-Hydraulic Study of ARIES-CS Ceramic Breeder Blanket Coupled with a Brayton Cycle

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Outline

- Considerations on choice of blanket design and power cycle
- Ceramic breeder blanket design for ARIES-CS
- Constraints in evolving design configuration and operating parameters
- Brayton cycle configuration
- Example optimization studies
- Conclusions and future plans

Considerations on Choice of Module Design and Power Cycle

- **The blanket module design pressure impacts the amount of structure required, and, thus, the module weight & size, the design complexity and the TBR.**

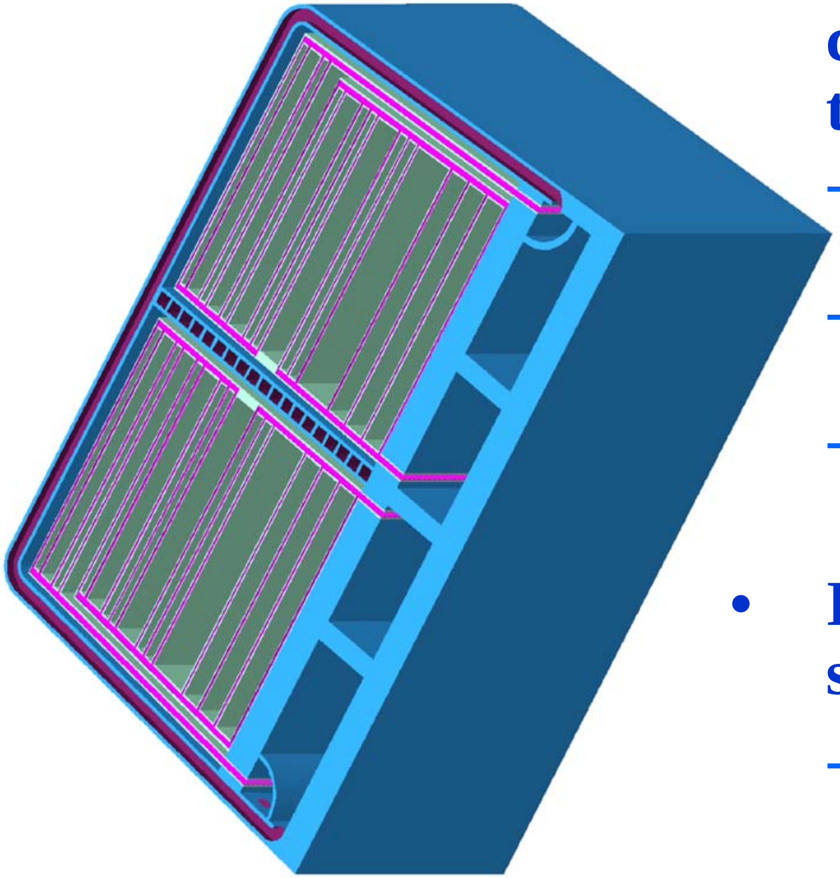
- **For a He-cooled CB blanket, the high-pressure He will be routed through tubes in the module designed to accommodate the coolant pressure. The module itself under normal operation will only need to accommodate the low purge gas pressure (~ 1 bar).**

- **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 still 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

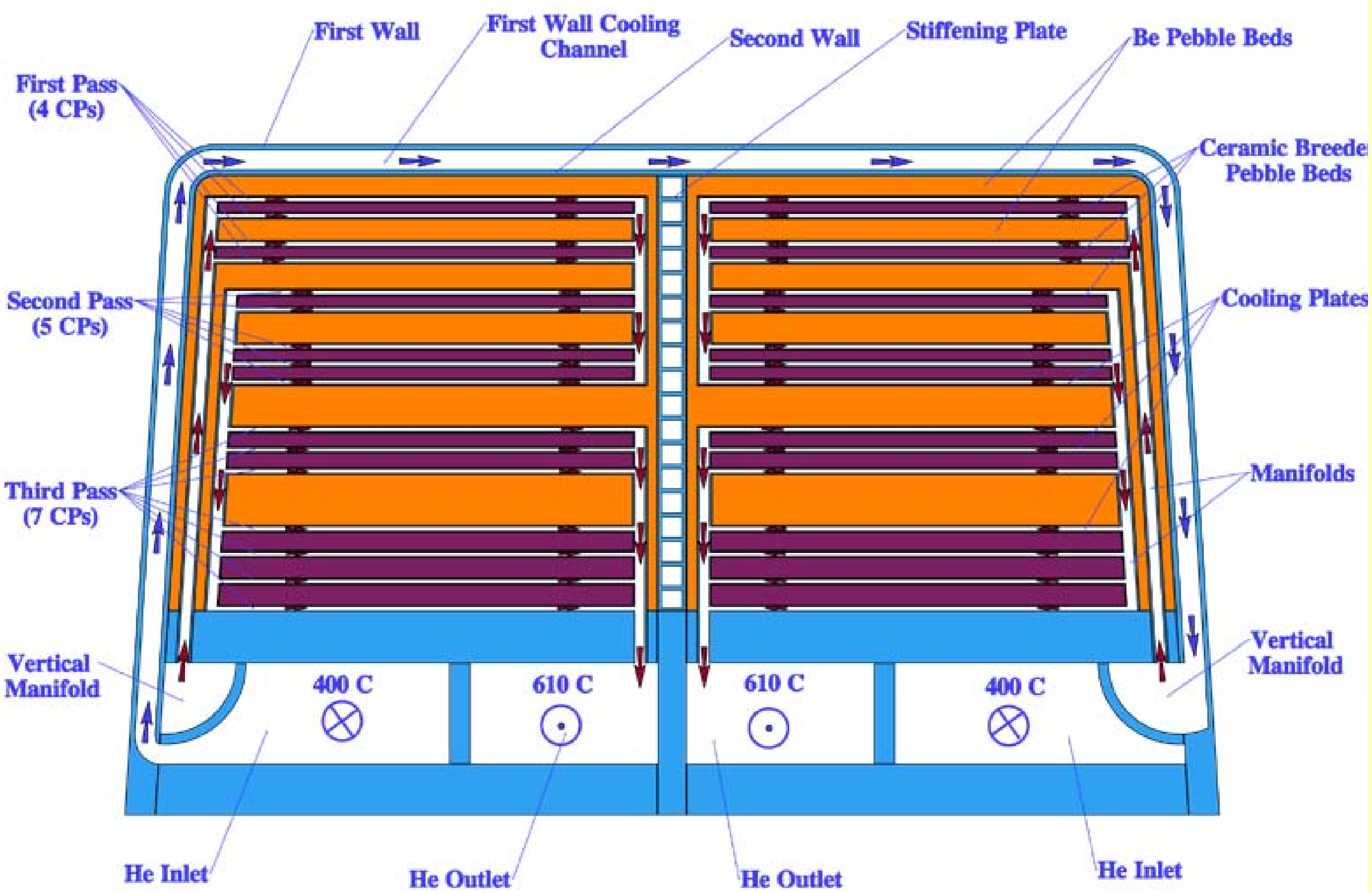


- **Simple modular box design with coolant flowing through the FW and then through the blanket**
  - 4 m (poloidally) x 1 m (toroidally) module
  - Be and CB packed bed regions aligned parallel to FW
  - Li_4SiO_4 or Li_2TiO_3 as possible CB

- **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

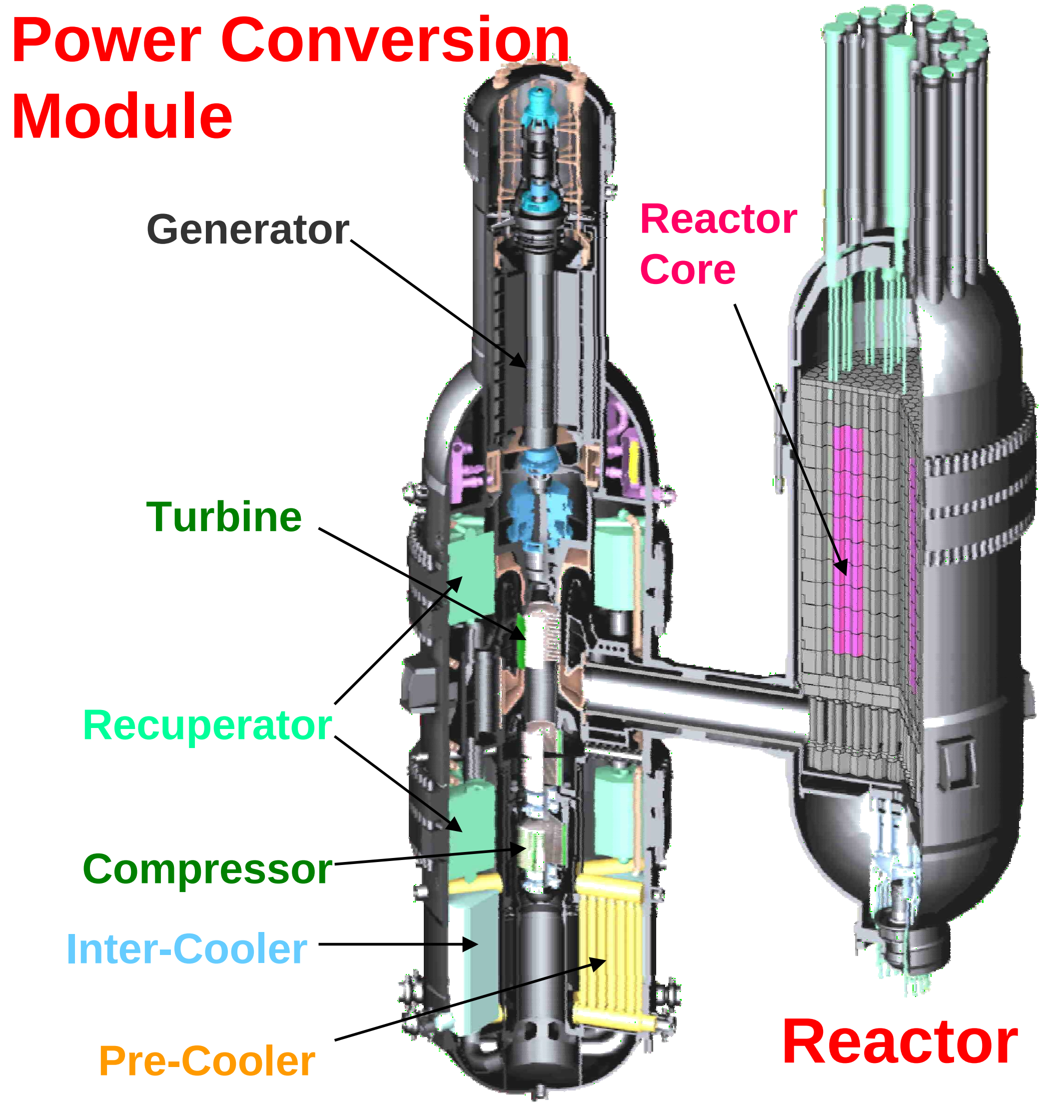
Ceramic Breeder Blanket Module Configuration

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



- **Initial number and thicknesses of Be and CB regions optimized for TBR=1.1 based on:**
  - $T_{max,Be}$ < 750°C
  - $T_{max,CB}$ < 950°C
  - k_{Be}=8 W/m-K
  - k_{CB}=1.2 W/m-K
  - $\delta_{CB\ region}$ > 0.8 cm
- **6 Be regions + 10 CB regions for a total module radial thickness of 0.65 m**

Example Brayton Cycle:
350 MWE Nuclear CCGT (GT-MHR) Designed by U.S./Russia



He-Cooled Blanket + Brayton Cycle: Blanket Coolant to Drive Cycle or Separate Coolant + HX?

- **Brayton cycle efficiency increases with increasing cycle He max. temp. and decreases with increasing cycle He fractional pressure drop, $\Delta P/P$**
  - **Using blanket coolant to drive power cycle will increase cycle He $\Delta P/P$**
  - **With a separate cycle He, $\Delta P/P$ can be reduced by increasing system pressure (~15 MPa)**
  - **From past studies on CB blanket with He as coolant, a max. pressure of ~ 8 MPa has been considered**
  - **Utilizing a separate blanket coolant and a HX reduces the maximum He temperature in the cycle depending on ΔT_{HX}**

- **Tradeoff study required on case by case basis to help decide whether or not to use separate He for cycle**

- **For this scoping study, a separate He cycle and a HX are assumed to enable separate optimization of blanket and cycle He conditions (in particular pressure) and to provide independent flexibility with increasing cycle He fractional pressure drop**

Two Example Brayton Cycle Configurations Considered

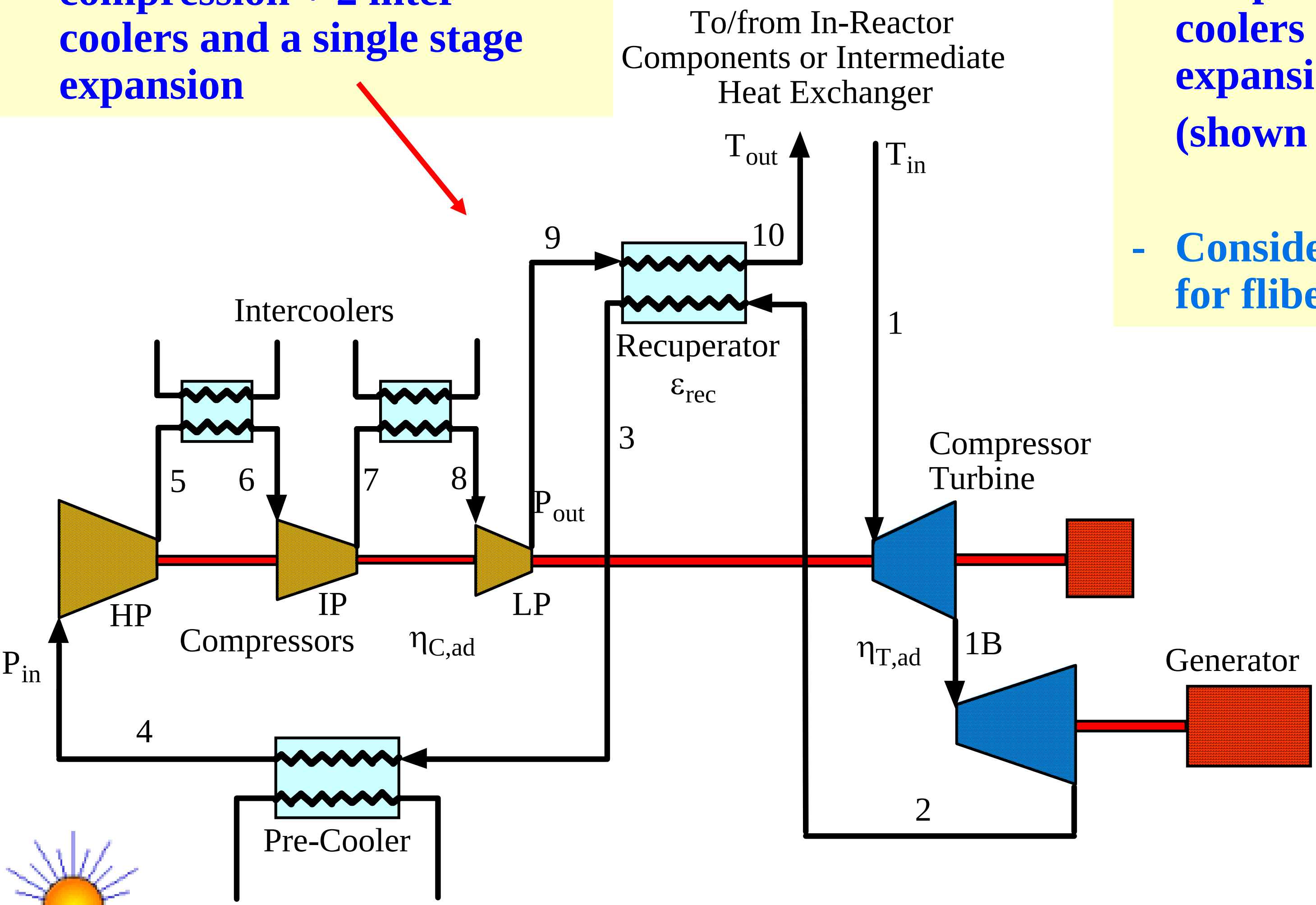
Brayton I:

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

Brayton II:

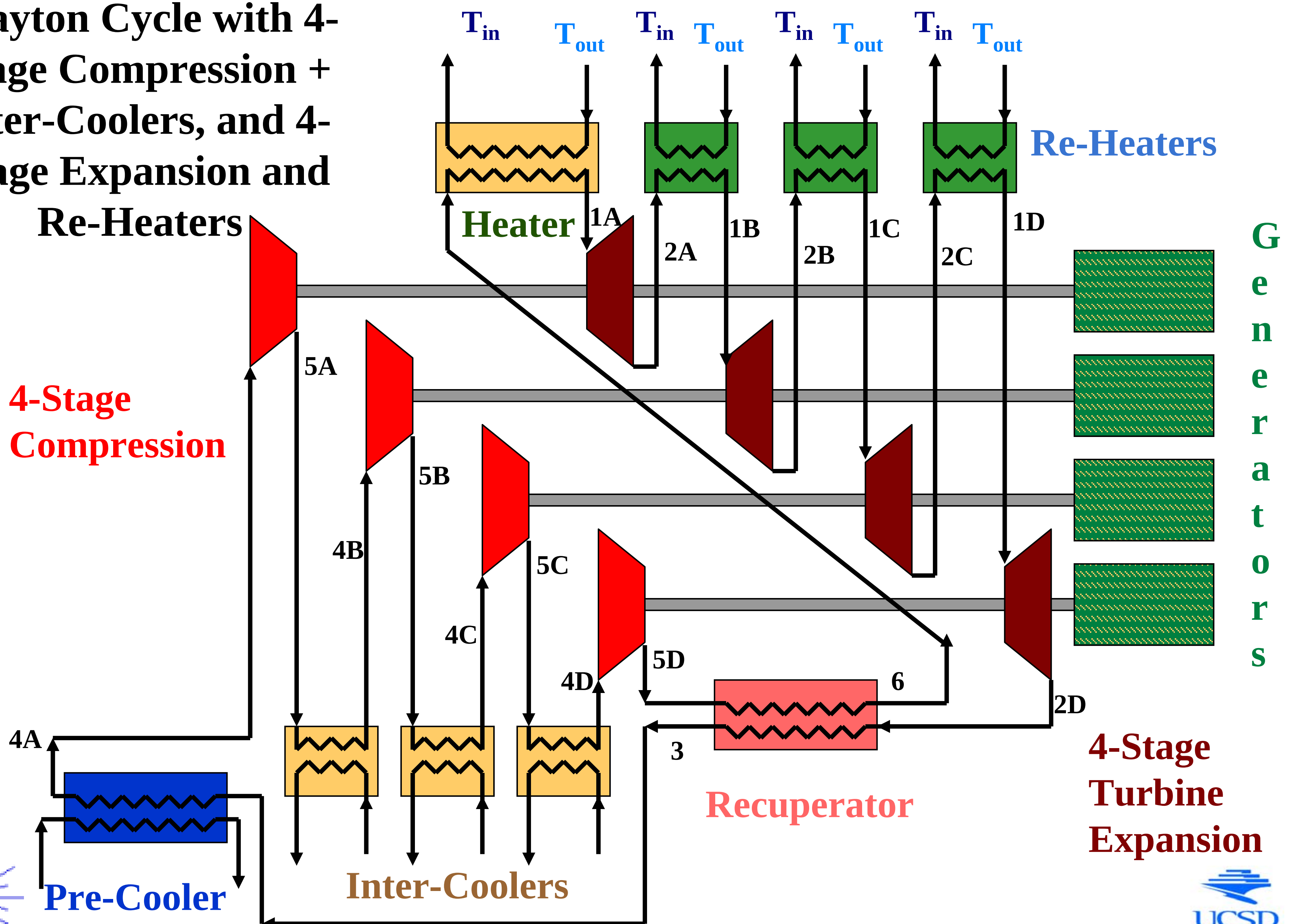
- **A higher performance - configuration with 4-stage compression + 3 inter-coolers and 4-stage expansion + 3 re-heaters (shown on next slide)**

- **Considered by P. Peterson for flibe blanket**

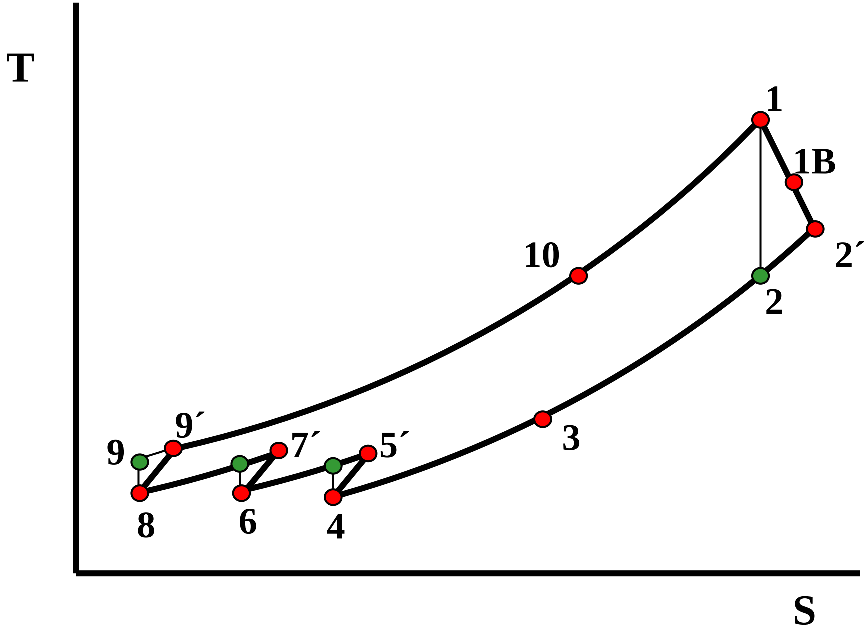


Brayton II

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

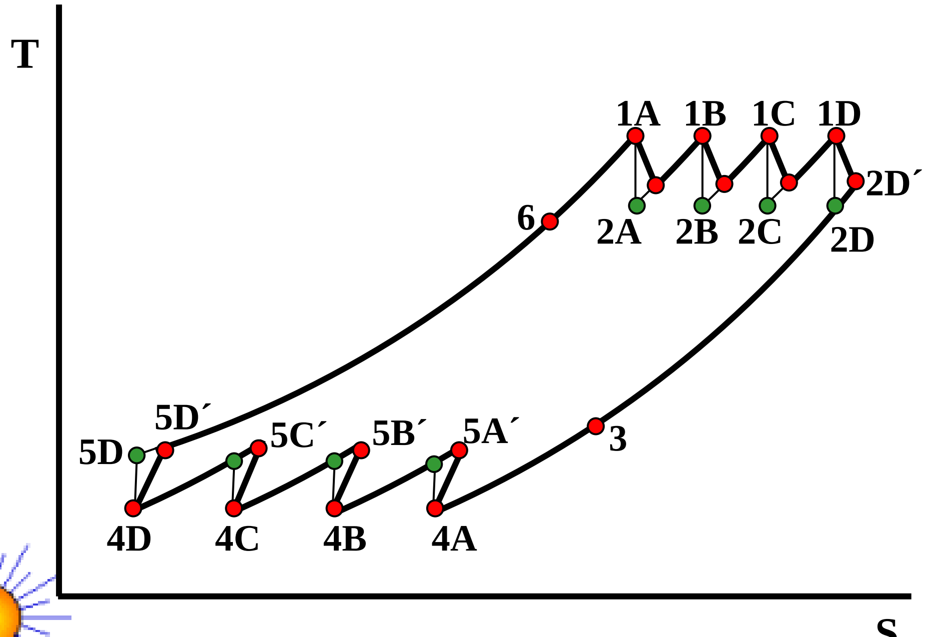


Comparison of T-S Diagrams of Brayton I and Brayton II



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

Procedure for Blanket Thermal Hydraulic and Brayton Cycle Analysis

- **Start with number of breeder and multiplier regions from initial neutronics optimization calculations to provide the required breeding, TBR=1.1**
  - 6 Be regions + 10 CB regions for a total module radial thickness of 0.65 m

- **Perform calculations for different wall loading by scaling the q_{vol}''' in the different regions and setting the individual region thicknesses and coolant conditions to accommodate the maximum material temperature limits and pressure drop constraints.**
  - $T_{max,Be}$ < 750°C; $T_{max,CB}$ < 950°C; $T_{max,FS}$ < 550°C or 700°C (ODS)
  - k_{Be}=8 W/m-K; k_{CB}=1.2 W/m-K
  - $\delta_{CB\ region}$ > 0.8 cm; $\delta_{Be\ region}$ > 2 cm
  - $P_{pump}/P_{thermal}$ < 0.05 (unless specified otherwise)

- **Coolant conditions set in combination with Brayton cycle under following assumptions:**
  - Blanket outlet He is mixed with divertor outlet He (assumed at ~750°C and carrying ~15%of total thermal power) and then flown through HX to transfer power to the cycle He with ΔT_{HX} = 30°C
  - Minimum He temperature in cycle (heat sink) = 35°C
  - $\eta_{Turbine}$ = 0.93; $\eta_{Compressor}$ = 0.89; $\varepsilon_{Recuperator}$ = 0.95
  - Total compression ratio < 2.87

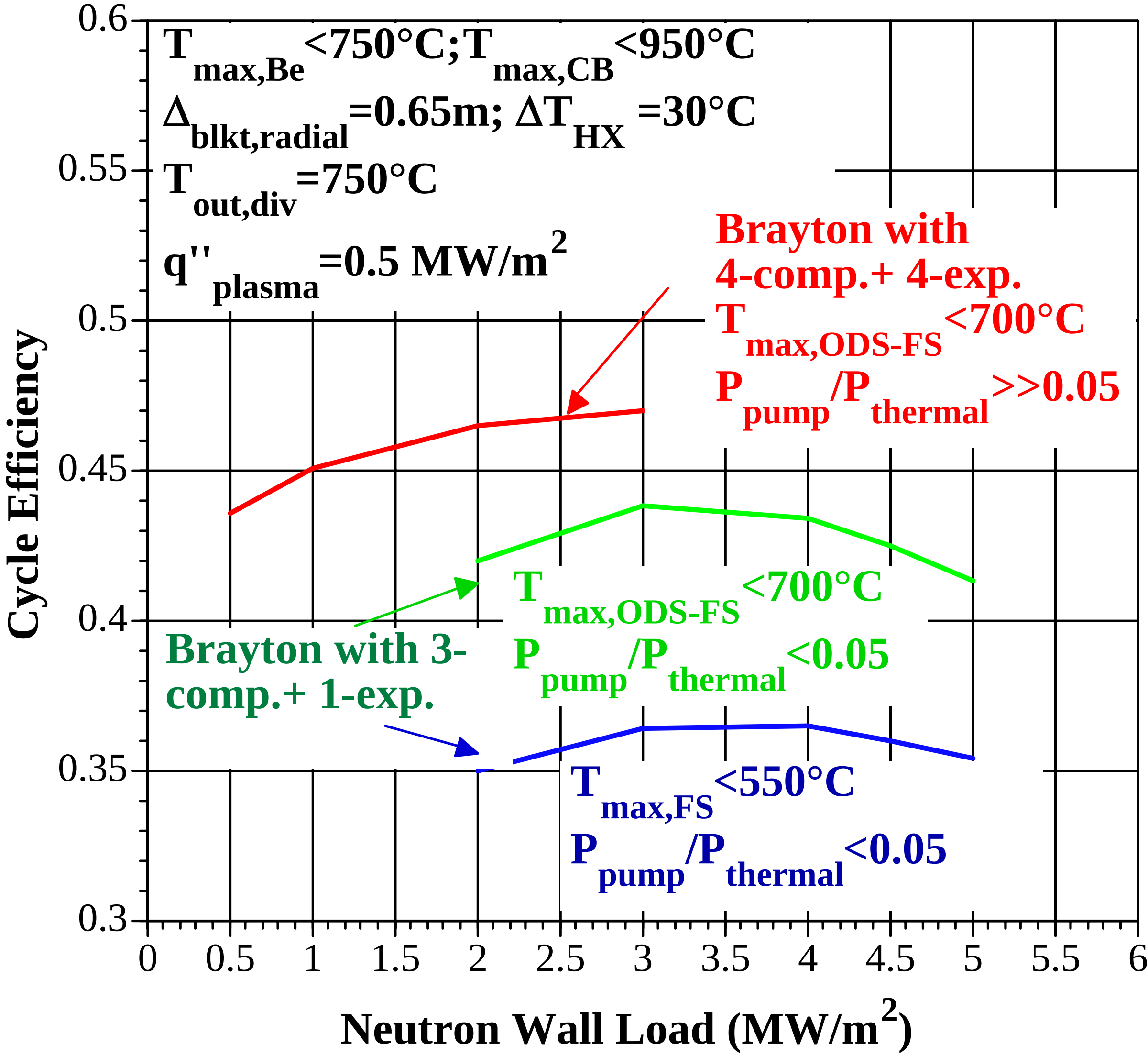
Radial Build from Original Neutronics Optimization Calculations

- q_{vol}''' based on wall load of 4.5 MW/m^2 and scaled for different wall loads
- q_{plasma}'' unspecified and assumed as 0.5 MW/m^2 in all calculations (unless otherwise specified)

Radial Builds	Thickness (m)	q'''(MW/m^3)
Layer 1, FW Steel	4.00E-03	5.48E+01
Layer 2, FW Cooling channel	2.00E-02	8.93E+00
Layer 3, FW Steel	4.00E-03	4.99E+01
Layer 4, Be #1	2.00E-02	2.17E+01
Layer 5, CP #1	6.00E-03	2.36E+01
Layer 6, SB #1	9.00E-03	4.70E+01
Layer 7, CP #2	6.00E-03	2.15E+01
Layer 8, Be #2	2.20E-02	1.65E+01
Layer 9, CP #3	6.00E-03	1.87E+01
Layer 10, SB #2	1.00E-02	3.67E+01
Layer 11, CP #4	6.00E-03	1.68E+01
Layer 12, Be #3	2.50E-02	1.25E+01
Layer 13, CP #5	6.00E-03	1.44E+01
Layer 14, SB #3	1.00E-02	4.04E+01
Layer 15, CP #6	6.00E-03	1.29E+01
Layer 16, Be #4	3.00E-02	9.22E+00
Layer 17, CP #7	6.00E-03	1.07E+01
Layer 18, SB #4	1.00E-02	3.71E+01
Layer 19, CP #8	6.00E-03	9.54E+00
Layer 20, SB #5	1.10E-02	3.38E+01
Layer 21, CP #9	6.00E-03	8.41E+00
Layer 22, Be #5	4.00E-02	5.77E+00
Layer 23, CP #10	6.00E-03	6.64E+00
Layer 24, SB #6	1.30E-02	2.13E+01
Layer 25, CP #11	6.00E-03	5.84E+00
Layer 26, SB #7	1.40E-02	1.85E+01
Layer 27, CP #12	6.00E-03	5.06E+00
Layer 28, Be #6	5.40E-02	3.25E+00
Layer 29, CP #13	6.00E-03	3.77E+00
Layer 30, SB #8	1.80E-02	1.04E+01
Layer 31, CP #14	6.00E-03	3.27E+00
Layer 32, SB #9	2.00E-02	7.49E+00
Layer 33, CP #15	6.00E-03	2.81E+00
Layer 34, SB #10	2.00E-02	6.60E+00
Layer 35, CP #16	6.00E-03	2.42E+00
Breeder+Multiplier+FW (per module) =	**0.45 m**	
Back wall + Manifold =	**0.2 m**	
Total Blanket Module Thickness =	**0.65 m**	

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 ($\Delta_{blkt,radial}$) of 0.65 m (required for breeding), a maximum Γ of 5 MW/m^2 can be accommodated with:
  $T_{max,FS}$<550°C; η ~ 35%
  $T_{max,FS}$<700°C; η ~ 42%
- The max. η corresponds to Γ ~3 MW/m^2:
  $T_{max,FS}$<550°C; η ~ 36.5%
  $T_{max,FS}$<700°C; η ~ 44%
- The max. η ~ 47% for Γ ~3 MW/m^2 for Brayton II.
- However, as will be shown, $P_{pump}/P_{thermal}$ is unacceptably high in this Brayton II case.

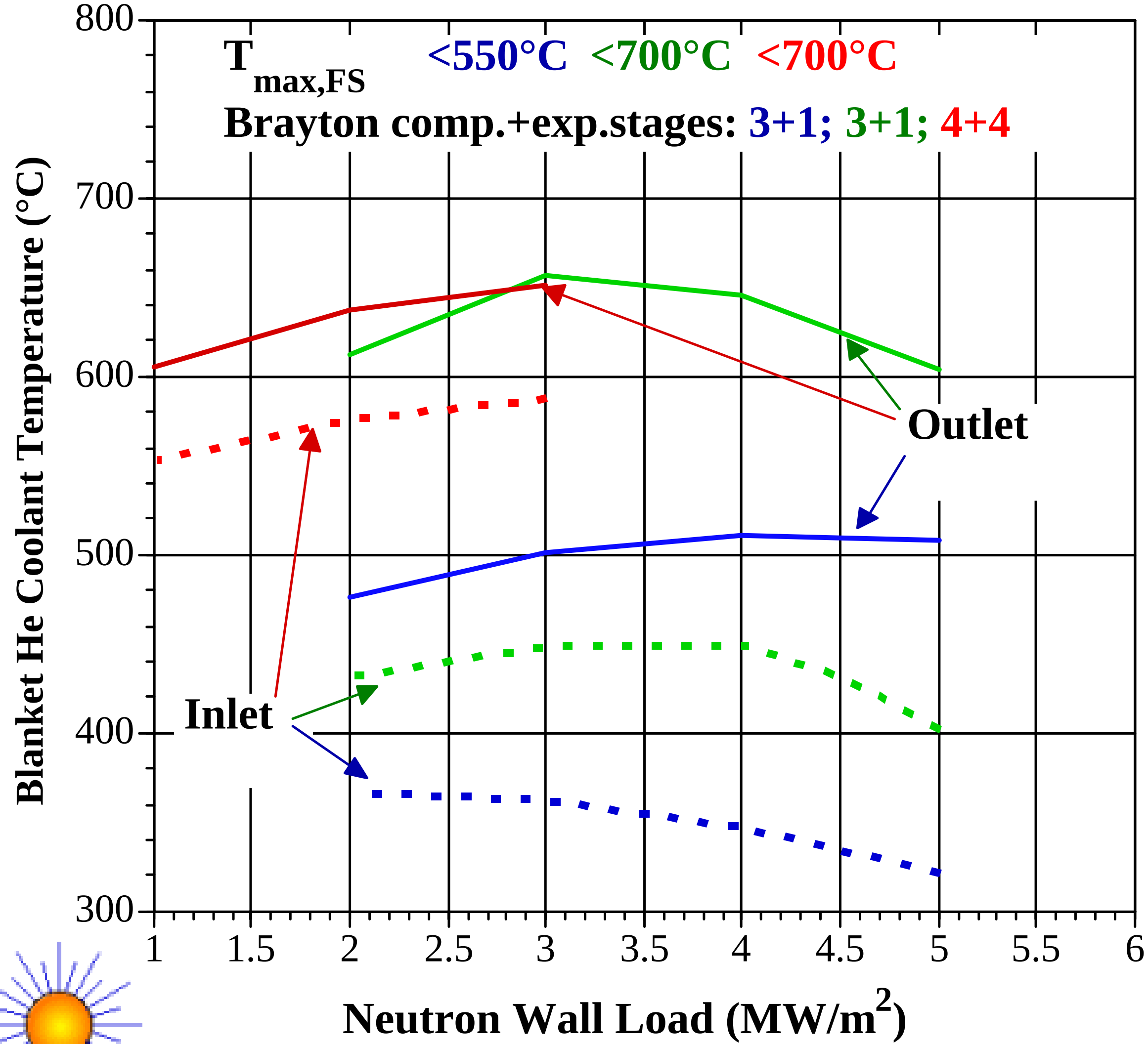


UCSD

Corresponding He Coolant Inlet and Outlet Temperatures

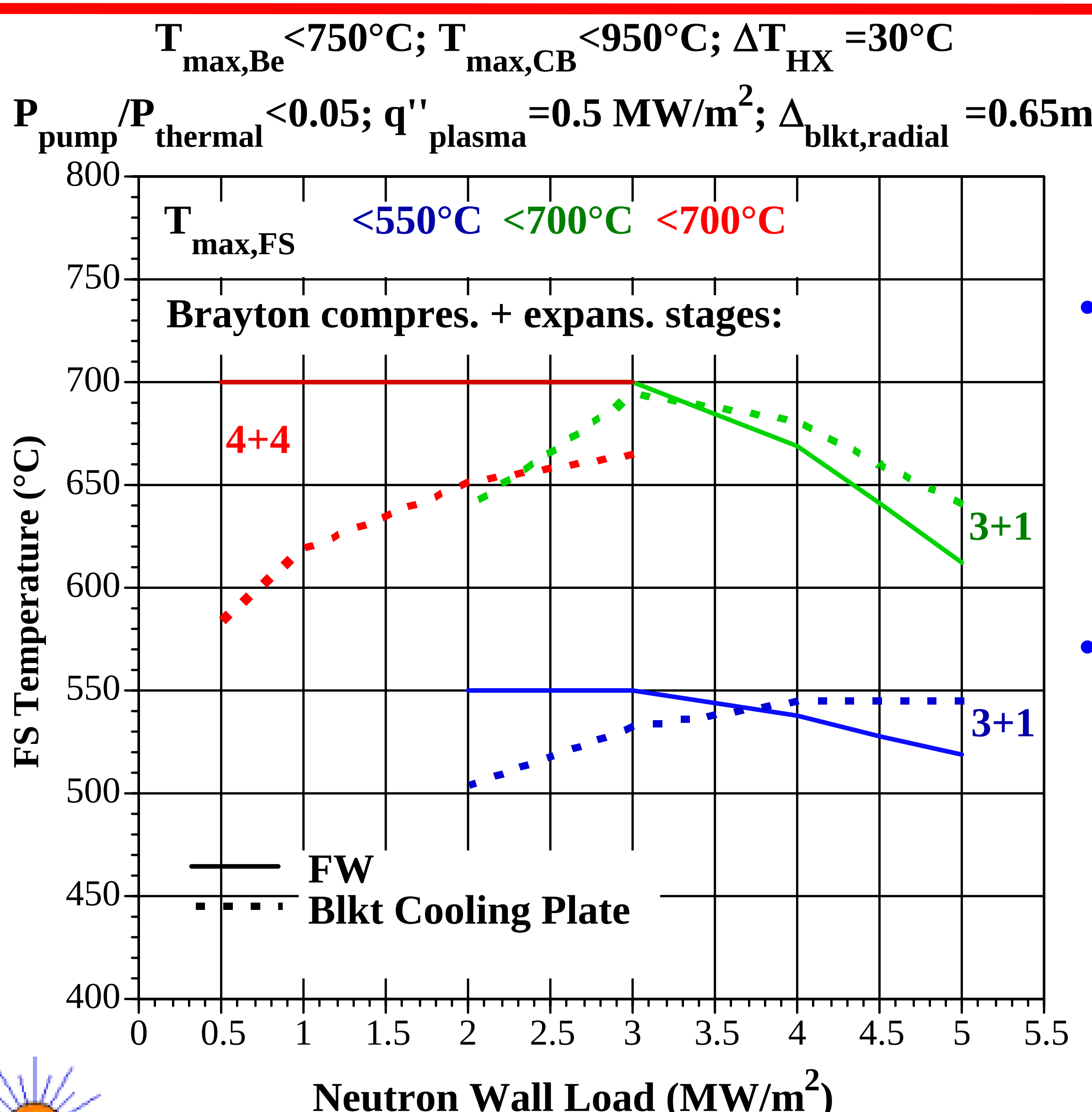
$T_{max,Be}$<750°C; $T_{max,CB}$<950°C; ΔT_{HX} =30°C

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



- **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**

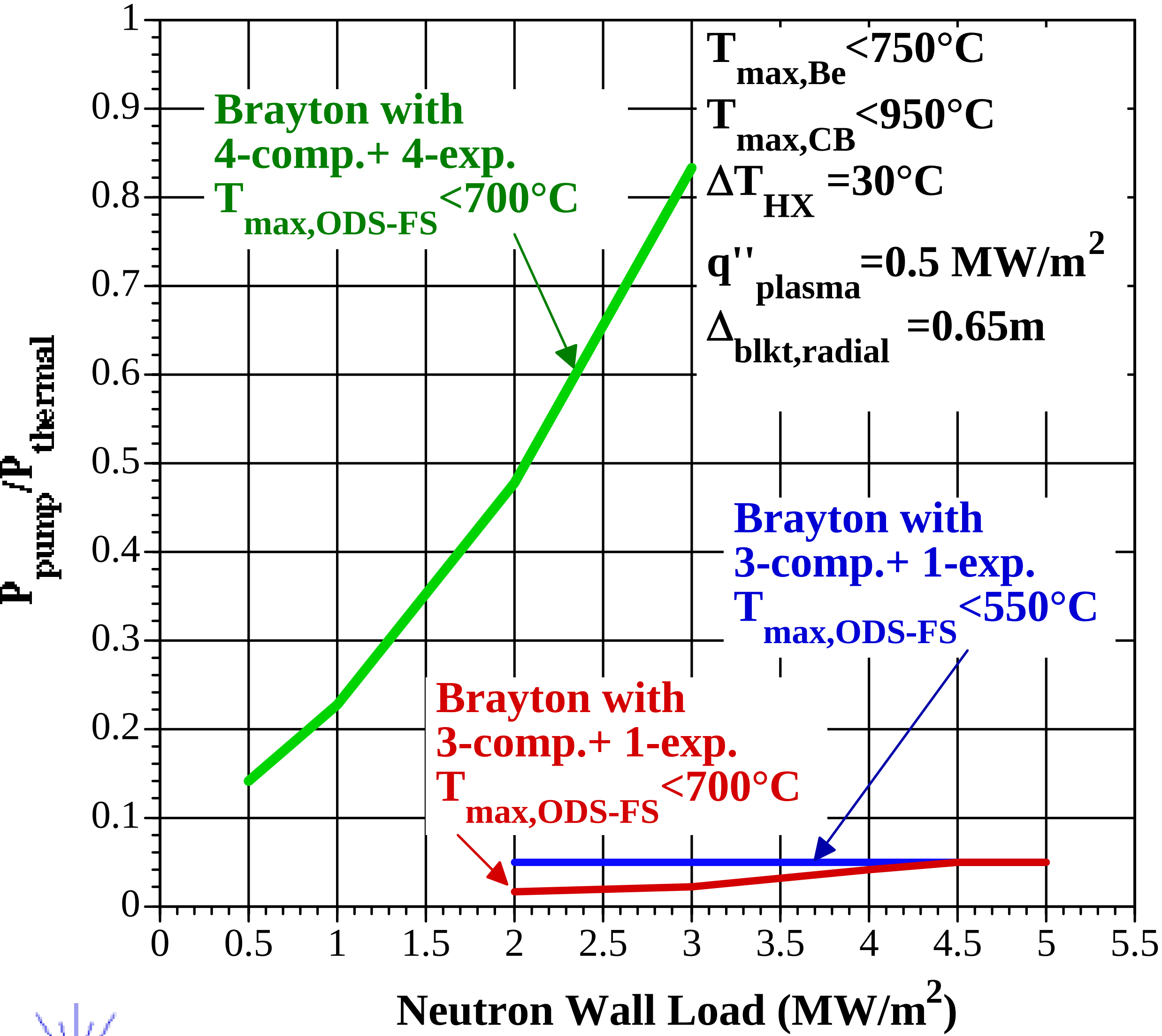
Corresponding Maximum FS Temperature



- For lower Γ (<~3 MW/m²), $T_{max,FS}$ limits the combination of blanket outlet and inlet He coolant temperatures

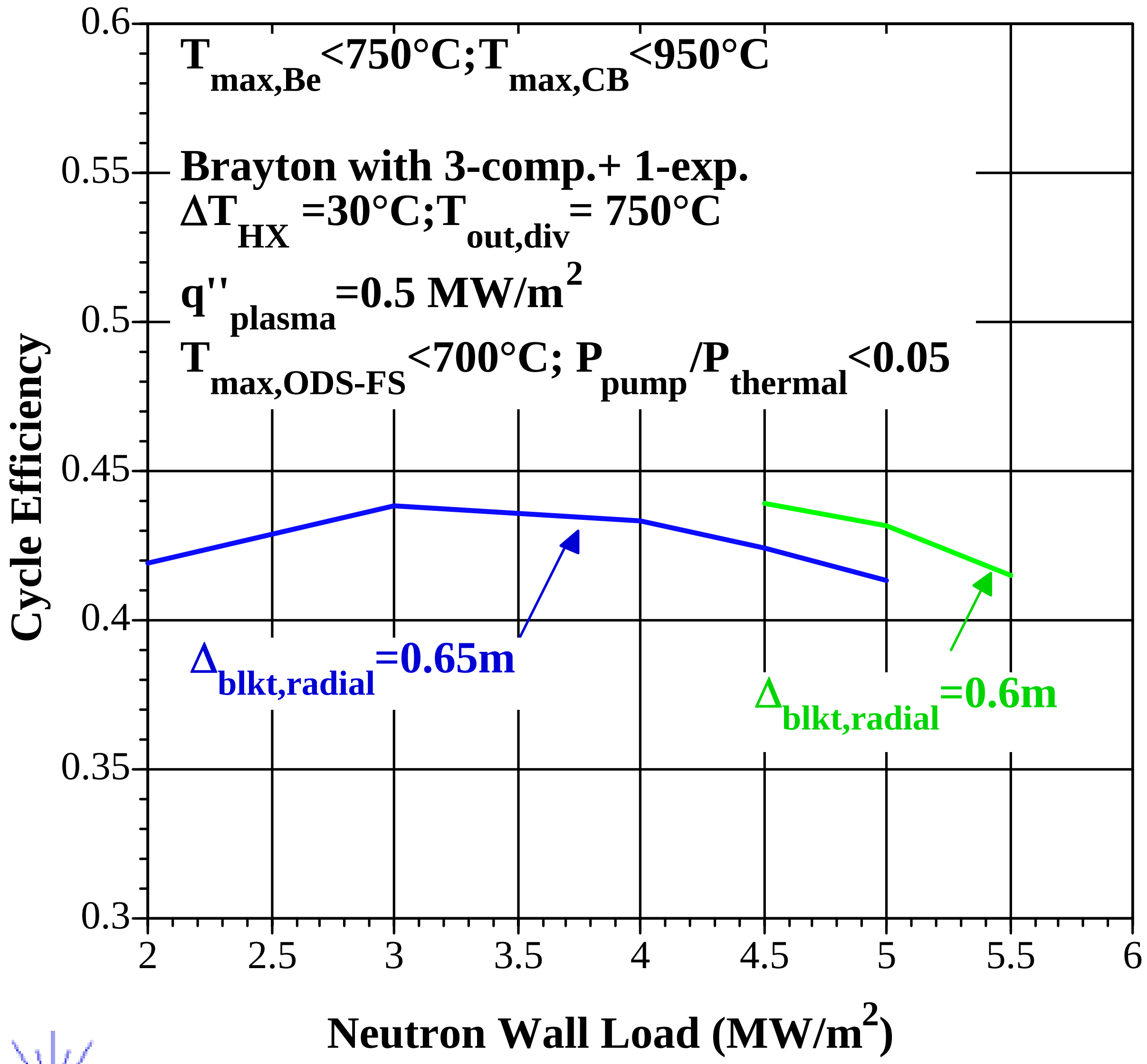
- For higher Γ(>~3MW/m²), $T_{max,CB}$ and $T_{max,Be}$ limit the combination of blanket outlet and inlet He coolant temperatures

Corresponding Ratio of Pumping to Thermal Power for Blanket He Coolant



- An assumed limit of $P_{pump}/P_{thermal}$ < 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 $P_{pump}/P_{thermal}$ 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

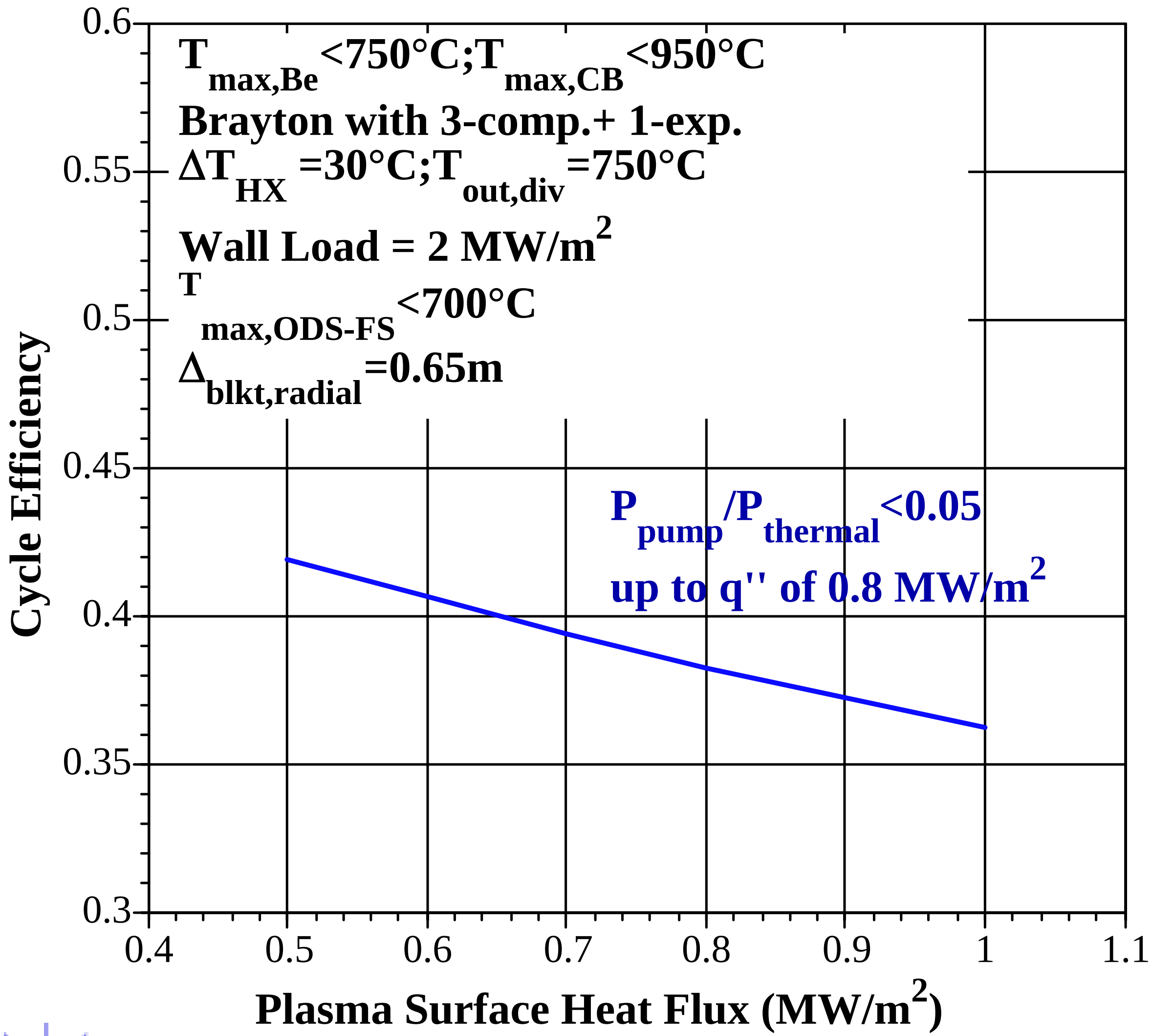
Effect of Changing Blanket Thickness on Brayton Cycle Efficiency



- Decreasing the total blanket thickness to from 0.65 m to 0.6 m allows for accommodation of slightly higher wall load, ~ 5.5 MW/m2 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?

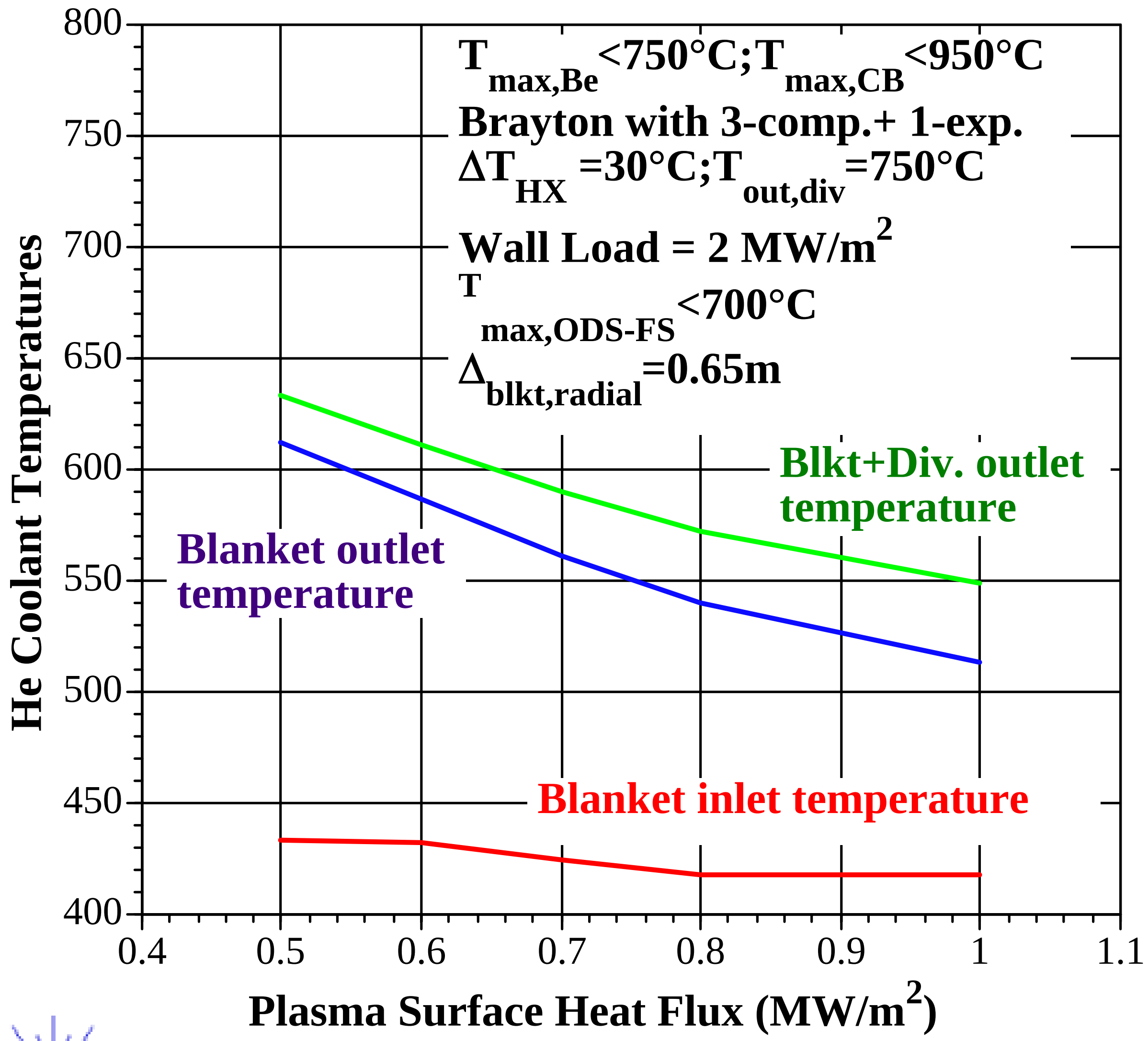
Effect of Changing the Plasma Surface Heat Flux on Brayton I Cycle Efficiency



- 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).

  (see next slide)

Effect of Changing the Plasma Surface Heat Flux on Blanket He Temperatures



- **The key constraint is the max. FS temp. limit in the FW (700°C).**
- **To accommodate the increase in plasma heat flux, the He coolant temperatures must be decreased, in particular the outlet He temperature**
- **Challenging to accommodate this design with a Brayton cycle for plasma heat flux much higher than 0.5 MW/m^2**

Observations from Scoping Study of ARIES-CS Ceramic Breeder Blanket Coupled with a Brayton Power Cycle

- **A Brayton cycle seems possible with He-cooled CB blanket under certain conditions**
  - **This would remove a potential safety problem associated with steam generator failure in the case of a Rankine cycle**
  - **Blanket coupled to power cycle via a He/He HX**

- **Scoping studies indicate the possibility of accommodating Γ = 5-5.5 MW/m^2 for $T_{max,FS}$<700°C with corresponding η = 0.42–0.43 (for Brayton I cycle) for total blanket module radial thickness of 0.6-0.65 m (to be set by TBR requirements).**

- **For this CB blanket, cycle efficiency optimization seems to correspond to Γ = 3-3.5 MW/m^2 with η = 0.365 for $T_{max,FS}$<550°C and η = 0.44 for $T_{max,FS}$<700°C.**

- **A max. η ~ 47% can be obtained for Γ ~3 MW/m^2 with the high performance Brayton II cycle.**

- **However, the smaller coolant temperature rise in this case requires higher flow rate (also for better convection) and $P_{pump}/P_{thermal}$ is unacceptably large (particularly for higher wall loads).**

- **On this basis, the Brayton II cycle does not seem suited for this type of blanket as the economic penalty associated with pumping power is too large**

Observations from Scoping Study of ARIES-CS Ceramic Breeder Blanket Coupled with a Brayton Power Cycle (cont.)

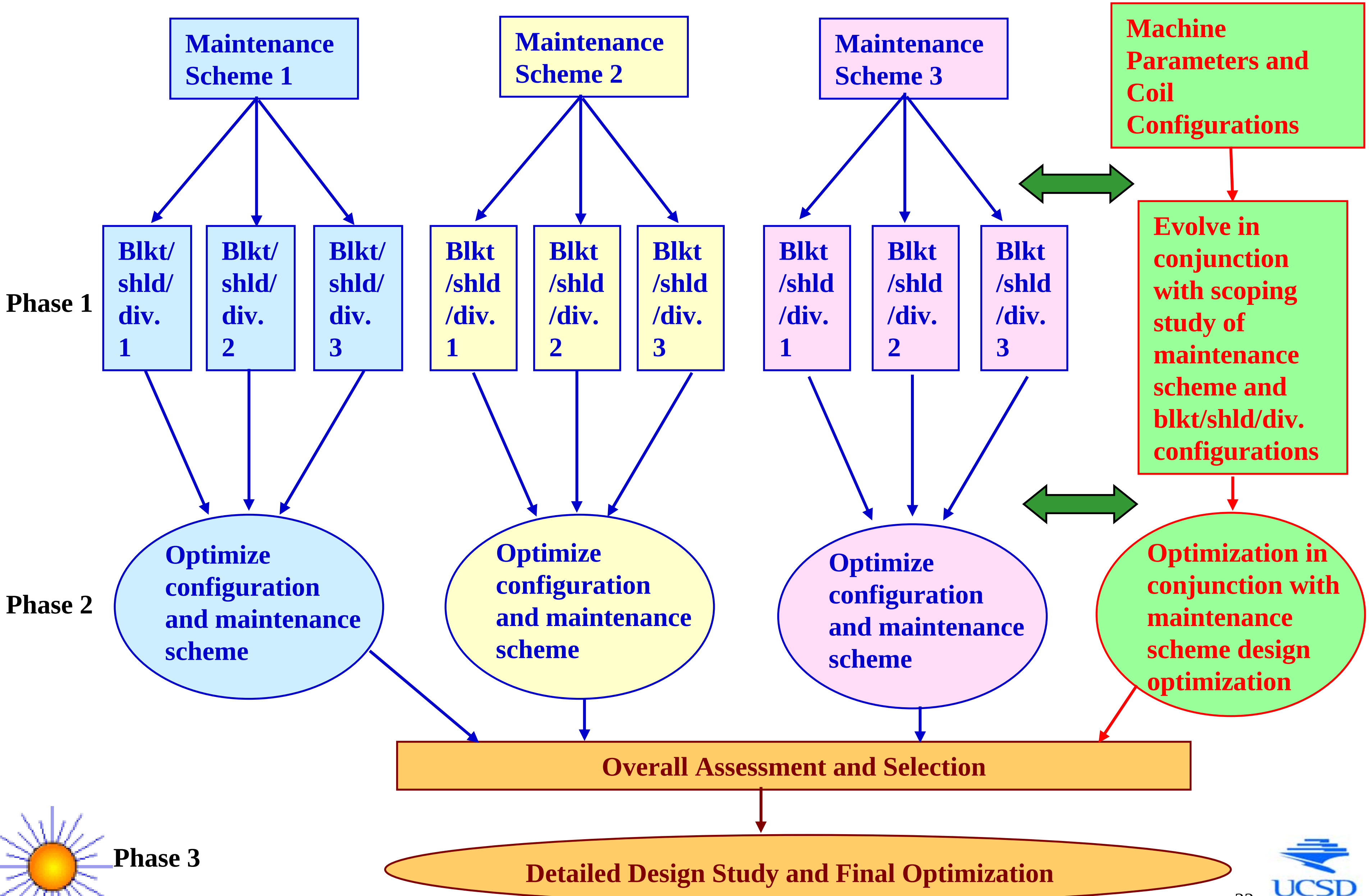
- **The key constraint in accommodating higher plasma surface heat fluxes is the maximum FS temperature limit in the FW.**

- **To accommodate the increase in plasma heat flux, the He coolant temperatures must then be decreased, in particular the outlet He temperature, with a significant decrease in the corresponding cycle efficiency.**

- **Challenging to accommodate this design with a Brayton cycle for plasma heat flux much higher than 0.5 MW/m^2**

- **These results tend to give a good indication of the relative performance of such a blanket coupled with a Brayton cycle and provide a good scoping study basis for the comparative assessment of the different blanket concepts within the next few months.**

Original Plan for Engineering Activities



Engineering Activities: Phase 1

- **Perform scoping assessment of different maintenance schemes and consistent design configurations (coil support, vacuum vessel, shield, blanket).**
  - **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)** ✓

  - **Blanket/shield concepts:**
    1. **Self-cooled liquid metal blanket(Pb-17Li) (probably with He-cooled divertor depending on heat flux)**
       a) **with SiC_f/SiC** ✓
       b) **with insulated ferritic steel and He-cooled structure**

    2. **He-cooled blanket with ferritic steel and He-cooled divertor** ✓
       a) **liquid breeder (Li)**
       b) **ceramic breeder**

    3. **Flibe-cooled ferritic steel blanket (might need He-cooled divertor depending on heat flux)** ✓

Future Engineering Activities

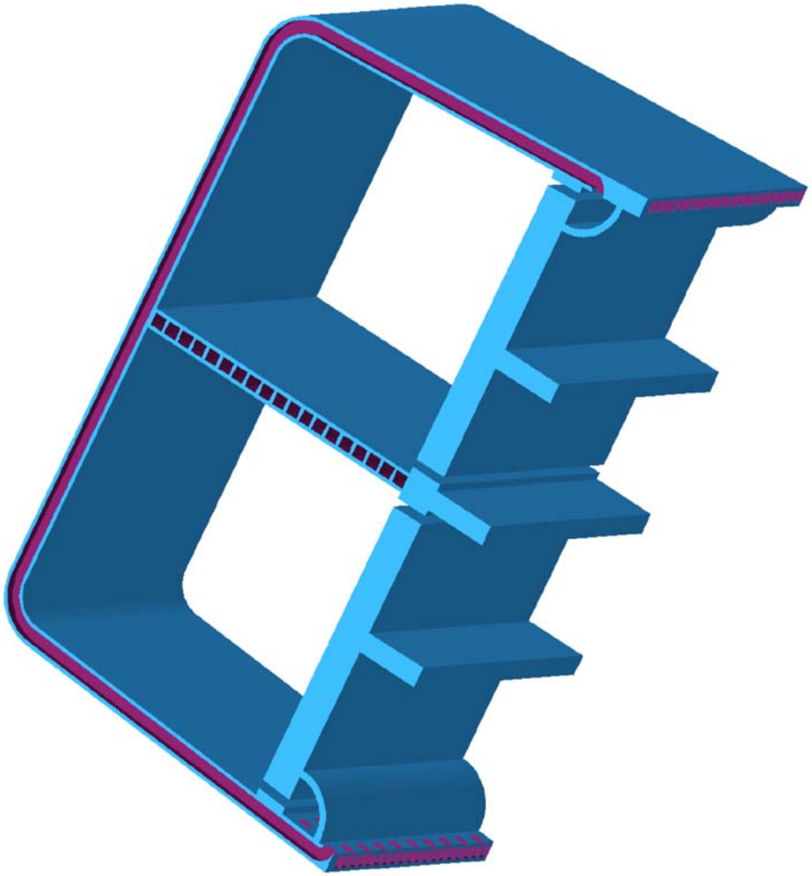
- **On the engineering front, we are making good progress in many areas:**
  - Blanket/vessel/coil configuration
  - Maintenance scheme
  - Ready to start converging on a couple of concepts for more detailed study within the next few months
  - Start detailed point design study within a year

- **However, one key area where we are lagging is the divertor**
  - Need better definition of location and heat loads
  - Need an idea of divertor design for proceeding with more detailed blanket studies to make sure that they are fully compatible
  - Should be the focus of our immediate effort
  - Tools for calculating heat flux on physics side (UCSD,PPPL,RPI)
  - Further scoping analysis of generic He-cooled configuration under high heat fluxes (~10 MW/m^2 or more) (UCSD, GaTech)

- **In response to Farrokh's questions:**
  - Are we missing analytical tools? **Yes, to calculate divertor heat loads and location.**
  - Are there technical areas receiving insufficient attention? **Yes, the divertor.**
  - What should be the priorities for our research direction? **The divertor.**

Extra Slides

Blanket Module Structure



Comparison of Brayton and Rankine Cycle Efficiencies as a Function of Blanket Coolant Temperature (under previously described assumptions)

- **For CB blanket concepts, max. T_{He} from past studies ~ 450-600°C**
- **This range is in the region where at higher temperature, it is clearly advantageous to choose the Brayton cycle and at lower temperature the Rankine cycle**
- **The choice of cycle needs to be made based on the specific design**