Helium-Cooled Divertor Options and Analysis

By
X.R. Wang, S. Malang, R. Raffray and the ARIES Team

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Plate-Type Concept

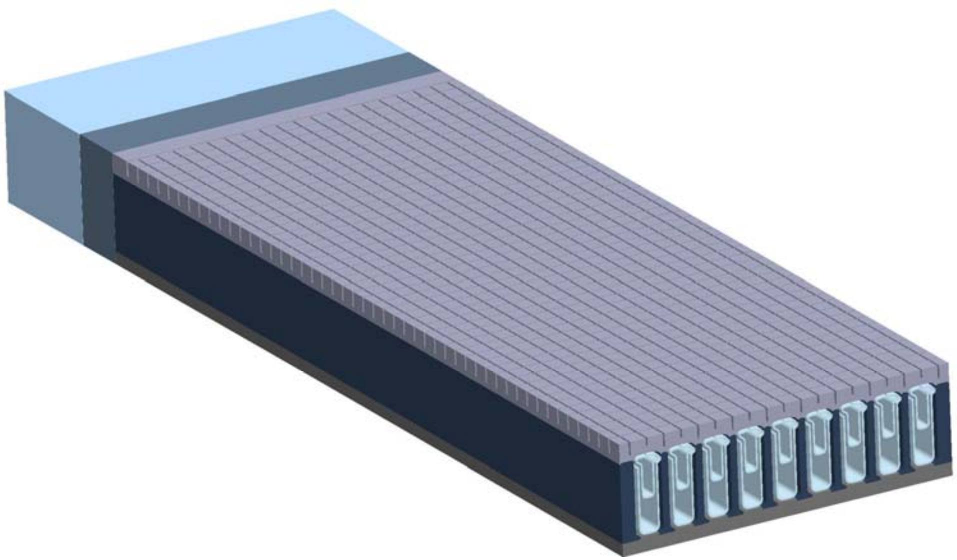


Plate-Type Divertor Concept for A Power Plant with ARIES-CS Power Levels

- The plate-type divertor configuration was initially developed based on ARIES-CS compact stellarator power levels, $q''=10\ MW/m^2$, $q_v=53\ MW/m^3$.
- The plate unit consists of a number of ~1.0 m long poloidal channel with 20 mm toroidal pitch.
- The plate is made of W-alloy with a 4.8 mm x 4.8 mm castellation tiles for minimizing stress transferring from the tiles to the structure.
- Impinging jet cooling scheme is used in the design to cool the heated surface (similar to the EU finger modular and the ARIES-CS T-tube concepts).
- In order to minimize thermal stresses, stagnant He insulating gap was used for making uniform temperature distributions in the side and back plates.
- Results of the CFD thermo-fluid and ANSYS thermo-mechanical indicate that the temperature and stress are within design limits.

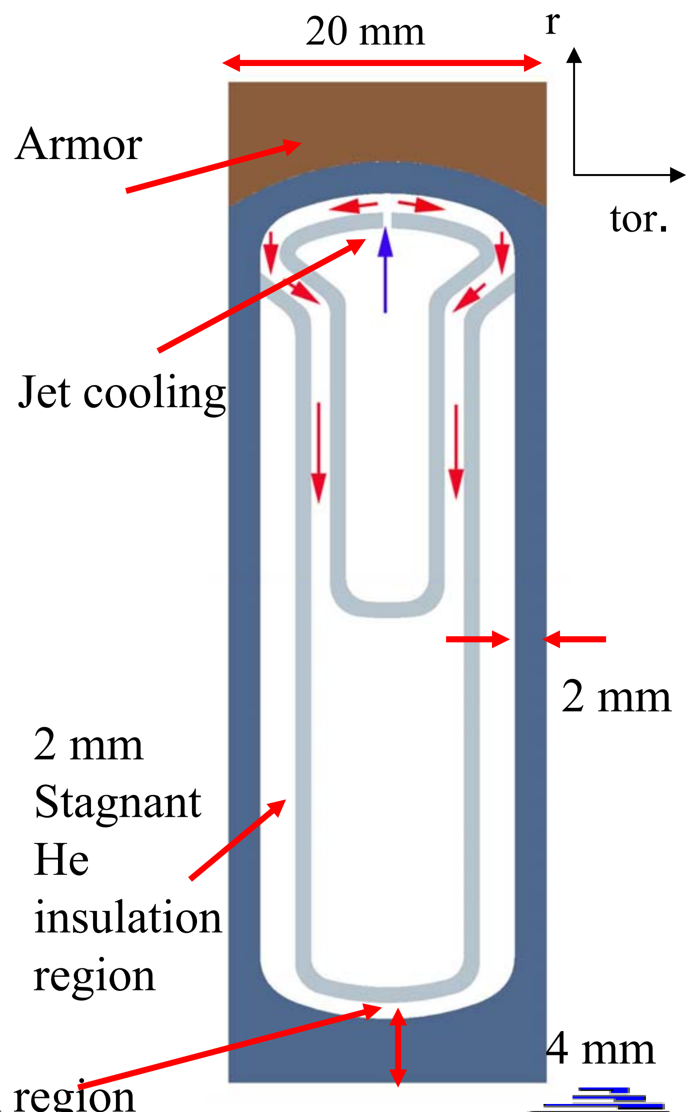


Plate-Type Configuration for A General Tokamak Power Plant (ARIES-AT)

- The plate-type divertor configuration based on ARIES-CS power loads causes high thermal stresses (>450 MPa) when it is used in a tokamak power plate, such as ARIES-AT.

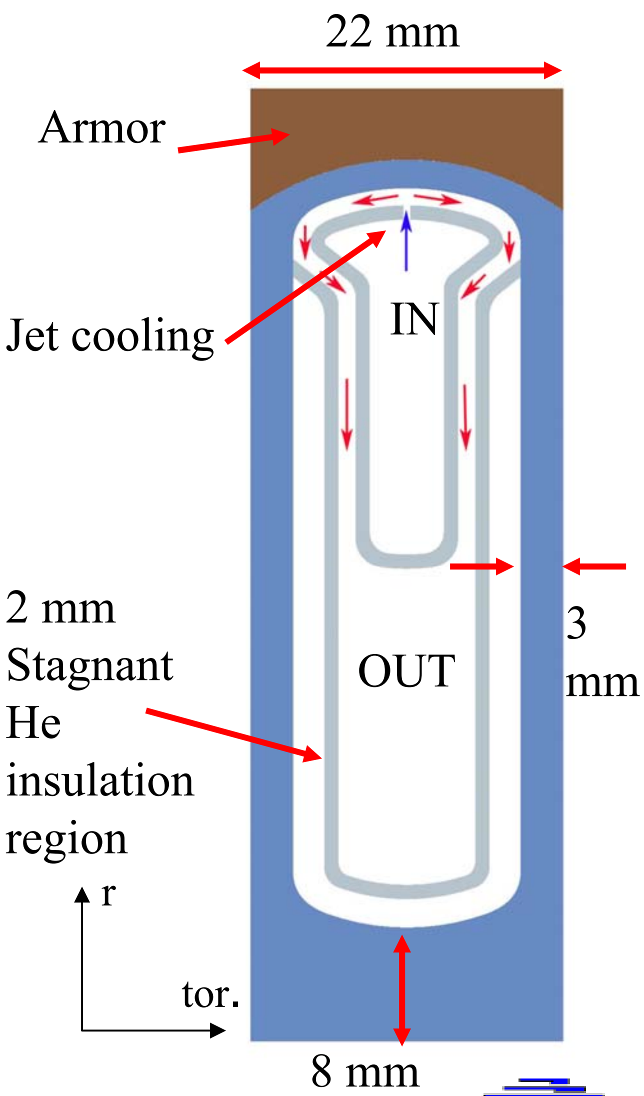
$$q''=10\ MW/m^2,\ q_v=17.5\ MW/m^3$$

- Modifications have to been made in order to reduce the thermal stress (because of the hot front structure and cold side and back plate):

✓increasing the side wall from 2 mm to 3 mm

✓placing the 2 mm insulating gap at the side and back

✓increasing the thickness of the back plate from 4 mm to 8 mm

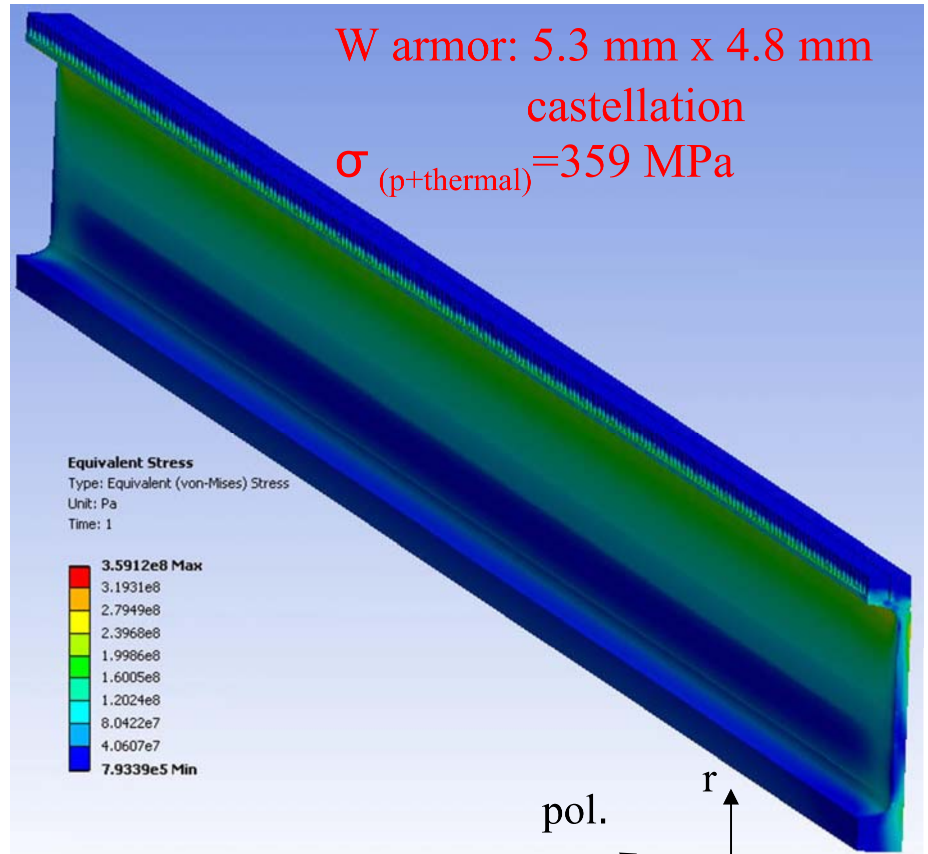


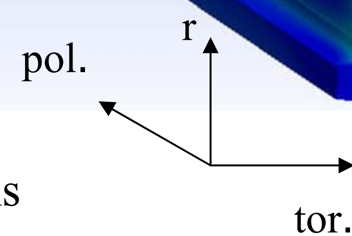
Example CFD and ANSYS Analysis Results for The Plate Concept with ARIES-AT Thermal Power Loads

- ARIES-AT thermal loads were assumed in analysis:
  - ✓Uniform surface heat flux, q''=**10** MW/m^2
  - ✓volumetric heat generation=**17.5** MW/m^3,
  - ✓He inlet/outlet temperature=**600/667** °C,
  - ✓He pressure=**10** MPs

- CFD and ANSYS results:
  - ✓Max. W armor temp.=1853 °C,
  - ✓Max. W structural temp.=1295 °C (recrystallization limit~1300 °C)
  - ✓$P_{pumping}/P_{thermal}$ <10%
  - ✓Max. thermal+primary stresses=359 MPa (assumed 3 Sm~450 MPa)
  - ✓Max. deformation=1.3 mm

- The thermo-fluid and thermo-mechanical results are encouraging; however concerns exist:
  - ✓the stress under lower heat flux region
  - ✓the dynamic stress during reactor startup or shutdown

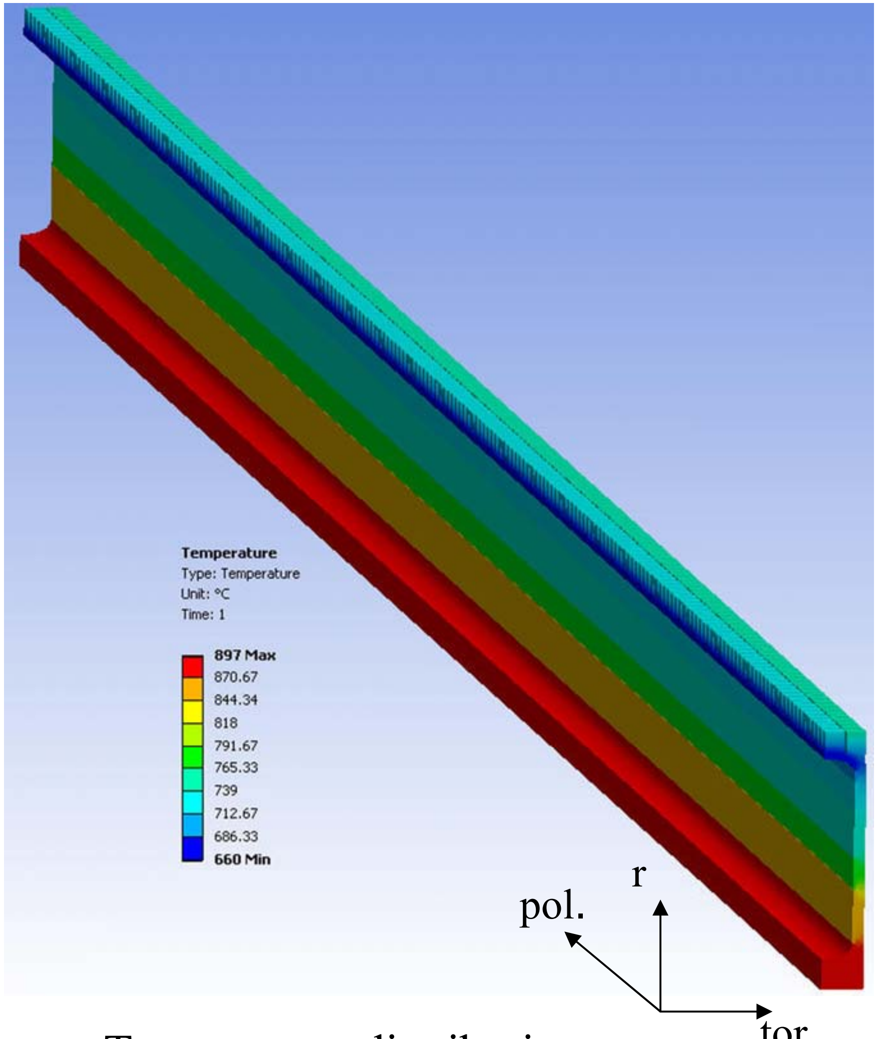




Stress distributions

Example Plate Concept with Lower Uniform Surface Heat Flux

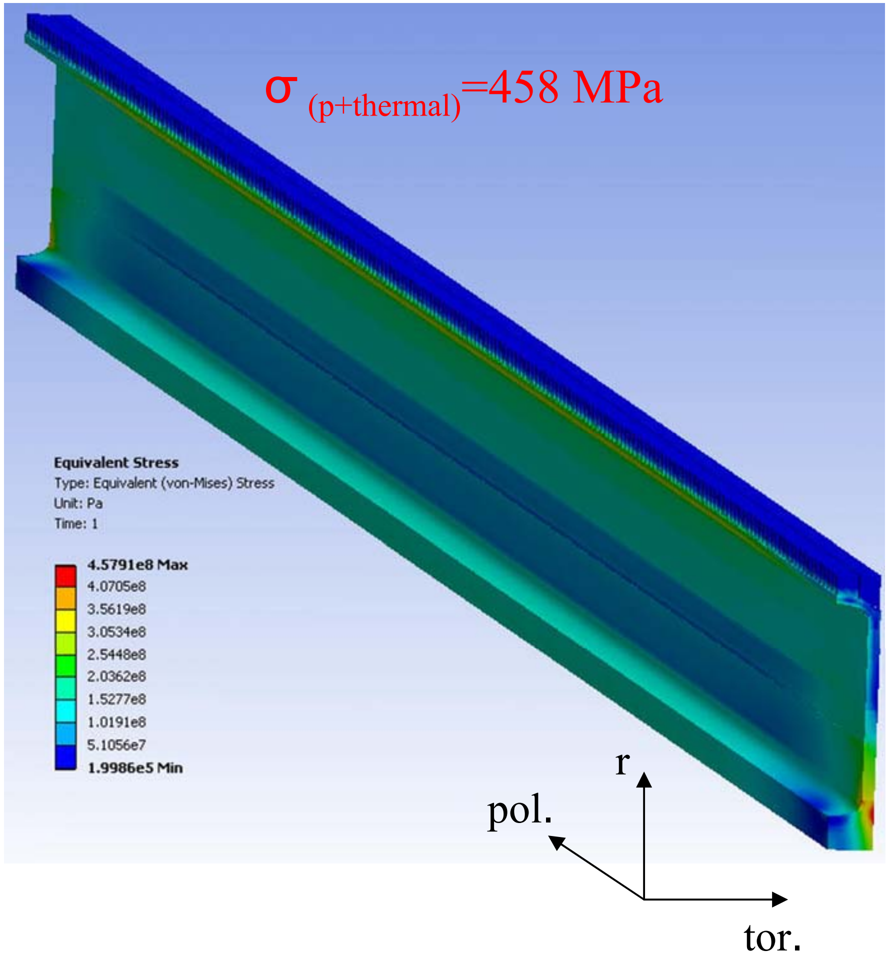
- The CFD analysis of a 100 cm long plate under non-uniform heat flux requests huge amount of elements and nodes.
  - ✓1.3 million grids for a 2 cm plate in CFD analysis.
- A simple case (the worst case for the stress) is assumed in CFD analysis:
  - ✓uniform heat flux, q"=**1.0** MW/m^2,
  - ✓volumetric heat generation=**17.5** MW/m^3,
  - ✓He inlet/outlet temperature=**600/667** °C,
  - ✓He pressure=**10** MPs
- Thermal-fluid results:
  - ✓Max. W armor temp.=750 °C,
  - ✓Max. W structural temp.=897 °C



Temperature distributions

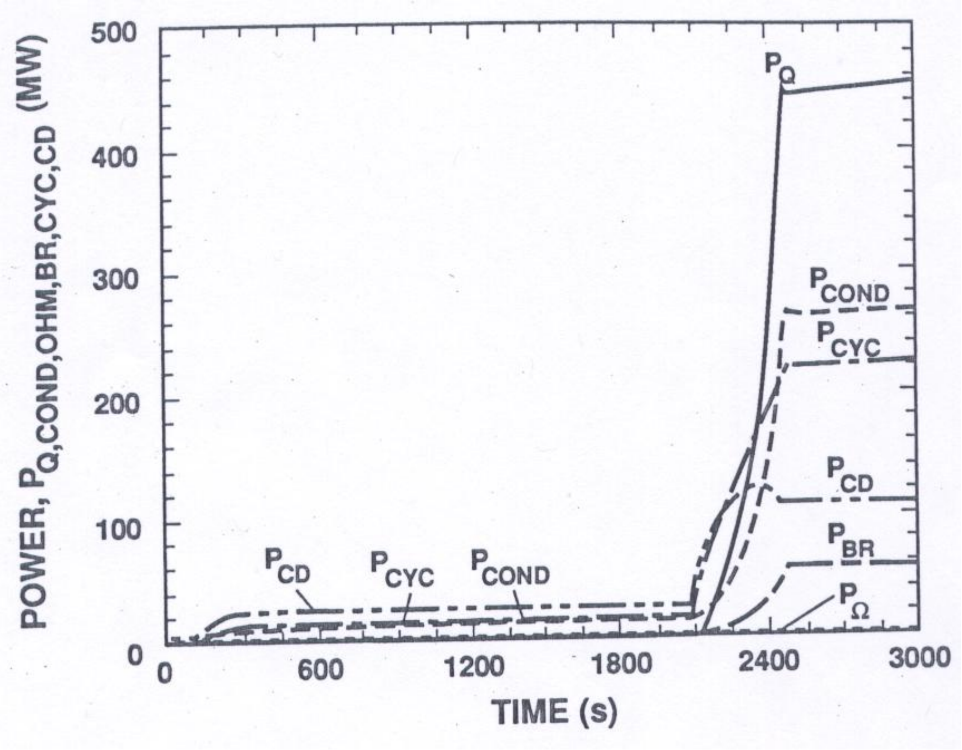
Example Thermo-Mechanical Analysis for Plate Concept with Lower Surface Heat Flux

- Max. thermal+primary stresses=458 MPa (assumed 3 Sm ~ 450 MPa)
- Max. deformation=0.3 mm
- These static results under uniform heat flux indicate that the plate concept design is better applicable to regions with moderate heat flux, q”<8 MW/m^2.
- For q”<8 MW/m^2, both the temperature and stress are well within design limit when reducing back plate to 4 mm and reducing the side wall to 2 mm.



ARIES-I Start-up Scenario Considered as Reference Time-Scale in Transient Response Analysis

- ARIES-I start-up scenario:
  - ✓ $0 \leq t \leq 2100$ s, $P_Q \sim 0$, others in lower power;
  - ✓ $2100 \leq t \leq 2500$ s, power ramp-up to full power;
  - ✓ at $t \approx 2500$ s, the steady-state conditions obtained.



P_Q: α-particle heating power; P_{COND}: transport power loss; P_Ω: ohmic dissipation; P_{BR}: bremsstrahlung power; P_{CYC}: synchrotron power; P_{CD}: current-drive heating.

Transient Thermal Response of the Plate-Type Divertor Concept for ARIES-I Startup Scenario

- Constant helium flow rate and constant helium inlet temperature of 600 ^{o}C, and constant helium pressure of 10 MPa

- In order to save computing time in the transient analysis, the W armor is assumed to be one piece without castellation and without mechanical connection to the W-alloy structure (simulated by using an artificial Young's Modulus of zero for the tiles)

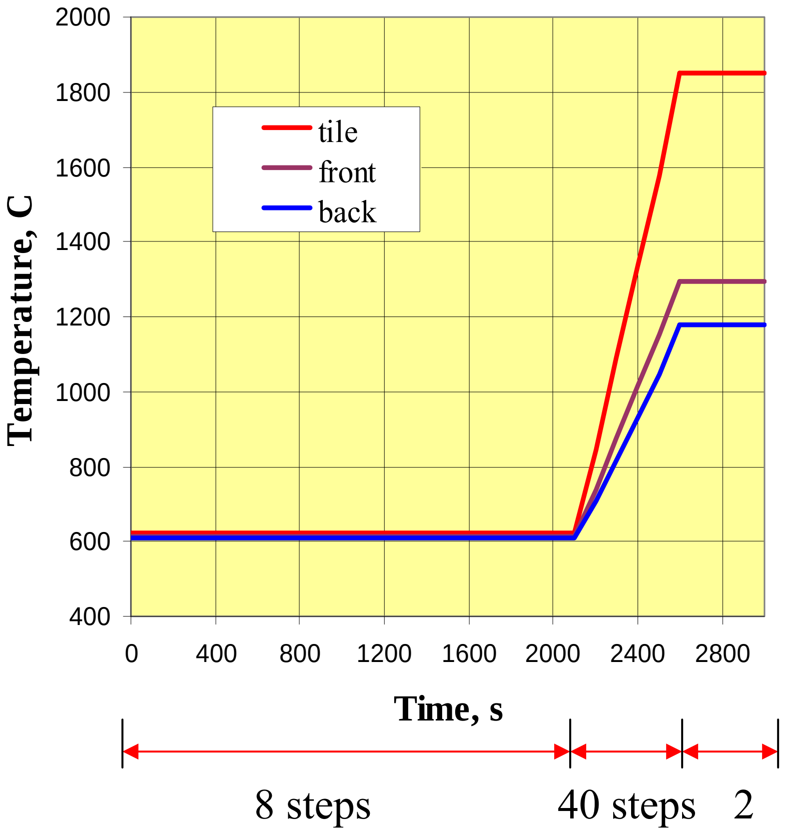
  time consuming in steady-state:

  - ✓3D model with castellation, ~28 hours
  - ✓3D model without castellation, ~1 hours

  In the steady-state, it has been demonstrated that the stress transferring from the armor to the structure would be minimized to zero if the armor castellation is small enough.

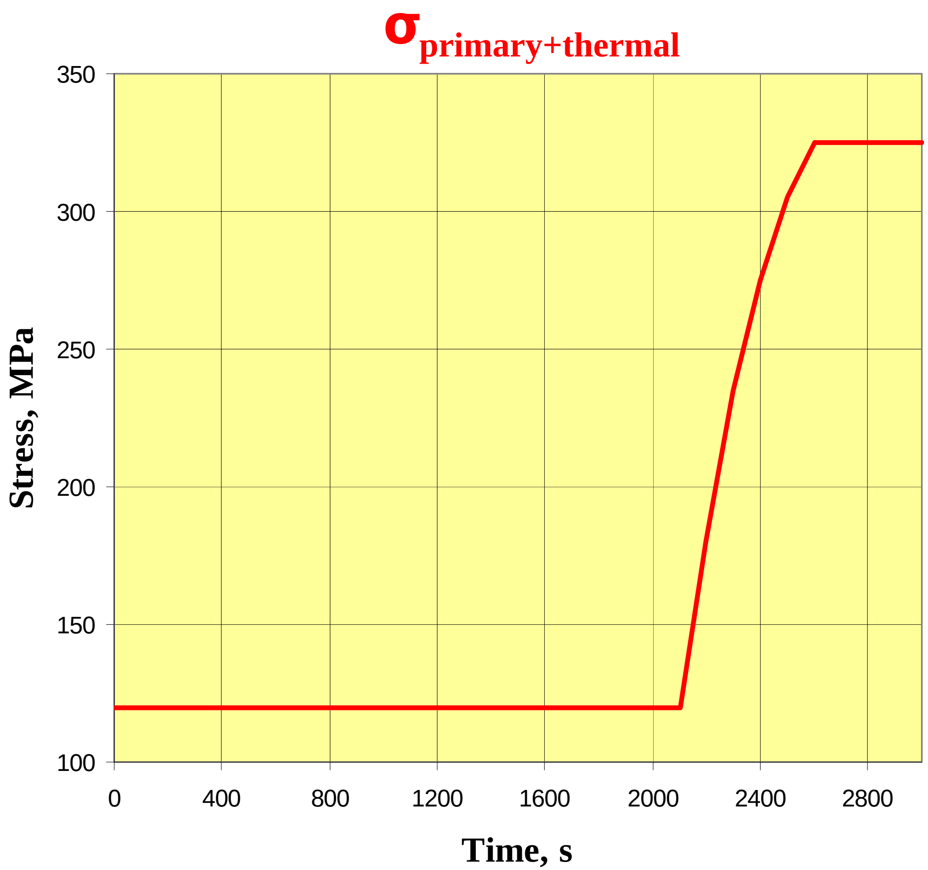
  time consuming in transient state, 50 time steps assumed:

  - ✓3D model with castellation, the least time~50x28 hours
  - ✓3D model without castellation, the least time~50x1 hours



Transient Mechnical Response of the Plate-Type Divertor Concept for ARIES-I Startup Scenario

- Transient thermal conditions (temperature distributions vs. time) are directly coupled into the transient structural model.
- Thermal stress is assumed to be zero at coolant inlet temperature (600 °C).
- Constant He pressure=10 MPa.
- No channel bending, but free expansion.
- The results indicate that the stress levels in the ARIES-I startup scenario to be within the design limits (3Sm ~ 450 MPa).



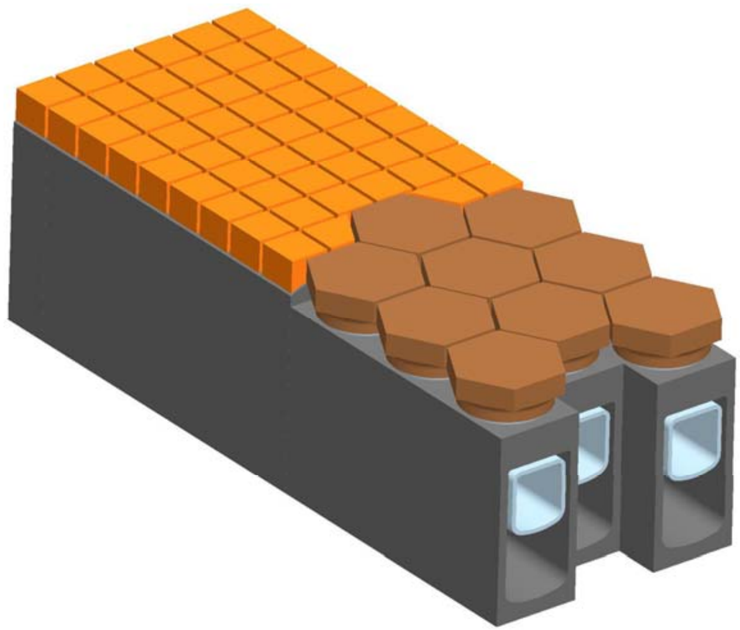
The transient thermal and mechanical response for reactor shutdown scenario has not done yet.

Summary for the Plate-Type Concept

- The plate-type divertor concept provides advantage of large modules and possibility of reducing the number of divertor units, fabrication complexity and cost of the divertor.

- The results indicate that the plate concept design is better applicable to the divertor with moderate heat flux, q”<8 MW/m^2.

Combined Plate/Finger Concept



Combined Divertor Configuration

➢Considering the large variation of the divertor heat flux profile, it brings up the possibility of optimizing the heat flux accommodation and reliability measure (based on numbers of pressure joints or units) by utilizing the smaller-scale designs (EU finger modular divertor) for high heat flux region and larger scale design (plate-type concept) for the lower heat flux region.

➢Two possible combined configurations:

✓Separate design with smaller units in the high heat flux region and the plate-type design in the lower flux region and routing the coolant so as to cool these regions in parallel.

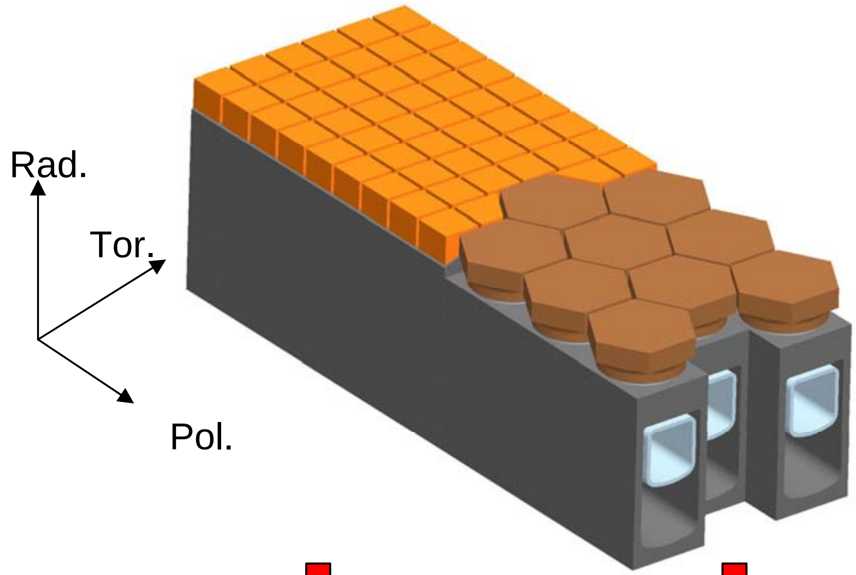
✓Integrated the smaller scale unit within the plate design and routing the coolant through the integrated unit.

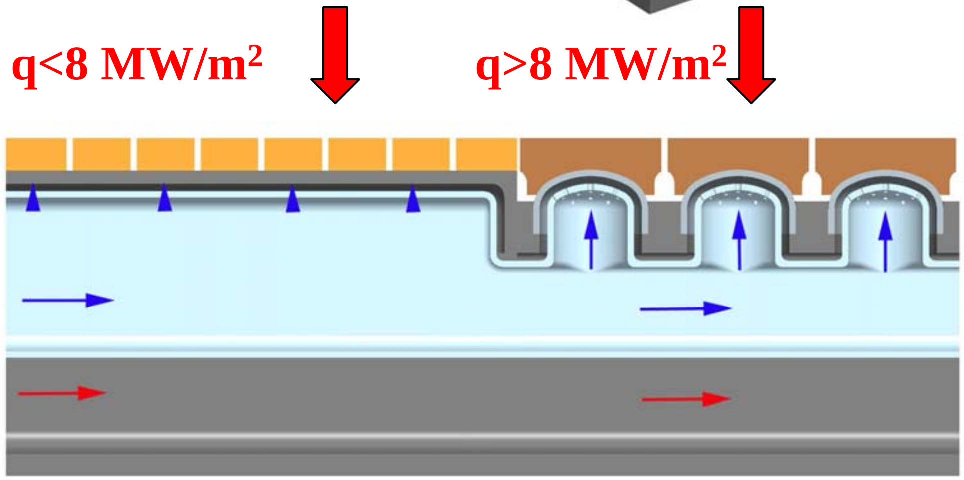
Key Features of the Typical He-Cooled Divertor Concepts for an Assumed Divertor Area of ~150 m^2

Divertor Concept	Unit Characteristic Dimensions	Number of Units for a Typical Tokamak	Allowable Incident Heat Flux (MW/m^2)
Finger	1.5 cm dia	~535,000	>12
T-Tube	10 cm x 1.5 cm	~110,000	~10
Plate	100 cm x 20 cm	~750	~8

Example Integrated Plate/Finger Concept

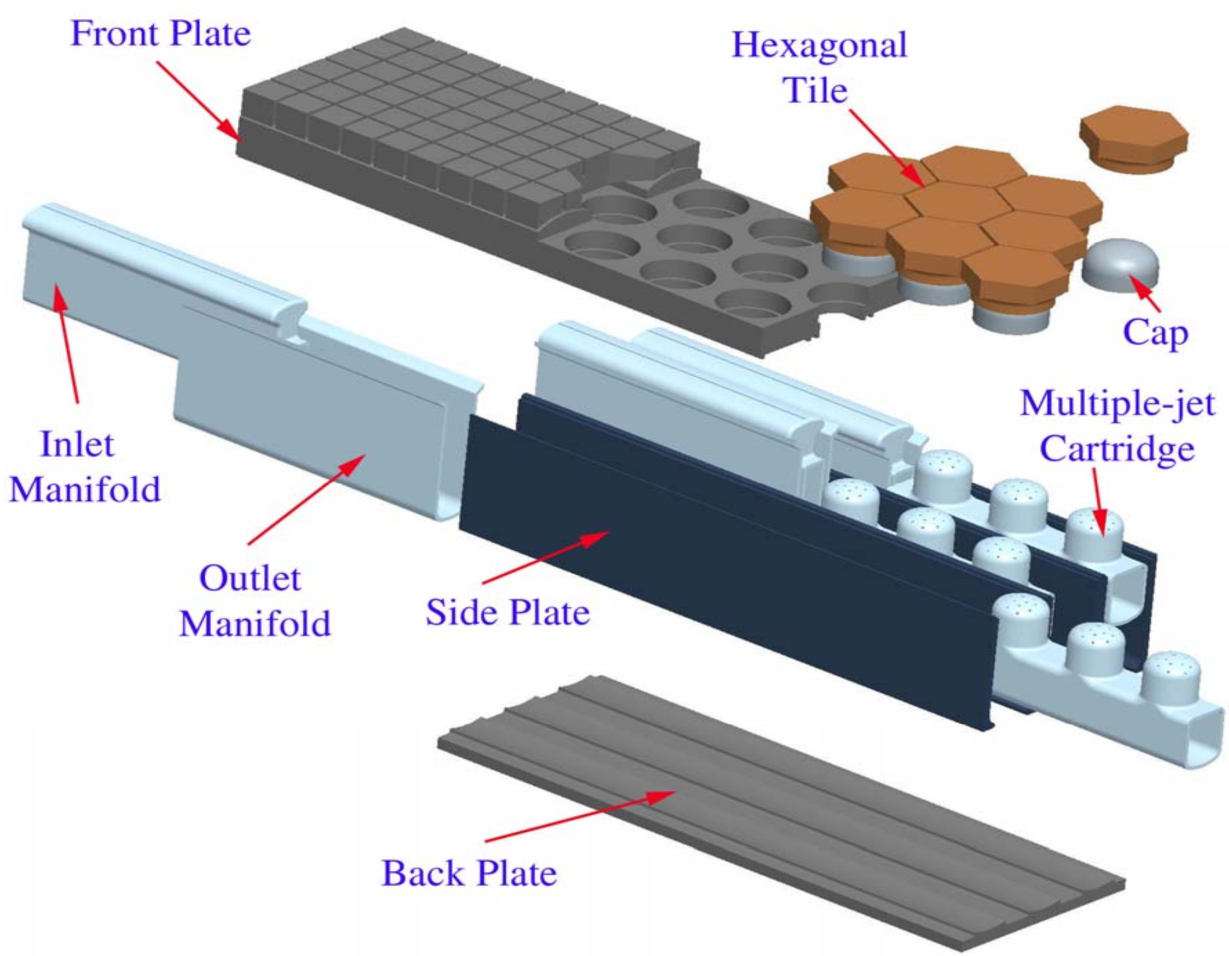
- The plate concept is used in the two zone divertor for zones with the heat flux < 8 MW/m^2, and the lower heat flux zone is~75 cm.
- The plate is modified to the modular concept, HEMJ (FZK), for the zone with heat flux >8 MW/m^2, the high heat flux zone is ~25 cm.
- The cooling method employed in the high heat flux zone is similar to the EU HEMJ (FZK) concept. However, the critical connection between W and steel is avoided with the integrated concept.
- For a high heat flux zone, the number of the finger units with the ~750 integrated plate components is ~87,820 (compared with the 535,000 finger units required for full target plate coverage).
- The helium flows into the entry manifold at one end of the plate to the exit manifold at the other end, and parallel cooling of the fingers.





Integrated Plate/Finger Concept Assembly

- A front plate with castellation in the low heat flux zone, grooves for brazing the side walls, and machined holes for inserting the modular tiles and caps in the high heat flux zone.
- A back plate with grooves for brazing in the side wall of the large helium channels.
- W hexagonal tiles and small W alloy caps, brazed together and inserted in the front plate in the high flux zone.
- Multiple-jet cartridges and slot-jet cartridge.
- Side walls.



CFD Analysis of the Integrated Plate/Finger Concept

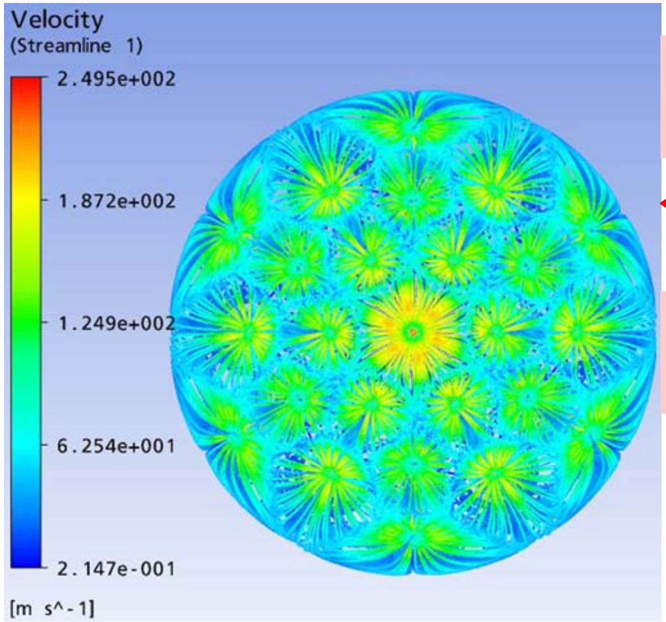
➢Parameters and results from thermo-fluid analysis (using CFX) for the integrated concept:

✓Incident q"=10 MW/m^2 and neutron volumetric heat generation=17.5 MW/m^3

✓He inlet/outlet temperature=600/700 ^oC; He pressure=10 MPa

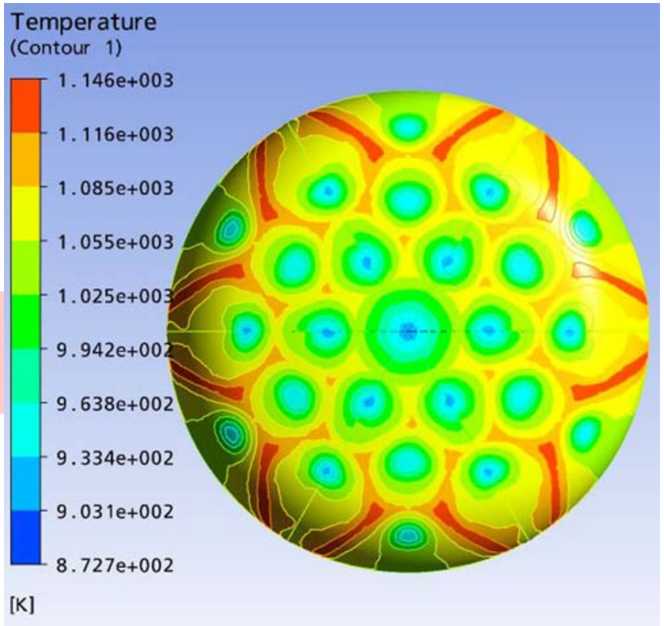
✓Max. jet velocity=~250 m/s; Max. h.t.c=5.84x10^4 W/m^2K

✓$P_{pumping}/P_{thermal}$ ~7.5 % (< design limit of 10%)

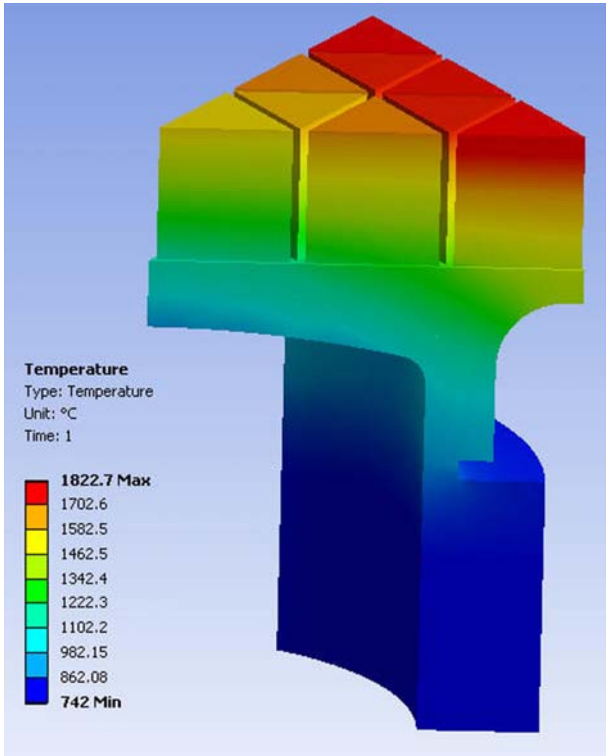


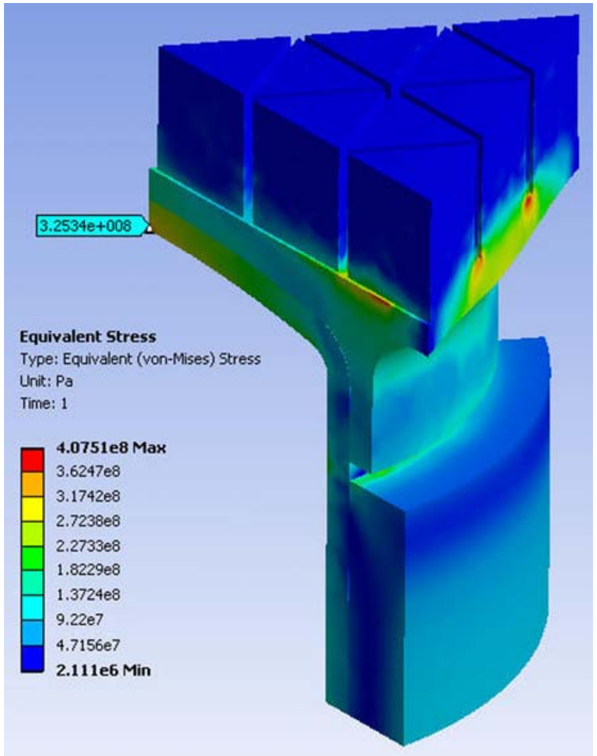
Velocity distribution in integrated finger

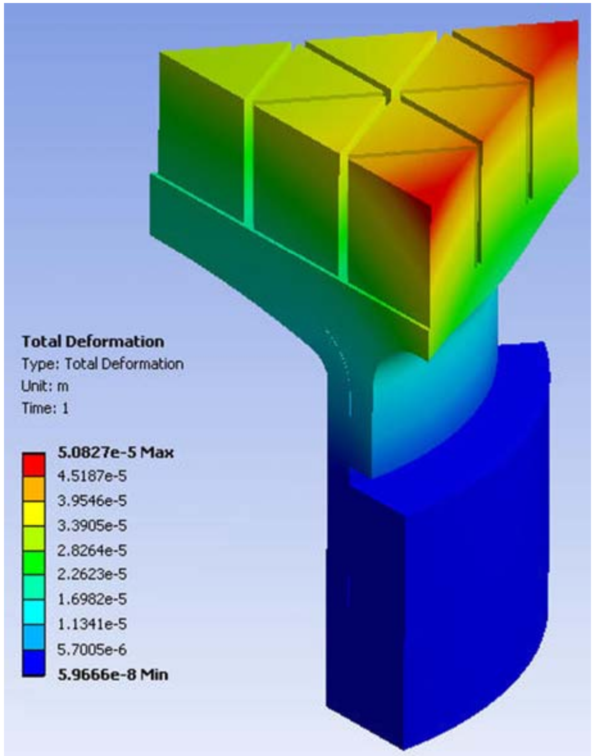
He/W cap interface temperature distribution



Thermo-Mechanic Analysis of the Integrated Plate/Finger Concept







- W armor is assumed to be castellated with ~4.45 mm long triangle, 0.25 mm gap and 4 mm deep.
- Max. Armor temperature=1823 °C
- Max. Thimble temperature=1210 °C (< assumed allowable of 1300 °C)
- Max. Armor stress σ_{p+s} =408 MPa, and Max. thimble stress σ_{p+s} =325 MPa
- Max. σ_p(pressure stress)=110 MPa

Summary for the Integrated Concept

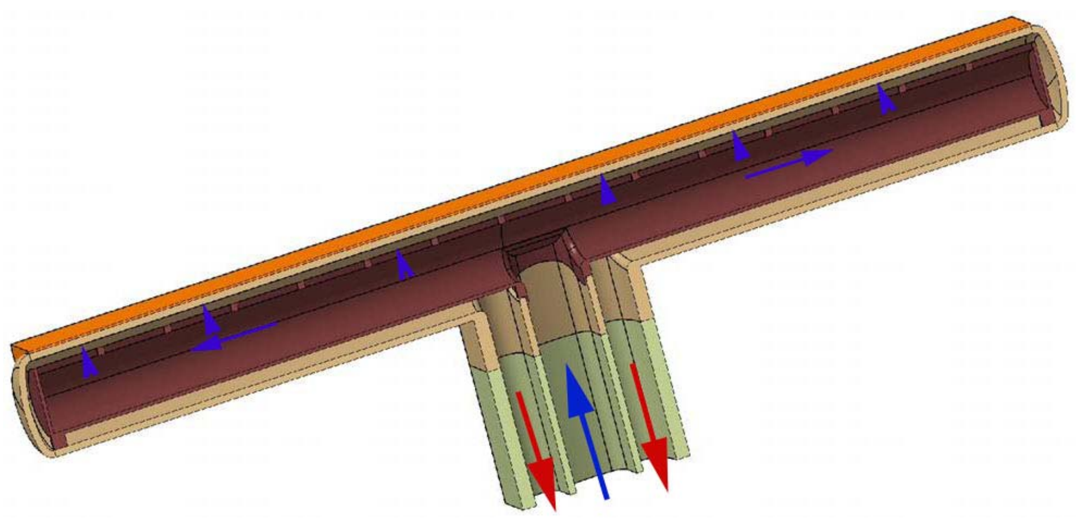
- A possibility of optimizing the helium-cooled divertor design is to combine different configurations in an integrated design based on the anticipated divertor heat flux, for example, a Gaussian profile.

- An example of such an integrated design has been proposed, consisting of small finger unit in the high heat flux region integrated in a larger plate design.

- Its performance in term of accommodating the incident heat flux within the material stress and temperature limits is comparable with original finger unit (EU HEMJ) but is achieved with much fewer units and pressure joints of materials with different thermal expansion coefficients.

- The initial results from supporting analysis are encouraging in assessing the potential of such a concept, but further work is needed for a more complete assessment, including more design details on the fabrication and assembly procedures, and detailed analyses of transient events.

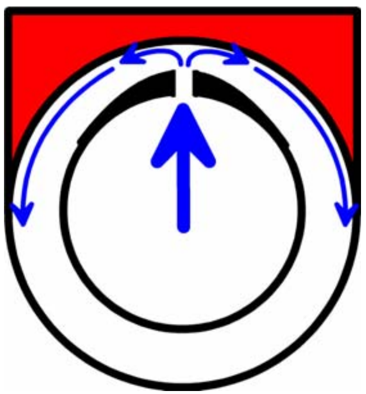
T-Tube Divertor Concept



T-Tube Divertor Concept for A General Tokamak Power Plant

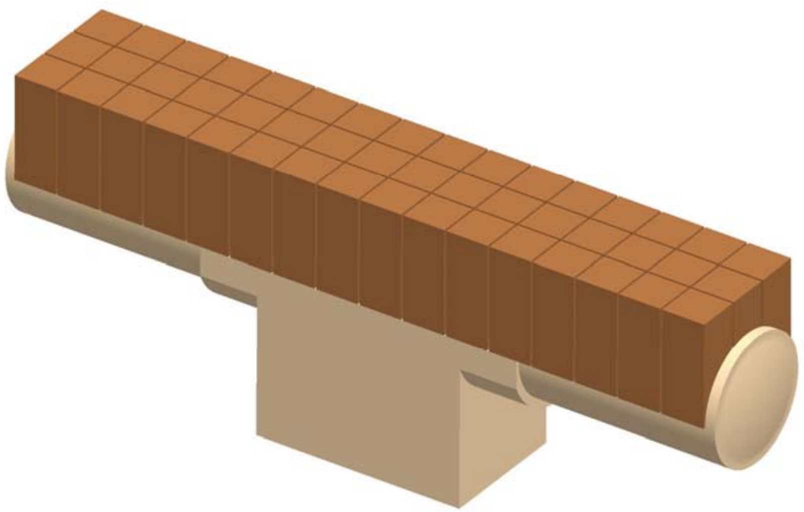
- He-cooled T-Tube divertor concept was proposed for the ARIES-CS power plant for accommodating a heat flux of 10 MW/m^2 and a neutron volumetric heat generation of 53 MW/m^3
    - ✓ ***slot-jet cooling, 10 MPa***
    - ✓ ***0.3 mm W tile***
    - ✓ ***need ~110,000 T-Tubes for a power plant (~535,000 finger units, ~750 plates)***

0.3 W mm armor



ARIES-CS Divertor

- 5 mm thick W armor will be assumed if the T-Tube concept used for a tokamak power plant.
- The W armor should be castellated in order to minimizing the stress transferring from the armor to the tube structure.
- No analysis has been done so far for the T-tube with 5 mm thick W armor under the ARIES-AT thermal loads.



T-Tube with 5 mm thick W armor