# Some of the Major Considerations in Designing a Ceramic Breeder Blanket for ARIES-CS

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# Considerations

- **Module Design Load**
- **Choice of power cycle: Rankine vs. Brayton**
- **Need for HX and separate power cycle working fluid**
- **Optimizing TBR: Orientation of breeder/multiplier regions**

# Module Design Pressure

- The module design pressure impacts the amount of structure required in the module design, 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 coolant tubes in the module; these tubes would be designed to accommodate the coolant pressure. The module itself under normal operation will only need to accommodate the low purge gas pressure  (order of 1 bar)

- The key question is whether there are accident scenario that would require the module to accommodate higher loads

# Possible Accident Scenario Impacting Required Module Design Pressure (from EU Study)

- **He-cooled ceramic breeder blanket in conjunction with a Rankine steam power cycle (with a steam generator)**

1. **Failure of blanket cooling tube leading to over-pressurization of blanket module, followed by depressurization (through pressure relief valves, rupture disk or blanket module failure)**

2. **Subsequent failure of a steam generator tube**
   - **These two failures can be independent or related (e.g. reverse stress in steam generator tube due to cooling tube depressurization)**

3. **Introduction of high pressure steam into the failed module by way of the primary cooling system.**

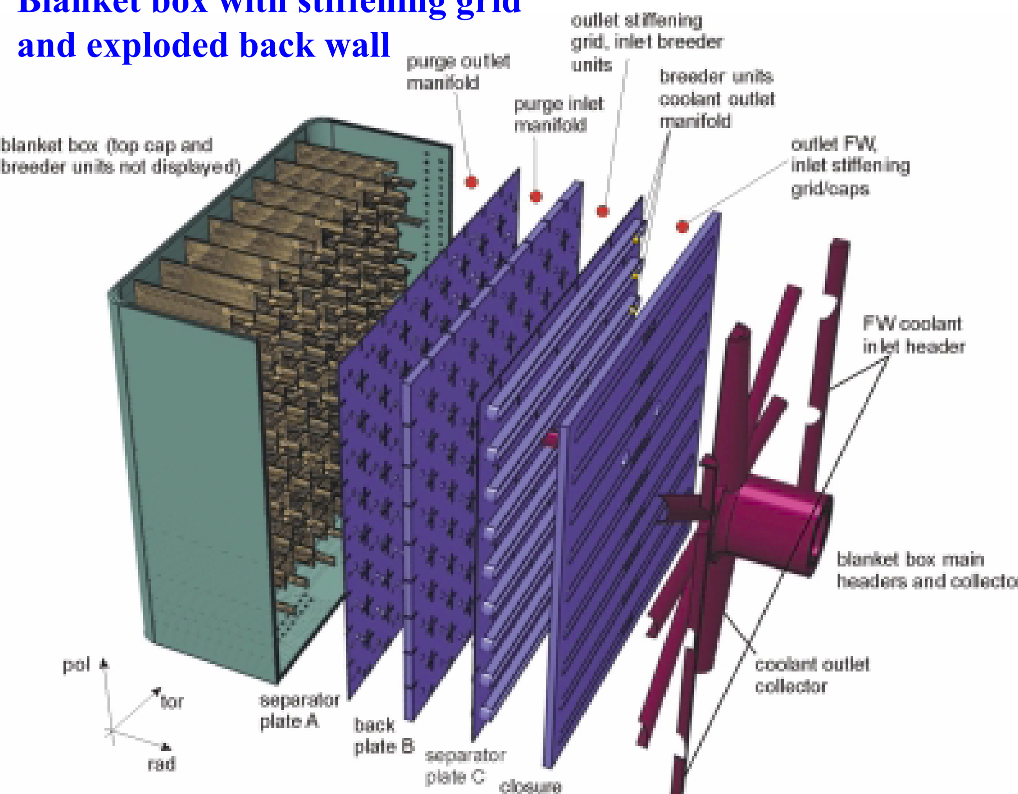
4. **Be/steam interaction and consequences (in particular if module has failed)**

# How to Accommodate this Scenario?

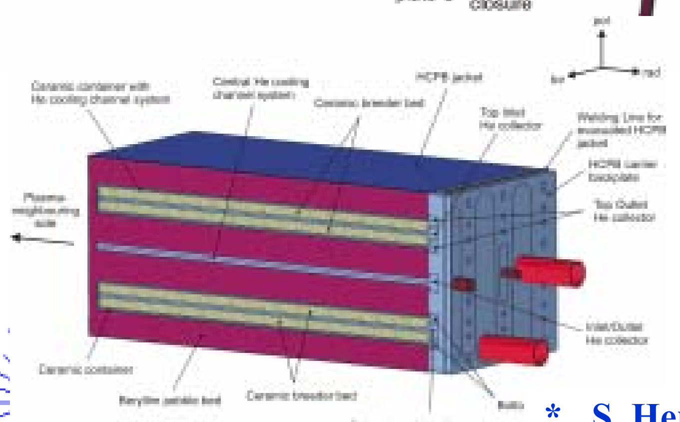
- Are passive means acceptable? (rupture disk, pressure relief valve…) or must the module be designed to accommodate the pressure?
- It depends on the probability of the accident (design basis or beyond design basis)
- Study by INEL (B. Merrill and L. Cadwallader)
  - to be presented next
- Results important as it will impact the CB module design

# Example He-Cooled Ceramic Breeder Blanket Module Designed for Module Pressurization (Current EU HCPB Concept)*

**Blanket box with stiffening grid and exploded back wall**




- **Module design**
  - **Dimension up to 4m x 2m x 0.8m**
  - **Box design with an array of stiffening grids (~20 cm spacing) to withstand coolant pressurization**
  - **Breeder unit design compatible with CB or Pb-17Li concepts**
  - **Busy design with impact on TBR also**
- **CB ($Li_2TiO_3$ or $Li_4SiO_4$) and Be in form of pebble beds, FS as structural material**



**Blanket breeder unit**

**Cool. $T_{in}/T_{out}$ =300/500°C**
**Cool. P =8 MPa**
**Max FS Temp. <550°C**
**Max. Be Temp. < 750°C**
**Max CB Temp. <920°**
**Energy Multip. =1.25**
**TBR = 1.14**
**Cycle Eff. ~37% (Rankine)**
**Lifetime = 15MW-a/m$^2$**

* **S. Hermsmeyer, et al., "Revision of the EU Helium Cooled Pebble Bed Blanket for DEMO," SOFE 2003**

# Low-Pressure Requirement on Module Leads to Simpler Design

## E.g. EU A-HCPB design*

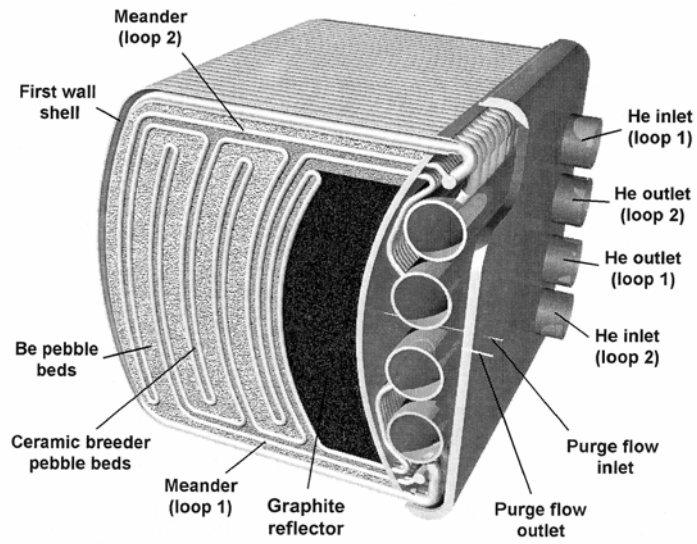



Fig.1: Isometric view of the A-HCPB blanket box.

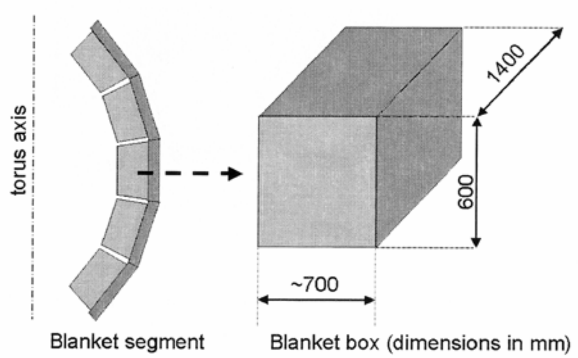



Fig.2: Blanket segment schematic picture and blanket box dimensions

- Simple box design with meandering coolant channels
  - Depending on design pressure (~ 0.5-1 MPa), module dimension up to ~0.7-0.8 m
  - Larger module would require supporting grid to accommodate pressure
  - Be and CB regions aligned parallel to first wall
  - Lower volumetric fraction of steel improves tritium breeding

- 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

* L.V. Boccaccini, et al., "Advanced He Cooled Pebble Bed Blanket," FZK report, June 2000



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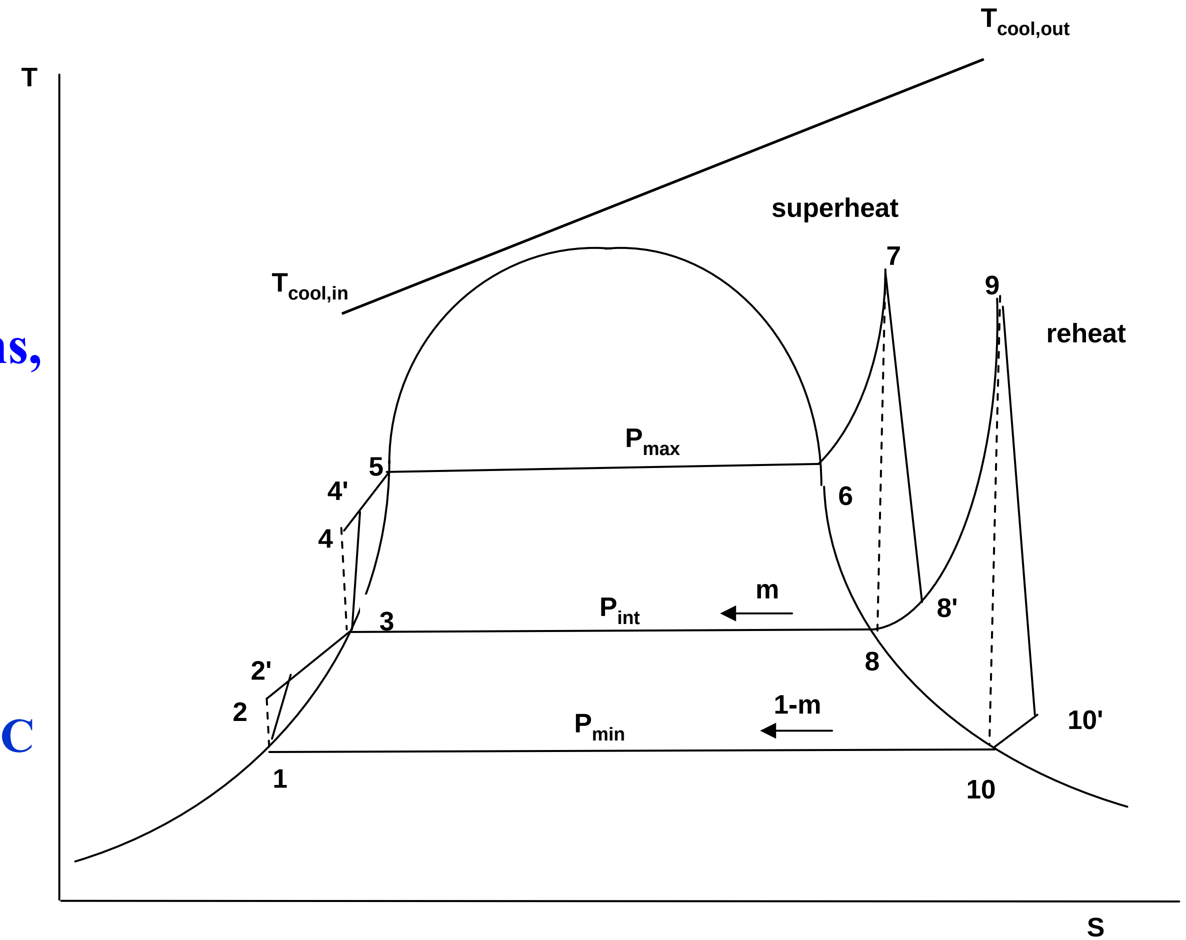
# Power Cycle Configuration

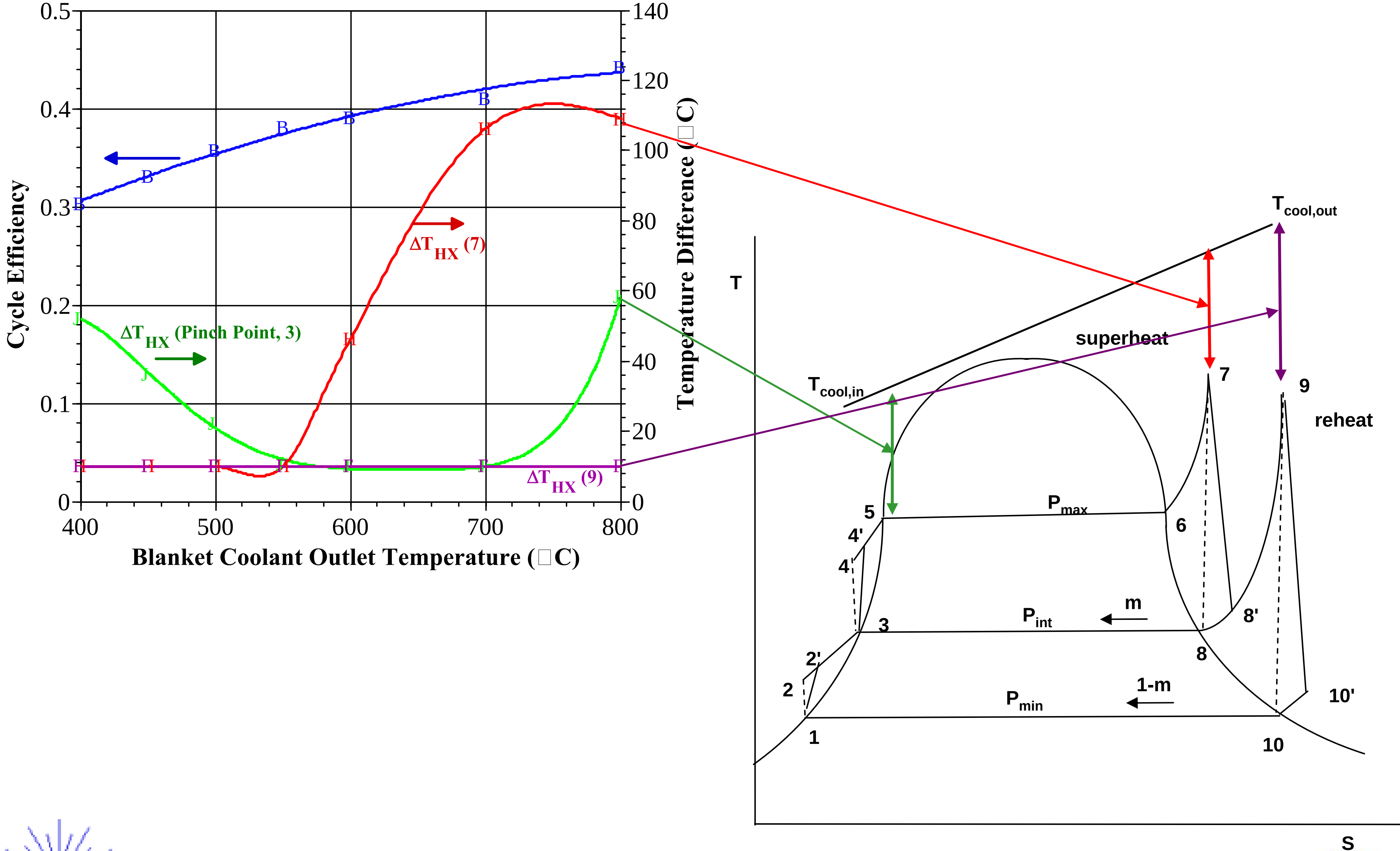
- **Rankine cycle (steam) vs. Brayton cycle (He)**
- **Typically, a Rankine cycle would offer better performance at lower He coolant temperature and a Brayton cycle at higher He coolant temperature.**
  - **What is the He coolant temperature at which it is beneficial to switch from a Rankine cycle to a Brayton range?**
  - **How does this temperature compared to the maximum He coolant temperature for a CB blanket**
  - **Most He-cooled CB blanket design up to now have assumed a Rankine power cycle**
- **Use of Brayton cycle would solve the safety issue discussed before**

# Example Rankine Cycle for Use with Ceramic Breeder Blanket Coolant with a Steam Generator

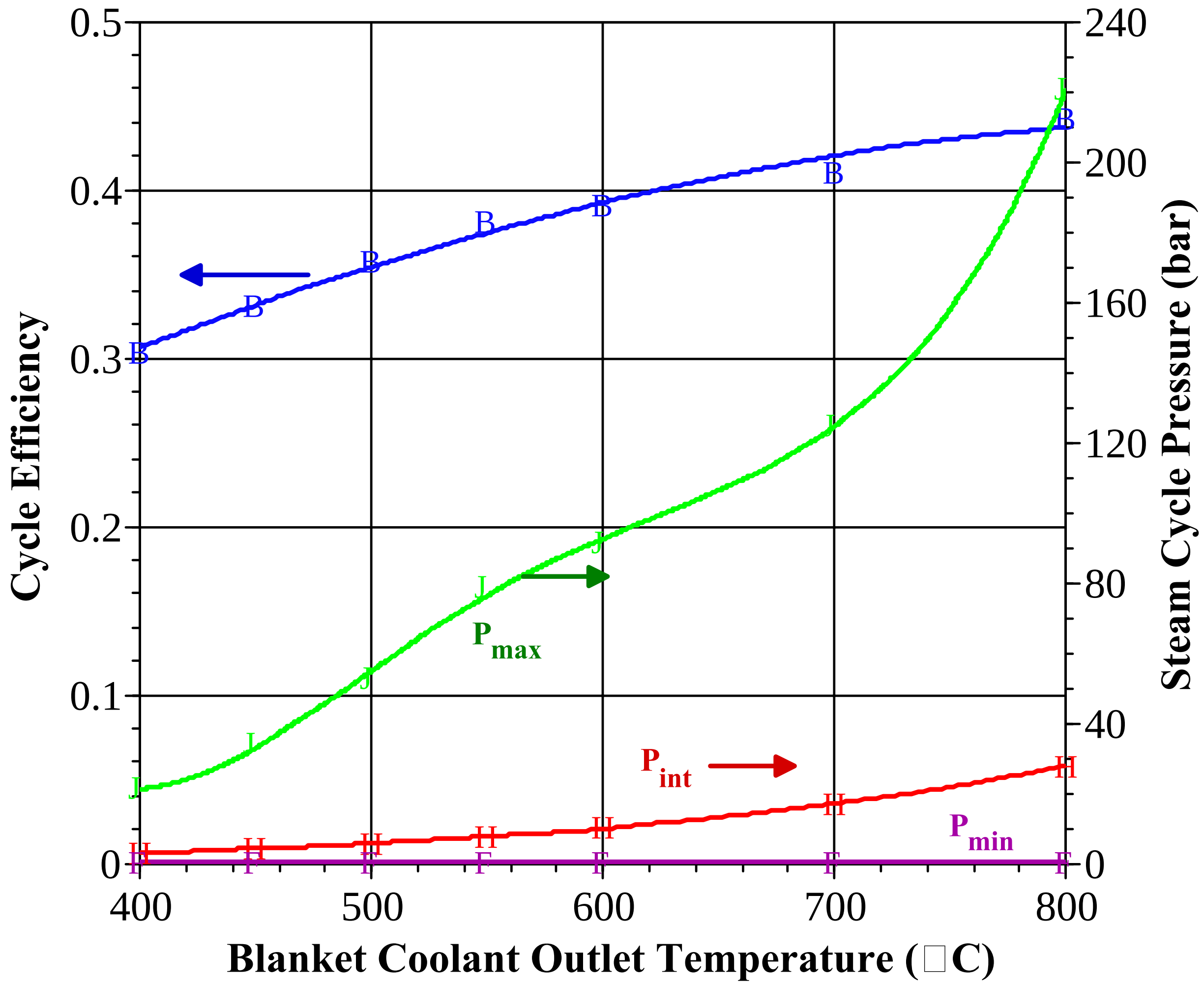
- **Superheat, single reheat and regeneration (not optimized)**
- **For example calculations, set:**
  - Turbine isentropic efficiency = 0.9
  - Compressor isentropic efficiency = 0.8
  - Min.($T_{cool}$–$T_{steam,cycle}$)> 10°C
  - $P_{min}$ = 0.15 bar



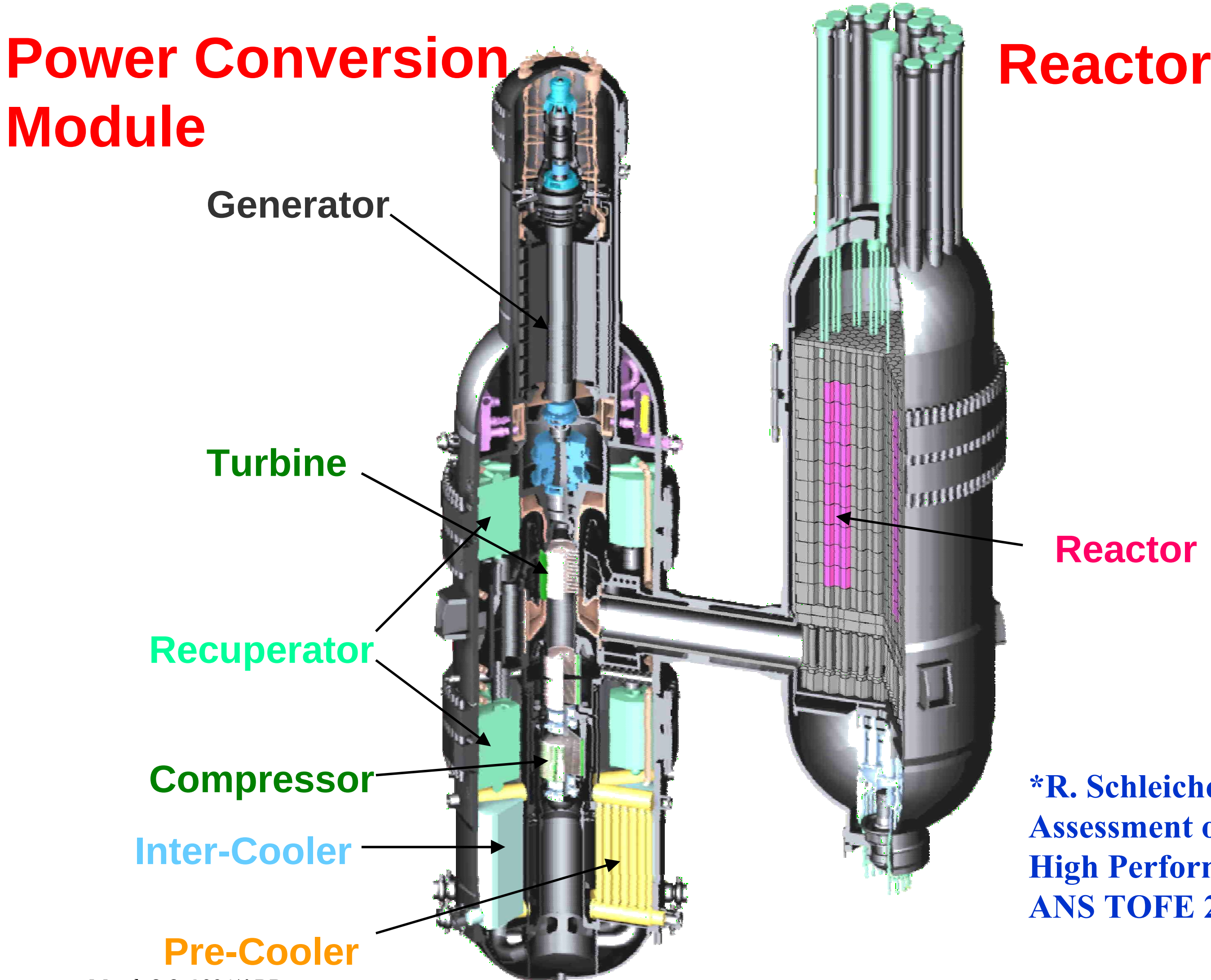
# Effect of Constraint on $(T_{cool}-T_{steam,cycle}) < 10°C$



# Rankine Efficiency and Corresponding Water Pressures as a Function of Coolant Outlet Temperature for Example Rankine Cycle



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

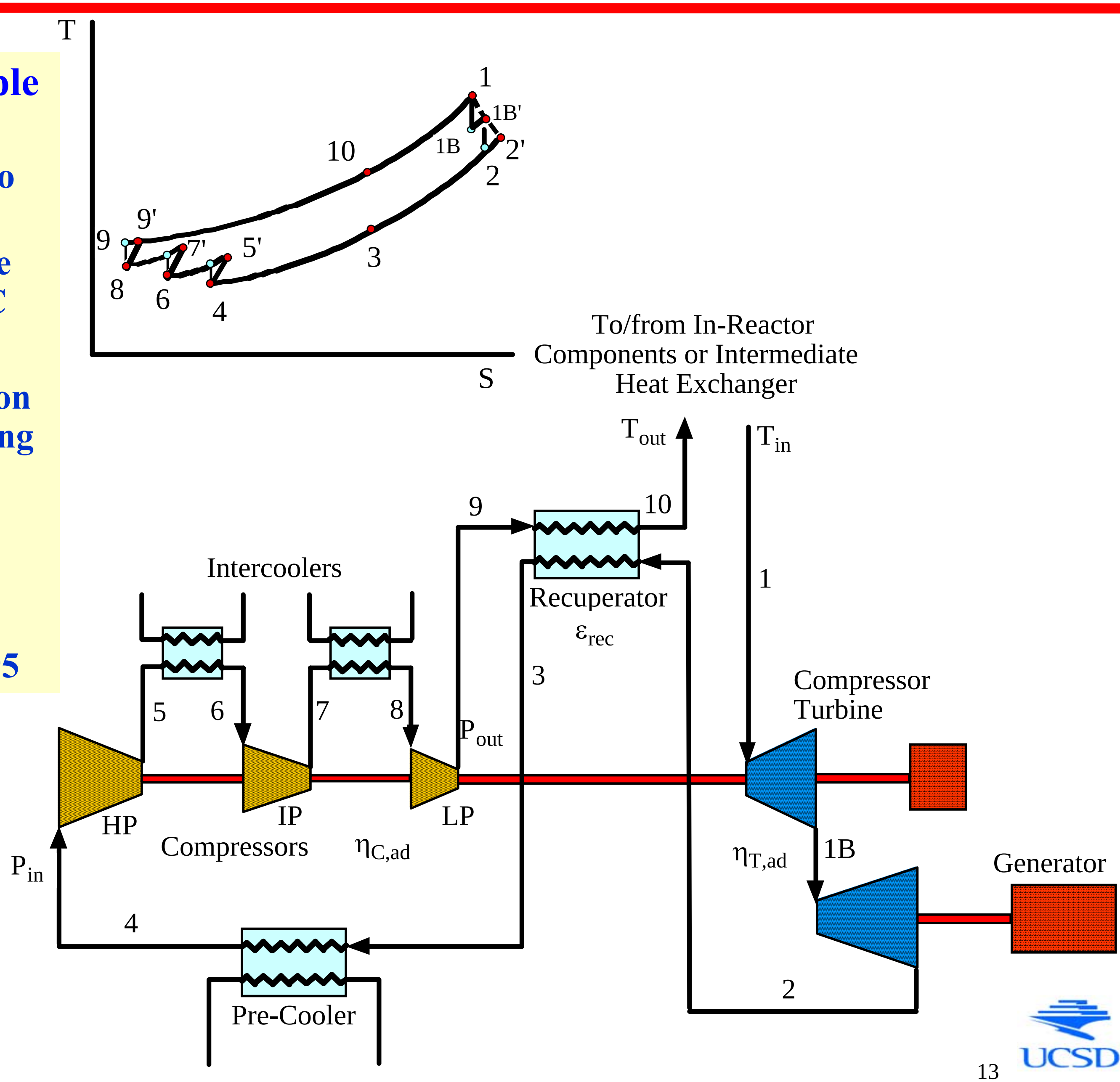



*R. Schleicher, et al., "An Assessment of the Brayton Cycle for High Performance Power Plants," ANS TOFE 2000

# Example Brayton Cycle Considered

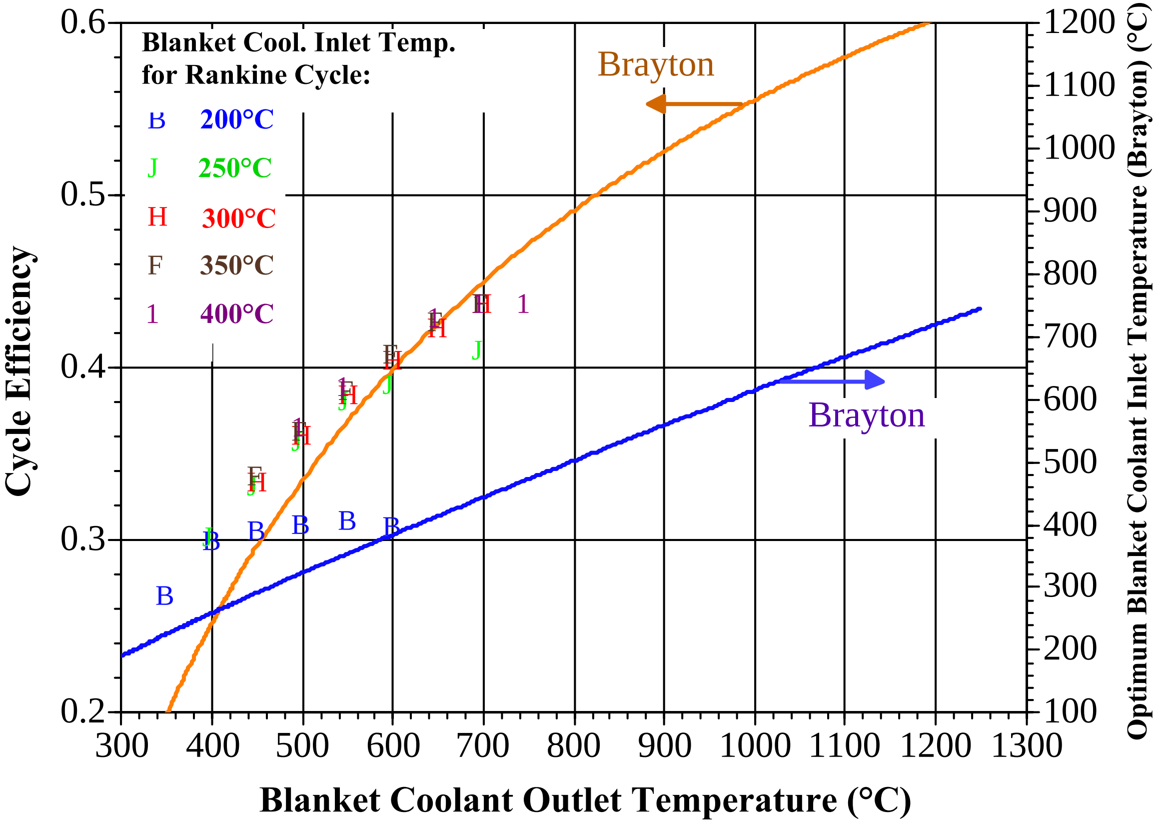
**Set parameters for example calculations:**

- **Blanket He coolant used to drive power cycle**
- **Minimum He temperature in cycle (heat sink) = 35°C**
- **3-stage compression**
- **Optimize cycle compression ratio (but < 3.5; not limiting for cases considered)**
- **Cycle fractional ΔP ~ 0.07**
- **Turbine efficiency = 0.93**
- **Compressor eff. = 0.89**
- **Recuperator effectiv.= 0.95**



# 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**



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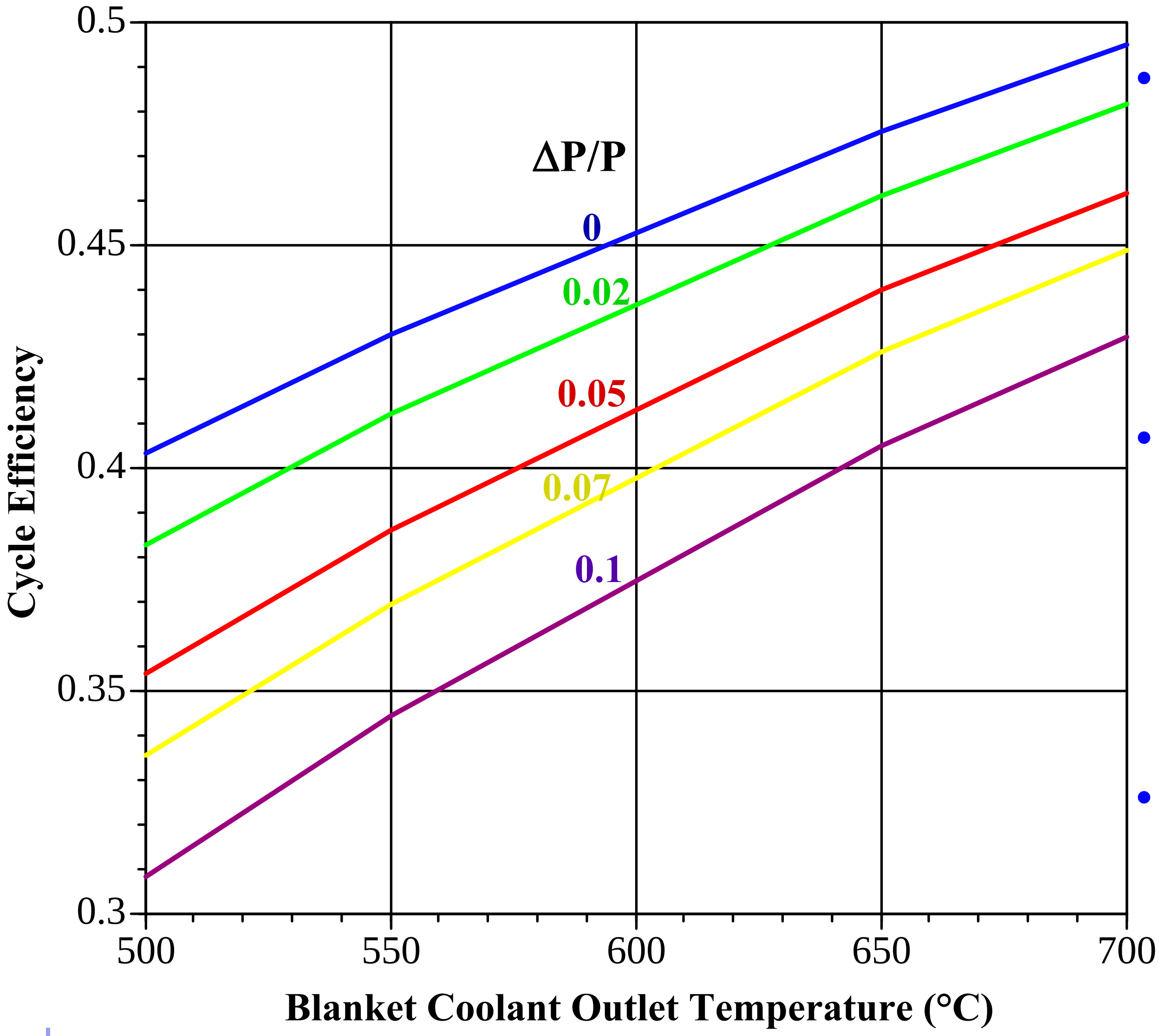
# He-Cooled Blanket + Brayton Cycle: Blanket Coolant to Drive Cycle or Separate Coolant + HX?

- **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 maximum 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 $\Delta T_{HX}$**

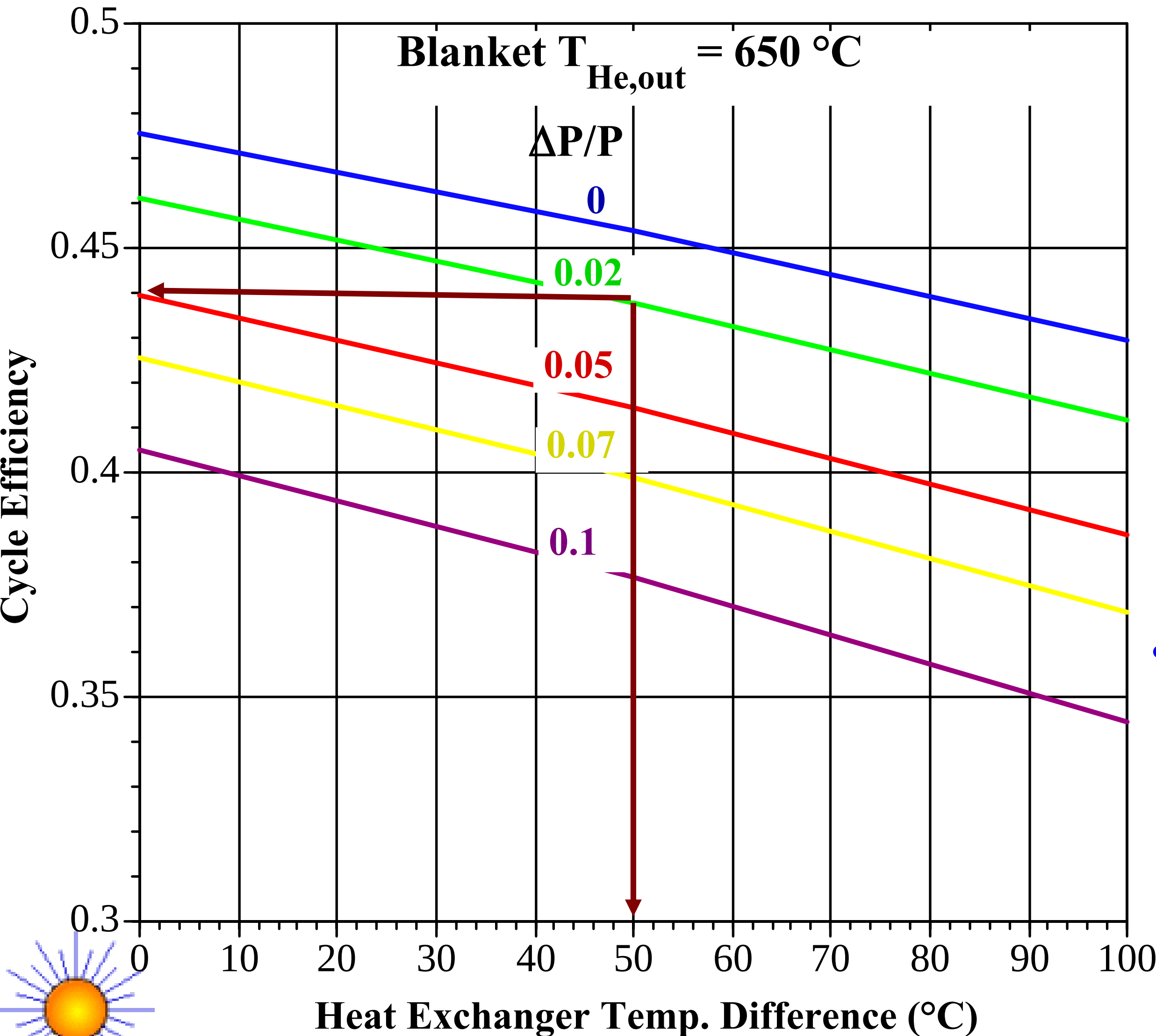
- **Tradeoff study was done to understand how these competing factors influence the efficiency**

# Effect of Fractional Pressure Drop on Brayton Cycle




- For a given blanket He outlet temperature, the cycle efficiency can be calculated as a function of the temperature difference in the HX, $\Delta T_{HX}$
- Assuming a maximum structural temperature of ~700°C (conservative limit for ODS FS), the maximum blanket He outlet temperature is ~650°C
- The cycle efficiency as a function of $\Delta T_{HX}$ for a blanket $T_{He,out}$=650° is shown on the next plot

# Comparison of Brayton Cycle Efficiencies Based on Using a Separate Blanket He Coolant and on Using the Blanket He Coolant for Driving the Cycle, Respectively




- **Example comparison showed assuming $\Delta T_{HX}$=50°C and ΔP/P=0.02 for a case with a separate cycle He**
- **For the case with the blanket He driving the power cycle ($\Delta T_{HX}$=0°C), the corresponding ΔP/P=0.05 for the same efficiency (≈0.44)**

  **(Decision would be based on whether the blkt increases ΔP/P by > or < than 0.03 )**
- **However, the cycle efficiency must be adjusted in the separate He case to account for the pumping power for the blanket He (in particular when including divertor coolant --> ΔP/P ~0.05 from initial estimate)**

# Including Effect of Blanket Pumping Power

- **For case with separate blanket He, the efficiency should be adjusted to account for the blanket He pumping power**

$$\eta_{eff} = \frac{Q_{elect} - Q_{pump,blkt}}{Q_{thermal}} = \frac{\eta_{Brayton} Q_{thermal} - Q_{pump,blkt}}{Q_{thermal}} = \eta_{Brayton} - \frac{Q_{pump,blkt}}{Q_{thermal}} \quad \textbf{(1)}$$

$$Q_{pump,blkt} = \left(\frac{\Delta P}{P}\right)_{blkt} \frac{P_{blkt}}{\eta_{pump}} \frac{m_{He}}{\rho} \qquad Q_{thermal} = m_{He} C_p \Delta T_{He} \quad \textbf{(2)}$$

- **Substituting for $Q_{pump,blkt}$ and $Q_{thermal}$ and for He ρ and $C_p$ in eq. (1):**

$$\frac{Q_{pump,blkt}}{Q_{thermal}} = \left(\frac{\Delta P}{P}\right)_{blkt} \frac{T_{He,in}(K)}{2.5311 \Delta T_{He} \eta_{pump}} \quad \textbf{(3)}$$

- **For example values of $T_{He,in}$=623 K, $\Delta T_{He}$=250°C, and $\eta_{pump}$= 0.9:**

$$\frac{Q_{pump,blkt}}{Q_{thermal}} = 1.1 \left(\frac{\Delta P}{P}\right)_{blkt} \quad \textbf{(4)}$$



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# Comparison of 2 Specific Example Cases

**Blanket He Used in Power Cycle**

Blkt & cycle P=8MPa

$T_{He,max}$=650°C

$(\Delta P/P)_{cycle}$=0.05

$(\Delta P/P)_{blkt}$ =0.05

$(\Delta P/P)_{total}$ =0.1

$\eta_{Brayton}$= 0.405

**Cycle He Separate from Blanket He**

Blkt P=8MPa
$(\Delta P/P)_{blkt}$ =0.05
$T_{He,blkt,out}$=650°C

$\Delta T_{HX}$=50°C
$T_{He,cycle,max}$=600°C
Cycle P=16MPa
$(\Delta P/P)_{cycle}$=0.025
$\eta_{Brayton}$= 0.435

$\eta_{eff}$= 0.38

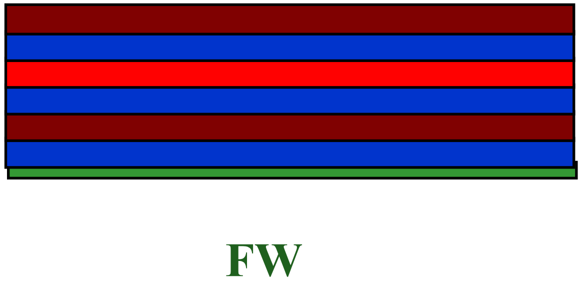
- Based on this example, it seems beneficial to use the blanket He as cycle He also
- However, this should be verified on a case by case basis with the actual blanket and cycle parameters

# Lessons from Power Cycle Study

- **Brayton cycle seems possible with He-cooled CB blanket**
- **This would remove a potential safety problem associated with steam generator failure in the case of a Rankine cycle**
- **Using the blanket coolant to drive the cycle seems preferable for the example cases considered**
- **Using the divertor He coolant for maximizing the He temperature would be a plus**
- **The exact power cycle choice and parameters should be verified on a case by case basis**

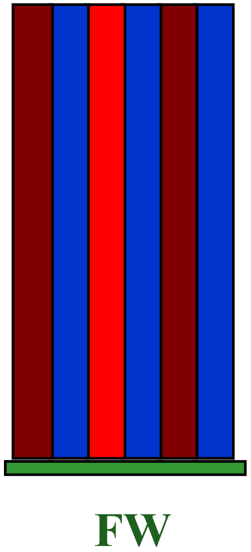
# Effect of Ceramic Breeder and Be Layer Orientation on Tritium Breeding Performance

- CB and Be layers parallel to FW as compared to CB and Be layers perpendicular to FW




- Breeding optimization would be a useful feature if TBR is marginal, for example in the case where the module must be designed to take pressurization and/or for CS cases with low blanket coverage

- Different orientations have been considered in past designs (but difficult to find a reference or documentation describing a comparison study of this)




- Should we perform a comparison of optimized concepts in each case and document the effort for future reference?

- It will also help our present design effort

# Summary

- **Module Design Load**
  - Safety study result will impact design pressure for module
  - Simpler design, better breeding associated with low design pressure
- **Power Cycle**
  - Brayton could be used with He-cooled CB
  - Eliminate safety issues associated with steam generator
- **Brayton cycle driving fluid (He) same as blanket coolant or separate**
  - Initial study indicates advantage of using blanket He to drive cycle
  - Final decision on case by case basis
- **Optimizing breeder/Be region geometry for maximum TBR**
  - Will help for cases with poor breeding or low blanket coverage in CS reactor