Improved Design of a Helium-Cooled Divertor Target Plate

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Critical Design Issues of the Helium-Cooled Finger Divertor Concepts

- A few advanced Helium-cooled W-alloy divertor concepts have been investigated for power plant application with a goal of accommodating a heat flux of 10 MW/m^2. The concepts include:
  a) EU FZK smaller scale finger concept
  b) ARIES mid size T-Tube concept
  c) ARIES larger scale plate-type divertor concept
  d) ARIES combined larger plate/finger or plate/T-tube concept
- Impinging jet-cooling schemes are utilized in all the divertor concepts.
- There are some crucial issues for this class of divertor which need to be addressed, including:
  - ✓ **Issue 1: Joints or transition zones between W-alloy and steel manifolds**

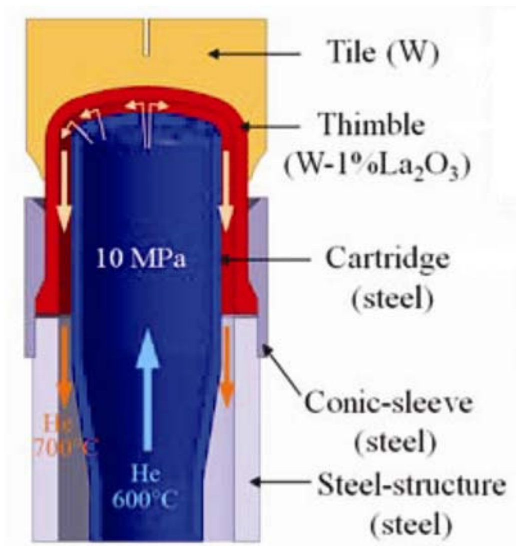
    Concept a and b

    The large number of the difficult joints or transition zones between the W-alloy and steel could significantly impact on the overall reliability.
  - ✓ **Issue 2: Containment of the high pressure helium**

    Concept a, b and d

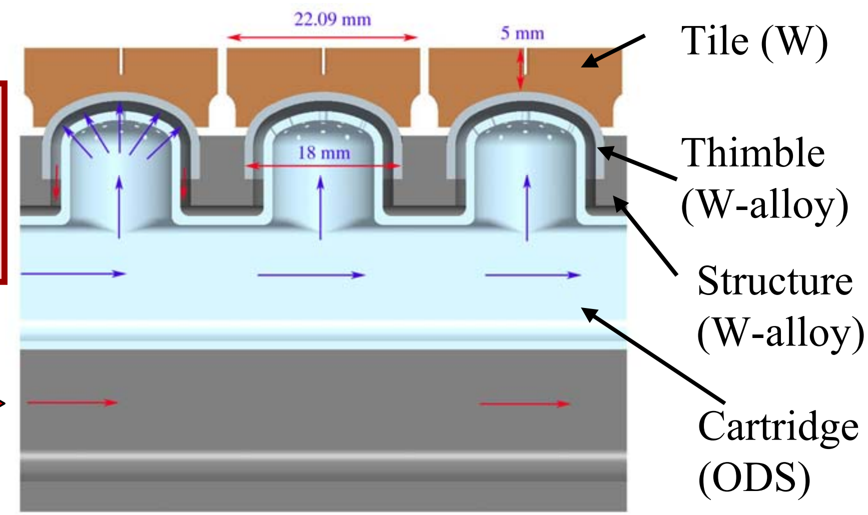
    Helium leak may occur at the 1 mm thick wall separating the high pressure helium and the plasma chamber. Concept a, b and d may have this issue.

Issue (1) Avoided in the Latest ARIES Divertor Design Concepts

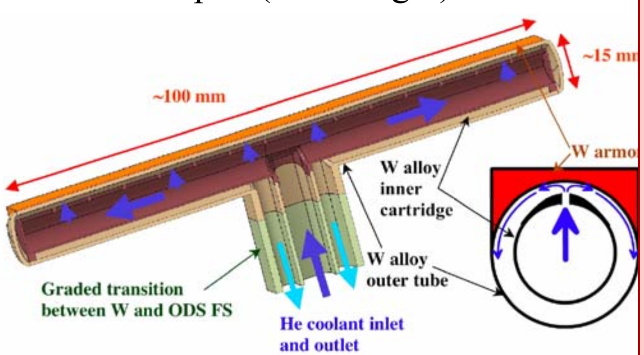


Concept a (FZK finger)

Joints are made of the same material.



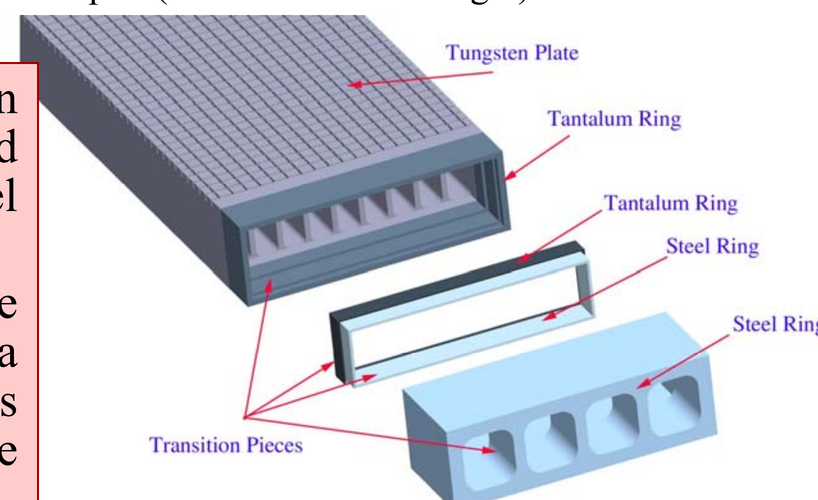
Concept d (ARIES modified finger)



Concept b (ARIES T-Tube)

Tantalum transition pieces are placed between W and steel at the plate ends.

This is not clear one could also use a tantalum ring as transition ring for the T-Tube.

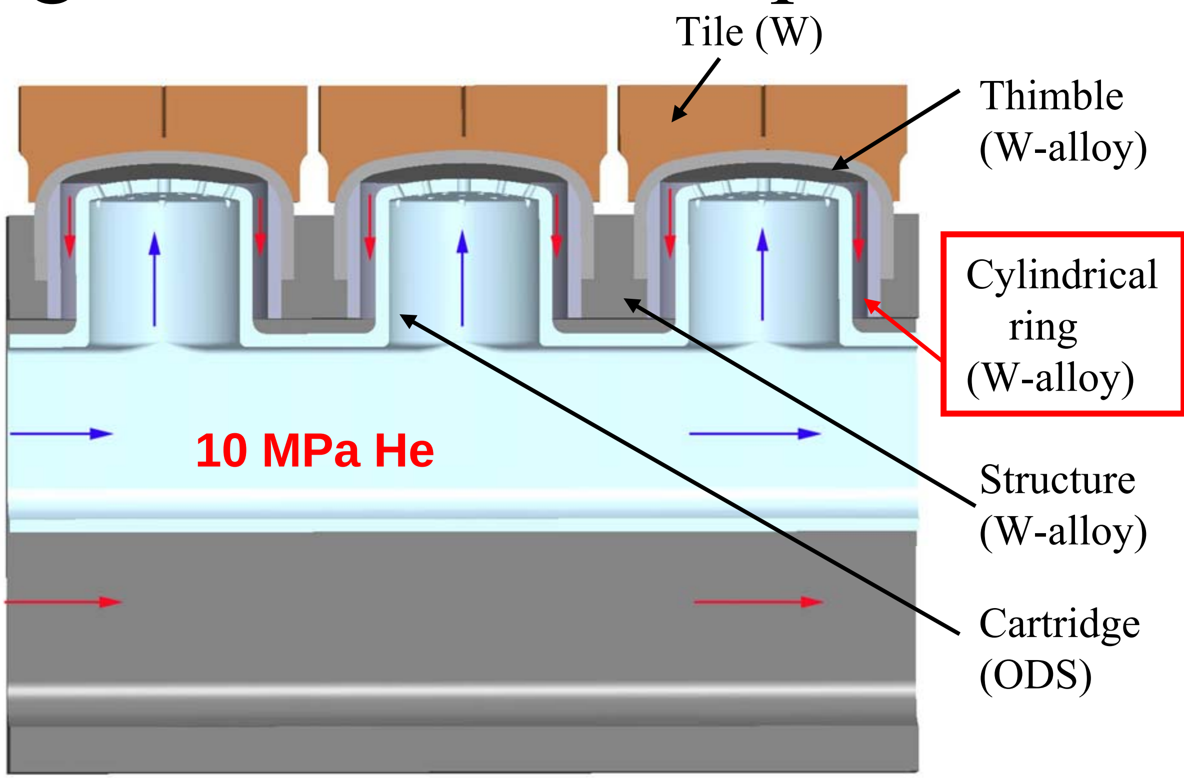


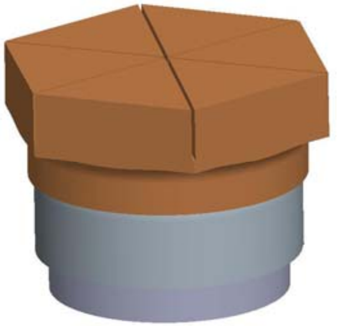
Concept c (ARIES plate-type concept)

New Modification and Improvement of the ARIES Finger Divertor Concept

For double containment purpose:

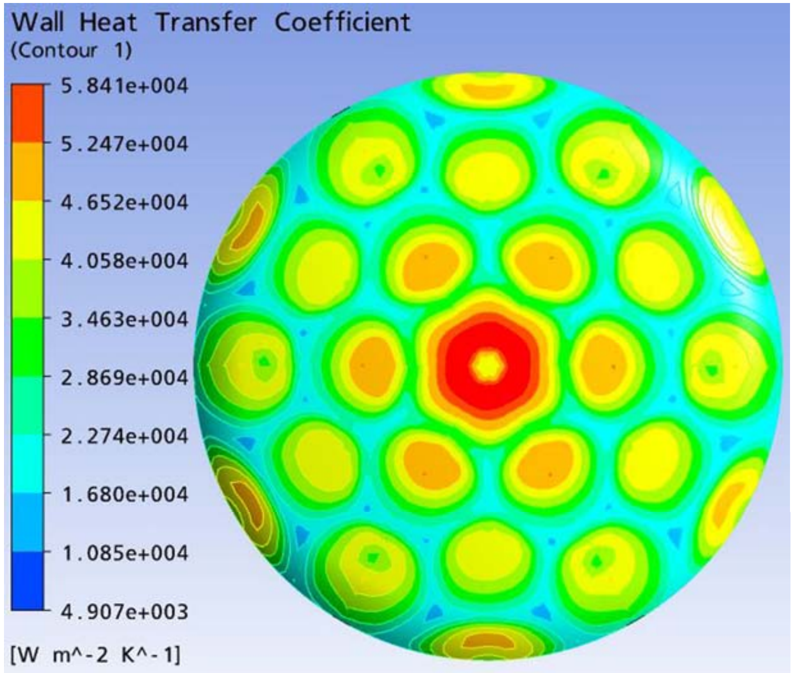
- Enlarging the outer diameter of the thimble from 18 mm to 20 mm, but keeping the same size of the W armor and the cartridge.
- Adding a 1 mm thick cylindrical ring covering the mantel of the thimble only to provide a double wall containment.
- The W armor, W-alloy thimble and W-alloy ring are brazed together into one armor unit, then brazed into the W-alloy front plate.
- This design avoids the joints between W and steel and reduces the concern of helium containment.
- **Does the double-wall impose temperature and stress penalties?**



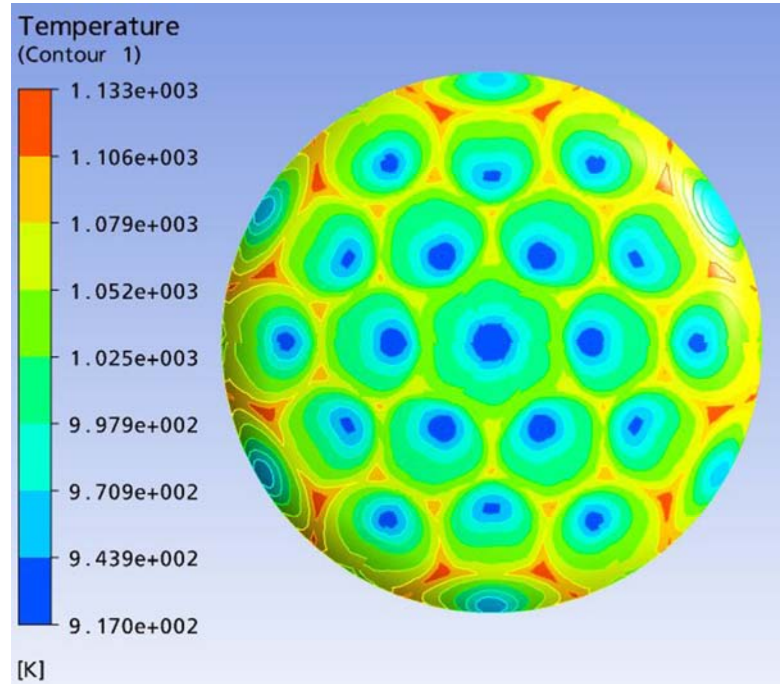


W Armor Unit

Thermo-fluid Analysis Results of the Modified Finger Module



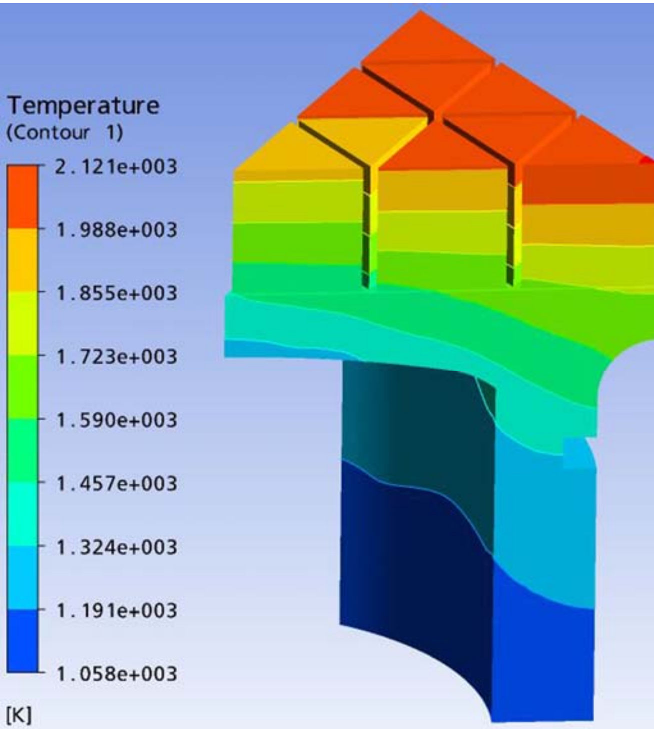
Heat transfer coefficient



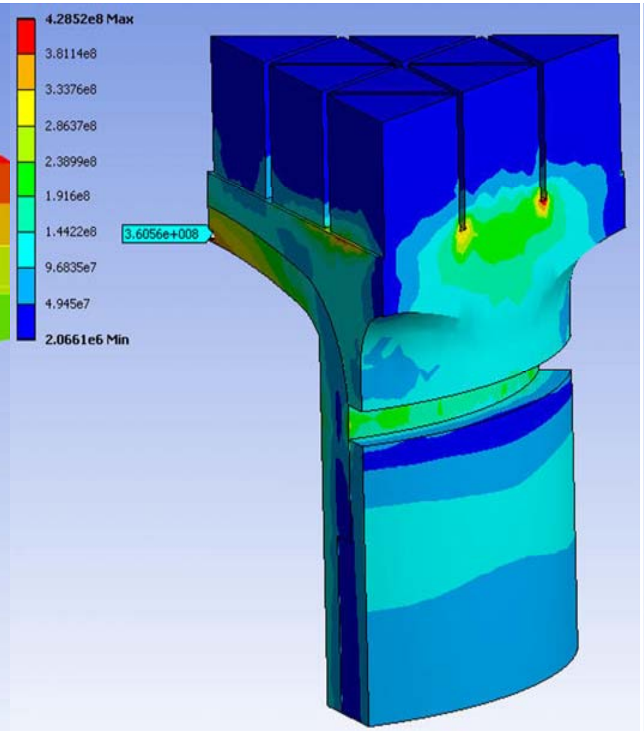
Temperature distribution of the fluid

- ARIES-DB thermal loads are assumed in the analysis, incident q"=10 MW/m^2, neutron volumetric heat generation=17.5 MW/m^3
- ~1.35 million tetrahedral elements, temperature dependant material properties, k-ε turbulent model
- He inlet/outlet temperature=600/700 °C, He pressure=10 MPa
- Max. jet velocity=~250 m/s; Max. H.T.C=~5.84x 10^4 W/m^{2}K
- $P_{pumping}/P_{thermal}$~7.5% (<design limit of 10%)

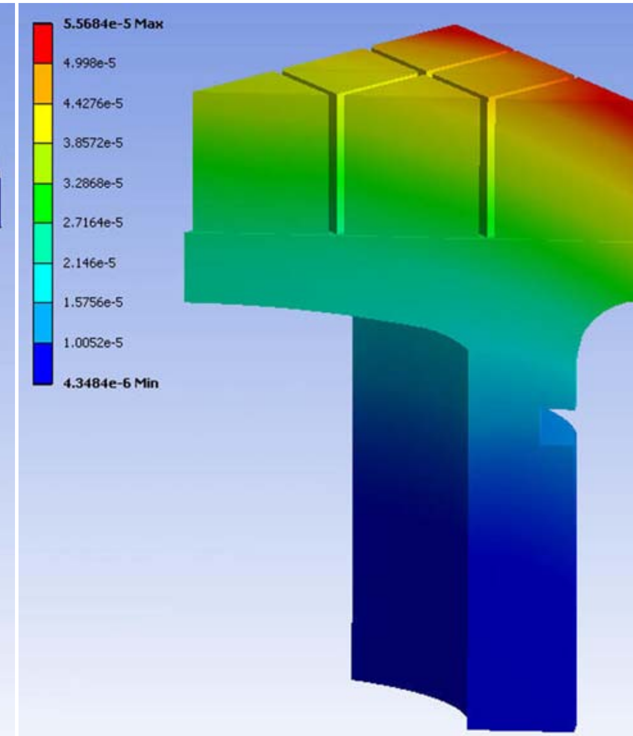
Thermo-Mechanical Results of the Modified Finger Module



Temperature



Stress



Deformation

- W armor is assumed to be castellated with small triangle, 0.25 mm gap and 4 mm deep.
- Max. Armor temperature=1848 °C
- Max. Thimble temperature=1222 °C (<1300 °C recrystallization temperature)
- Max. σ_{p+s}(primary+thermal stresses)=429 MPa, (Max. thimble stresses σ_{p+s} =360 MPa)
- Max. σ_p(pressure stress)=90 MPa; Max. Displacement=0.06 mm

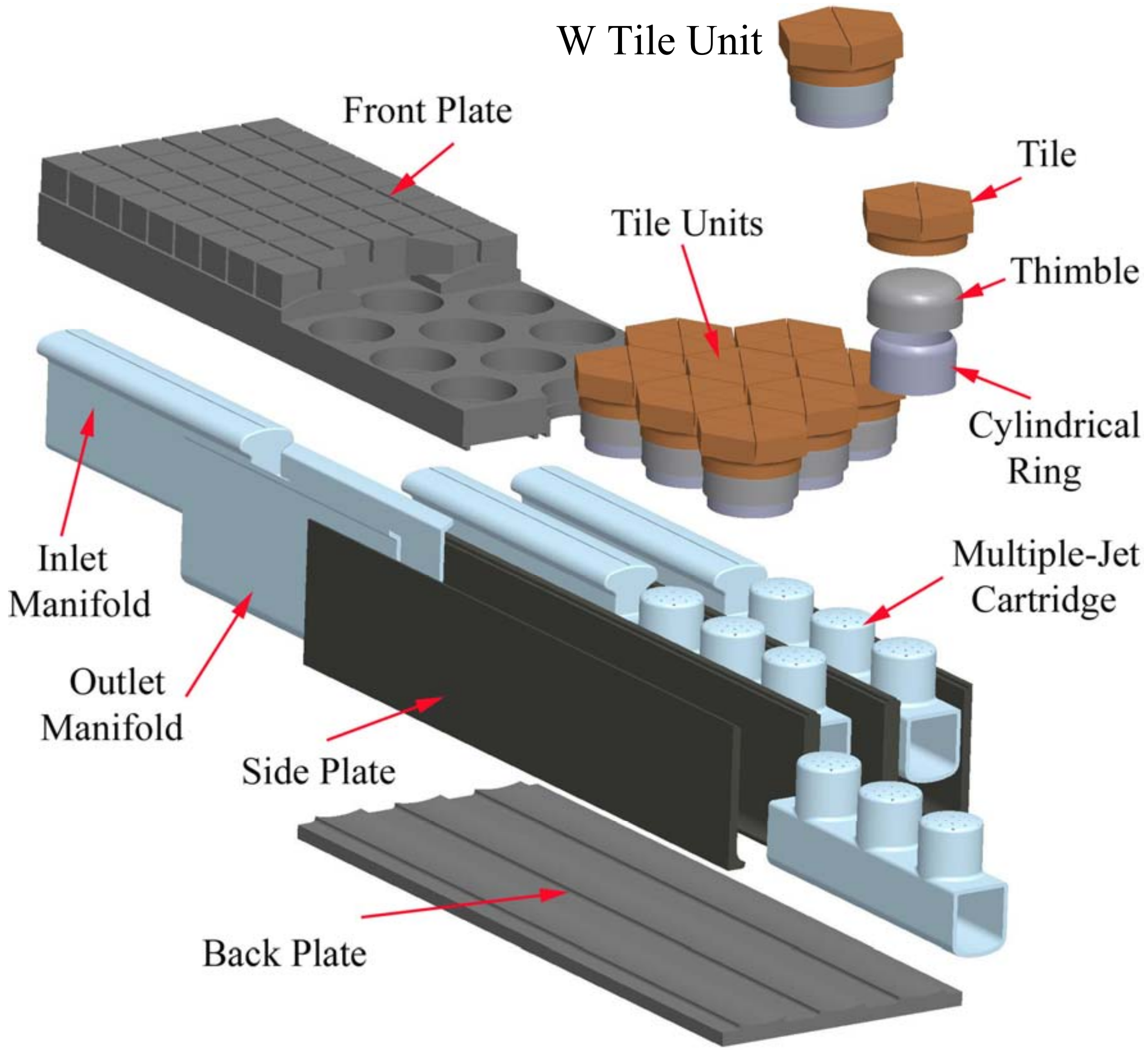
Double-Wall Provides a Double Containment without a Significant Impact on Temperature and Stresses

	Single Wall	Double Wall
Max. Jet velocity, m/s	250	250
Max. h.t.c, W/m^2K	5.84×10^4	5.84×10^4
$P_{pumping}/P_{thermal}$	7.5%	7.5%
Max. Armor temperature, °C	1823	1848
Max. thimble temperature, °C	1210	1222
Min. W structure temperature, °C	742	785
Max. Pressure stress, MPa	110	90
Max. Combined stresses, MPa	408	429
Max. Stresses of thimble, MPa	325	360
Max. Displacement, mm	0.05	0.06

- The double wall provides a double containment between the plasma chamber and the 10 MPa helium, and it does not impact the temperature and stresses, significantly, because it does not change the ratio between heated and cooled surface areas.

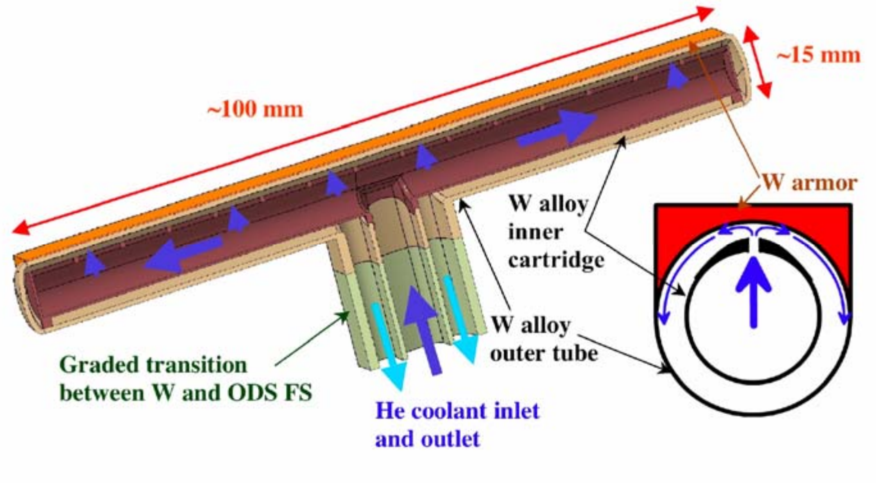
Integrated Plate/Finger Concept Assembly

- A front plate with castellation in the low heat flux zone, grooves for brazing the side plates, and machined holes for inserting the tile units in the high heat flux zone.
- A back plate with grooves for brazing in the side wall of the large helium channels.
- ***A W hexagonal tile, a W alloy thimble and a W alloy cylindrical ring brazed together into one unit and inserted in the front plate in the high flux zone.***
- Multiple-jet cartridges and slot-jet cartridge.
- Side plates.



Application of the T-Tube Divertor Concept in ARIES-DB 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***
  - ✓ ***3 mm W tile***
  - ✓ ***15 mm diameter***
  - ✓ ***10 cm length***
  - ✓ ***1 mm wall thickness of outer tube***

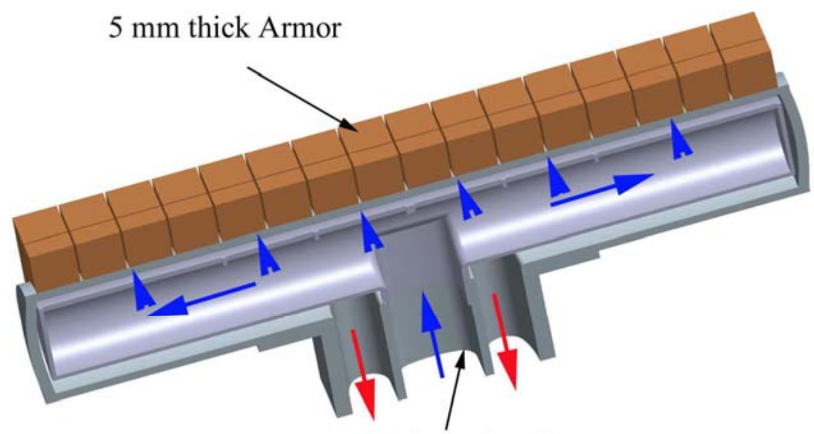


ARIES-CS divertor

- W armor will be increased from 3 mm to 5 mm when this concept is employed in a tokamak power plant.

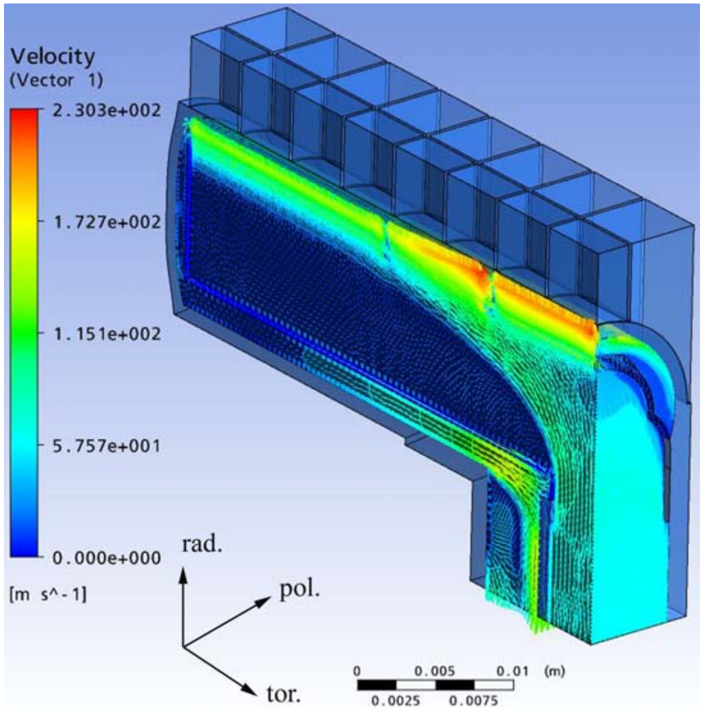
- The W armor should be castellated in order to minimizing the stress transferring from the armor to the tube structure.

- What is the impact of the thicker W armor impose on the T-Tube temperature and stresses?

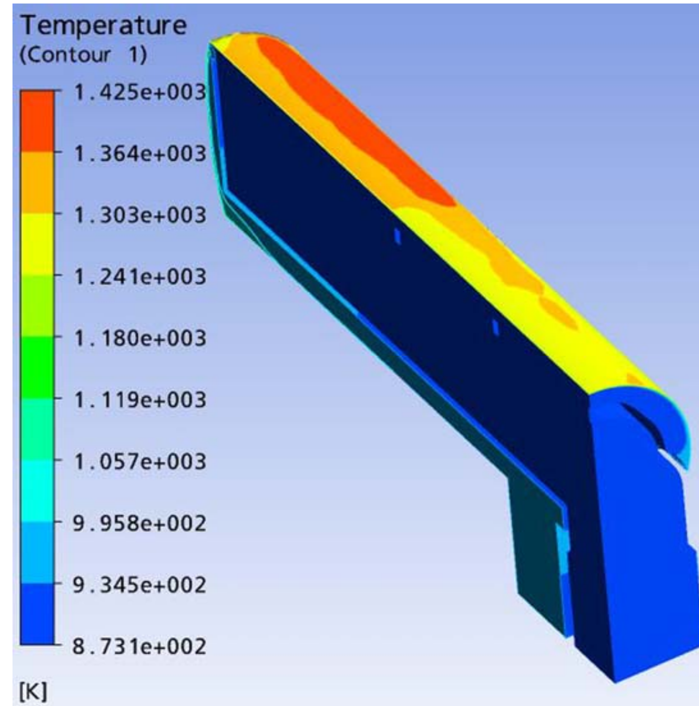


T-Tube concept for ARIES-AT

Example Thermo-Fluid Results of the T-Tube Concept Applied to ARIES-DB



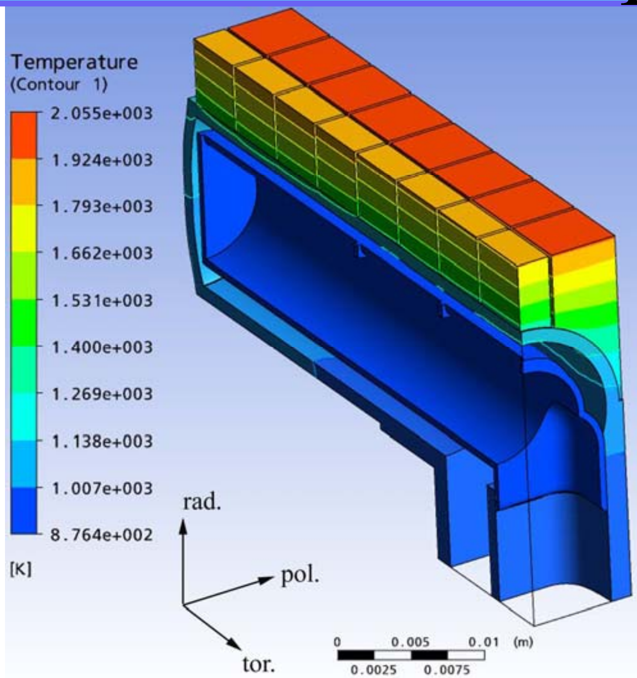
Velocity distribution



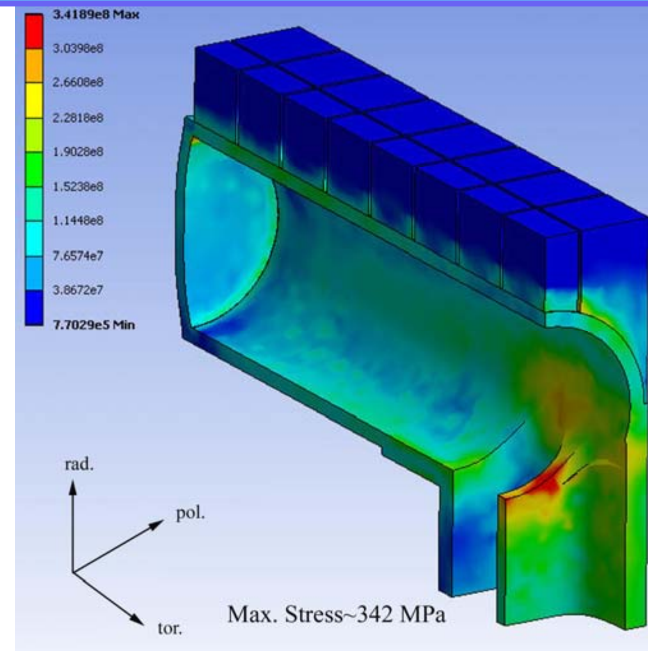
Coolant temperature distribution

- Thermal loads are assumed in the analysis: incident q"=10 MW/m^2, neutron volumetric heat generation=17.5 MW/m^3
- 1.7 million elements, k-ε turbulent model, temperature dependent material properties
- Max. jet velocity=230 m/s
- Coolant pressure drop=~0.12 MPa, and $P_{pumping}/P_{thermal}$=~5.7%
- Max. coolant temperature=1152 °C

Example Thermo-Mechanical Results of the T-Tube Concept Applied to ARIES-DB



Temperature distribution



Stress distribution

➢Interface temperature between the wall and coolant is coupled to ANSYS solid model for stress calculation

✓Max. W armor temperature=1782 °C

✓Max. W structure tube temperature=1240 °C (re-crystallization limit ~1300 °C)

✓Max. combined thermal and primary stresses=342 MPa (< 3Sm=450 MPa)

➢**Conclusion: The modified ARIES T-Tube can be utilized in the ARIES-AT to accommodate a heat flux of 10 MW/m².**

Possible Helium-Cooled Divertor Options for Integration of the ARIES-DB-DCLL

- The candidates include:

  a) FZK modular finger concept

  b) ARIES-CS T-Tube concept

  c) ARIES Plate-Type concept with parallel cooling channels

  d) ARIES combined plate/finger or Plate/T-tube concept

  e) ARIES plate concept where the entire plate is designed as the modified finger modules

- Preferred candidates are d and b.

Candidate a: FZK Finger Divertor Concept

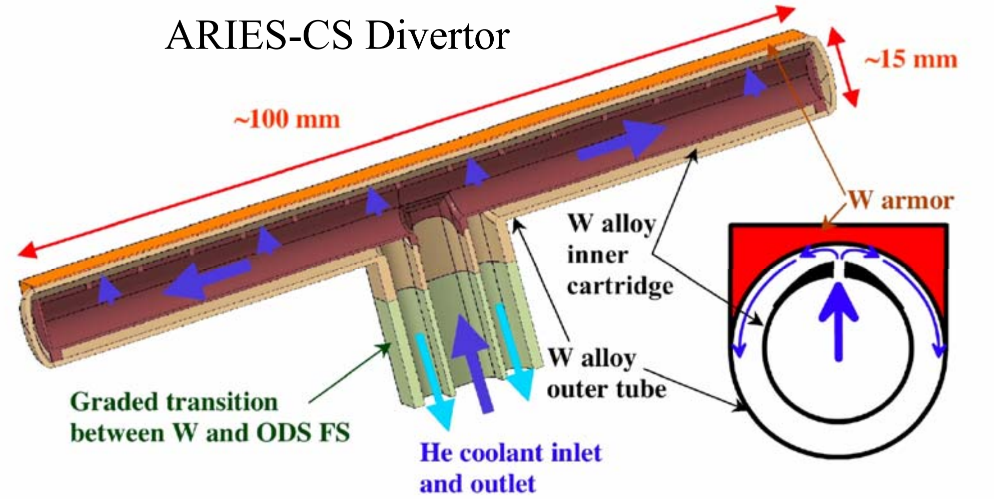
- Small-scale divertor unit with jet cooling
  - ✓Armor width between flat ~18 mm
  - ✓Outer diameter of thimble ~15 mm
  - ✓Inner diameter of thimble ~13 mm
  - ✓Outer diameter of the cartridge ~10.6 mm
- Allowable heat flux >10 MW/m^2
- Crucial issues:
  - ✓Difficult fabrication
  - ✓Large number of divertor units for a power plant, for example, ~550,000 for the ARIES-DB.
  - ✓Large number of joints or transition zones between the W-alloy in the front and the steel manifold in the back (impact on the overall reliability).
  - ✓Leak problem through the brazed joints

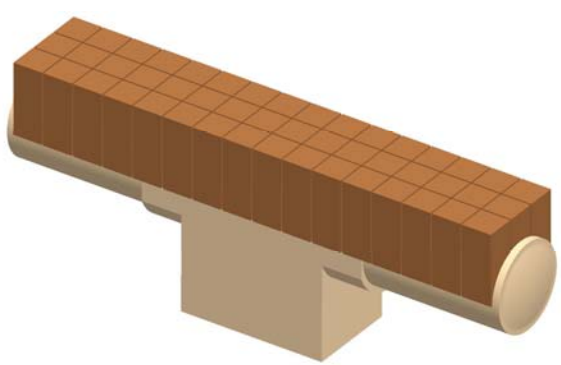
9-Finger module   1-Finger module

Candidate b:ARIES T-Tube Concept

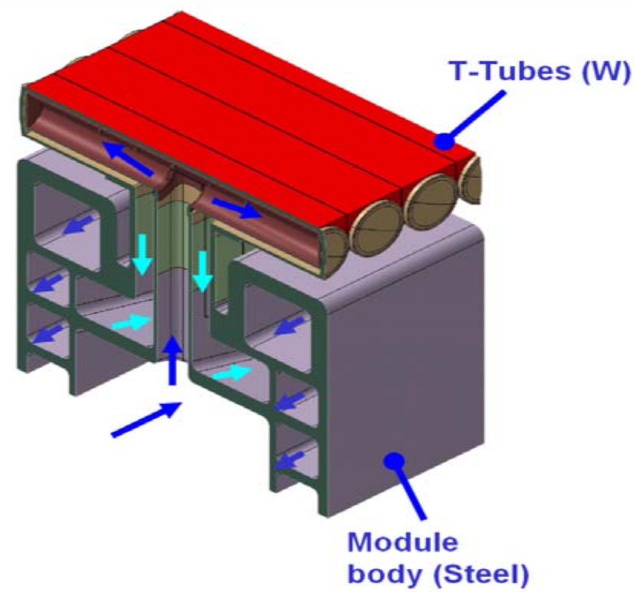
- Mid size divertor unit
  - 15 mm in diameter and 100 mm long
- Allowable heat flux >10 MW/m^2
- Crucial issues:
  - Difficult fabrication
  - Large number of the T-Tube units, ~110,000 T-Tube units for ARIES-DB
  - The large numbers of the transition zones between W-alloy and steel manifold in the back (impact on reliability)

ARIES-CS Divertor



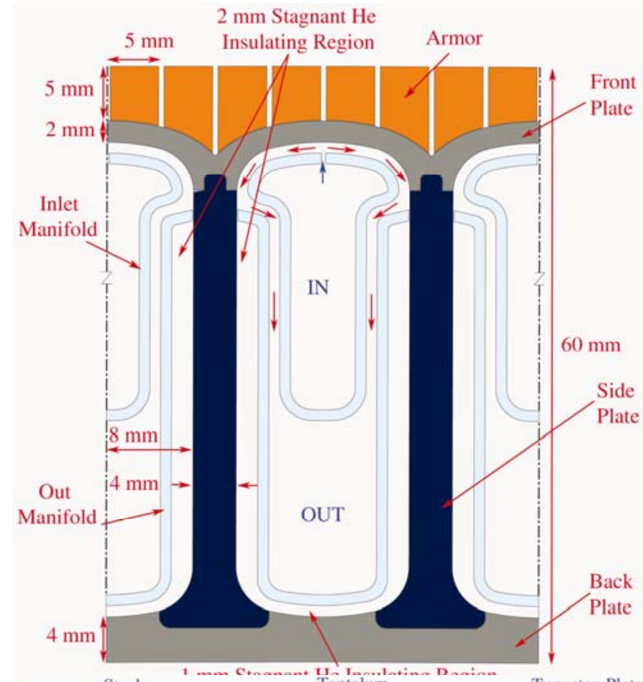


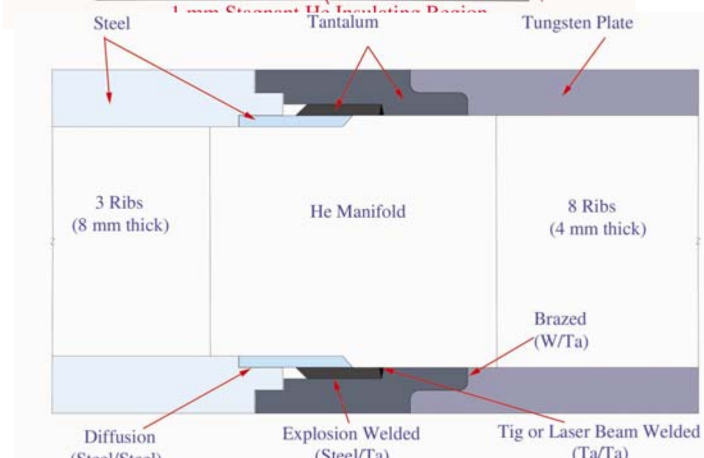
Applied to ARIES-AT



Candidate c: ARIES Plate-Type Concept

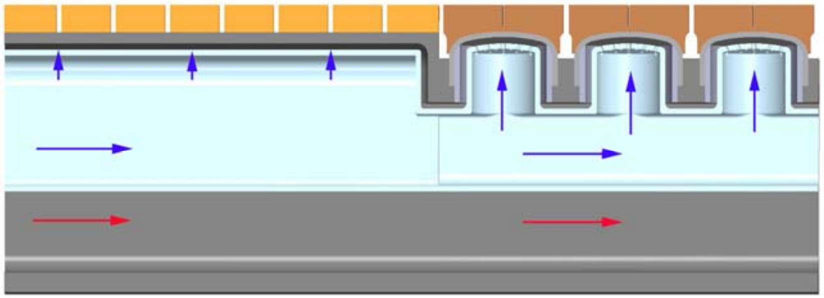
- ➢Larger scale divertor unit
  - ✓20 cm (tor.) x 100 cm (pol.) x 6 cm (rad.)
  - ✓2 mm thick in the front, 6 mm in the side wall, and 8 mm at the back
  - ✓The front plate with castellation and grooves brazed together with the side and back plates
- ➢Reducing the number of units, the assembly complexity and possibly costs, for example, ~ 750 plate units for ARIES-DB
- ➢Potential to reduce the helium leak concern with minimum wall thickness of 2 mm
- ➢Transition between W and steel located at both ends of the plate, with low heat flux loads. Analysis results of UCLA indicate that the transition design is very promising.
- ➢Complicated design with required thermal insulation of side walls with stagnant gaps, and the allowable heat flux limited to <10 MW/m^2
- ➢Concern with transient heat load scenarios

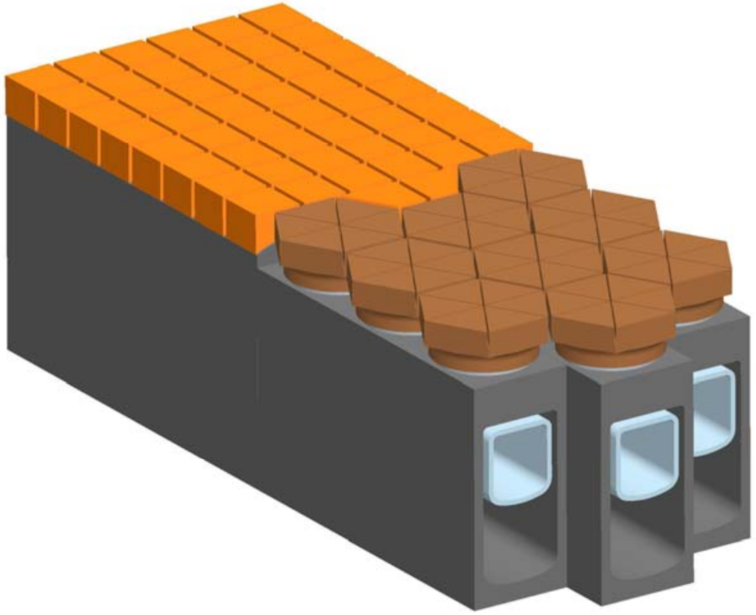




Candidate d: Combined Plate/Finger or Plate/T-Tube Concept

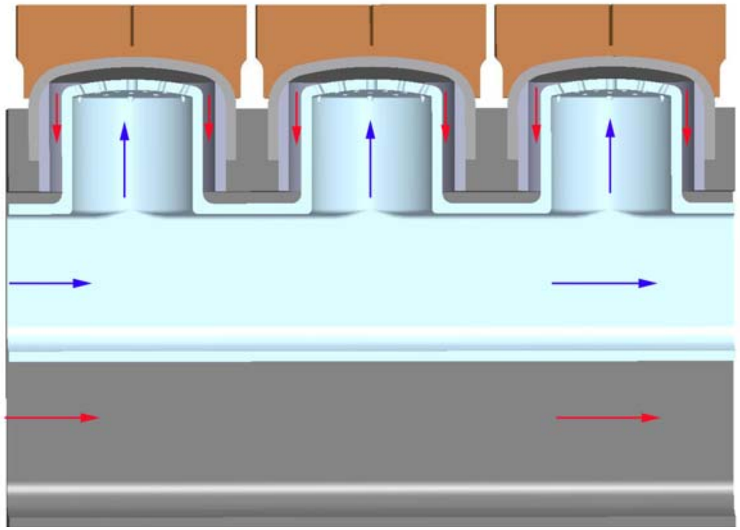
- The incentive to consider the two heat flux zone concept is a large peaking factor (>3) between the maximum and the average heat flux..
- This concept brings up the possibility of optimizing the heat flux accommodation and reliability (based on the numbers of joints or units)
- For a high heat flux zone (~20 cm length), the number of the figure units with the ~750 integrated plate components is ~87,820 (compared with 535,000 FZK finger units, 347,000 ARIES modified finger units required for full target plate coverage).
- The combined plate and T-tube concept is not shown.
- Crucial issues: TBD

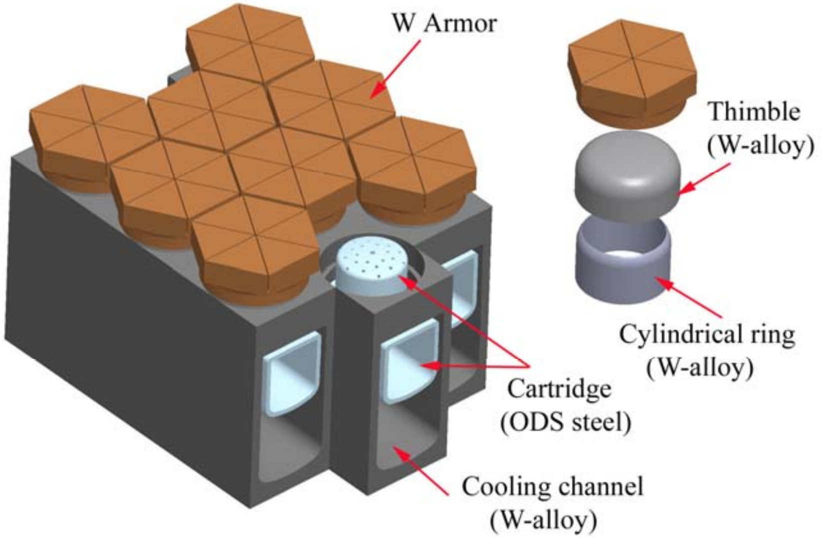




Candidate e: ARIES Modified Finger Concept

- If the peak factor of the heat flux is less than 2, the plate concept where entire plate is designed as the modified finger divertor modules can be adopted.
  - ✓Channel spacing, 20 mm, length, ~100 cm
  - ✓Side wall thickness, 4 mm
  - ✓Larger size finger unit
- The double-wall configuration provides a protection for high pressure helium leaking from the inside of the finger to the plasma chamber.
- There is no connection between W-alloy and steel required.
- The number of finger units is reduced to 63% of the FZK modules, ~347,000 finger units for ARIES-AT.
- The allowable heat flux limits to ~10 MW/m^2
- Crucial issues:
  - ✓a large number of units
  - ✓a large number of joints





Summary of the Helium-Cooled Divertor Activities

- A number of different helium-cooled divertor concepts have been proposed and investigated. These include smaller-scale finger concept, mid-size T-Tube, larger-scale plate-type concept and their combined configurations. All these designs utilize W or W alloy as structural material and employ the impinging jet cooling schemes to enhance the heat transfer performances.
- Typically, the smaller dimension concepts tend to accommodate higher heat flux but at the price of having a large number of units and associated pressure joints, which tend to negatively affect overall liability.
- Candidate d and b are the preferred concepts for the integration of the ARIES-DB-DCLL based on assessments of the performance and potential critic issues.
- Publications on this subject:

1. *X.R. Wang, S. Malang and A.R.Raffray, "Design Optimization of High-performance Helium-cooled Divertor Plate Concept", presented at 18th TOFE and to be published in Fusion. Science. & Design*
2. *X.R. Wang, S. Malang and A.R. Raffray, "Transient Thermal and Stress Response of A Helium-Cooled Tungsten Plate-Type Divertor for Fusion Power Plant," to be presented at the 23rd SOFE, 2009.*
3. *A.R. Raffray, S. Malang and X.R Wang, "Optimizing the Overall Configuration of a He-Cooled W-Alloy Divertor for a Power Plant," presented at the 25th SOFT, Sept. 2008.*
4. *Rene is organizing a journal paper with title "Recent US Activities on Advanced He-Cooled W-Alloy Divertor Concept for Fusion Power Plant," to be done.*

- We are now closing the helium-cooled Tungsten divertor activities and starting to look into the integration of the ARIES-DB-DCLL design.