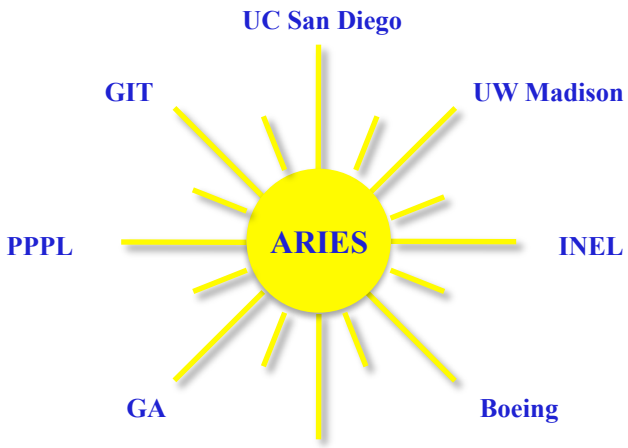
Overview of the ARIES-ACT2 Power Core



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UC San Diego

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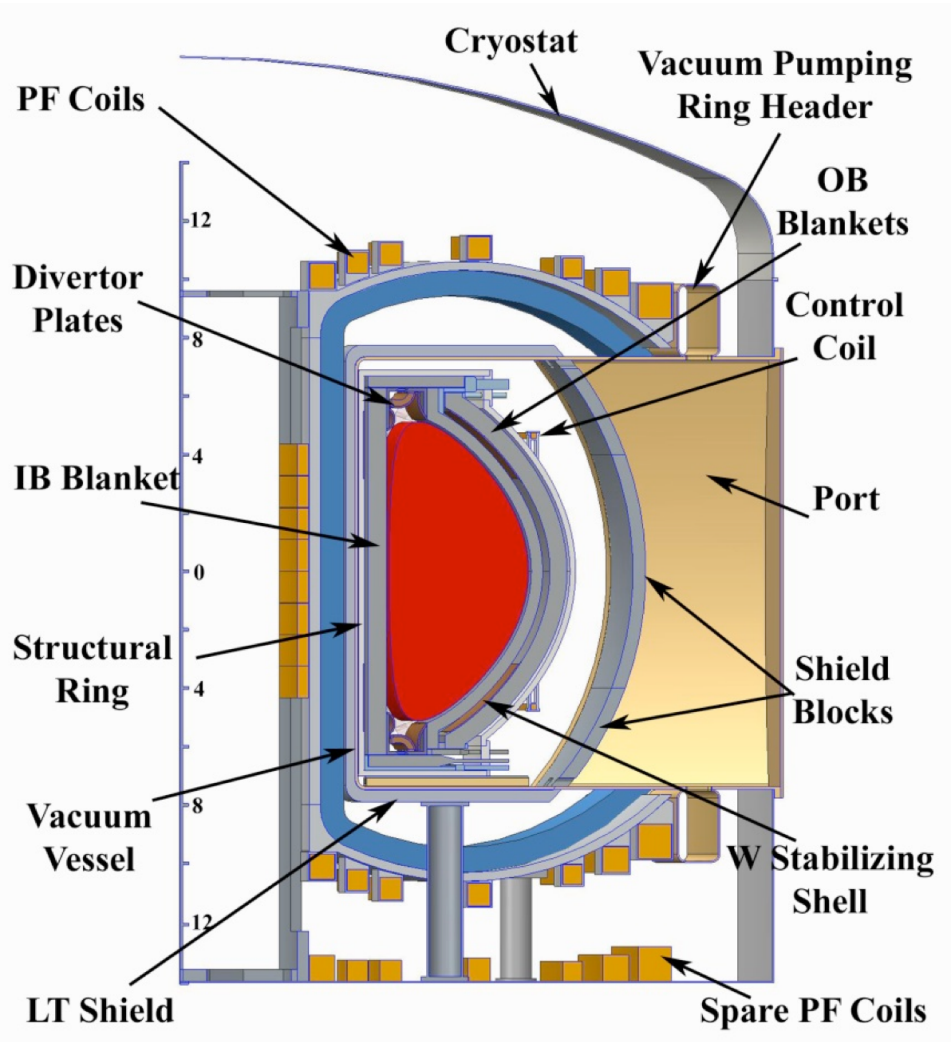
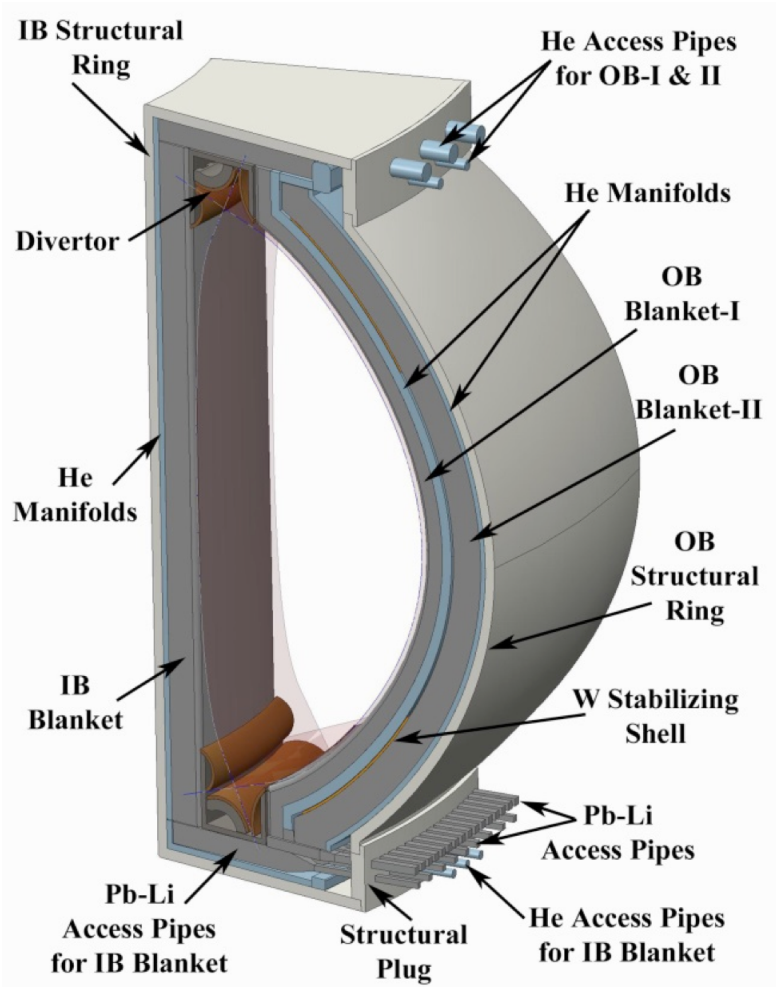
ACT2 characteristics affecting design choices

1. **The ACT2 plasma provides modest steady-state loads:**
   - Peak/average neutron wall loading P_{nw} = 2.2/1.5 MW/m^2
   - Peak divertor surface heat flux q_{div} < 10 MW/m^2
   - Peak FW heat flux q_{fw} = 0.28 MW/m^2
2. **A "conservative" DCLL blanket was explored by our Team for the *first time* in an *integrated tokamak power plant configuration*.**
   - ARIES-ST (spherical torus)
   - ARIES-CS (compact stellarator)
   - US ITER TBM (small test articles)
   - He-cooled RAFS structure (*e.g.* F82H), PbLi in SiC inserts
3. He-cooled W-alloy divertor was chosen as the only known option that meets requirements on safety, waste & performance.
4. Brayton power cycle is possible with η~45% (350°C blanket inlet)

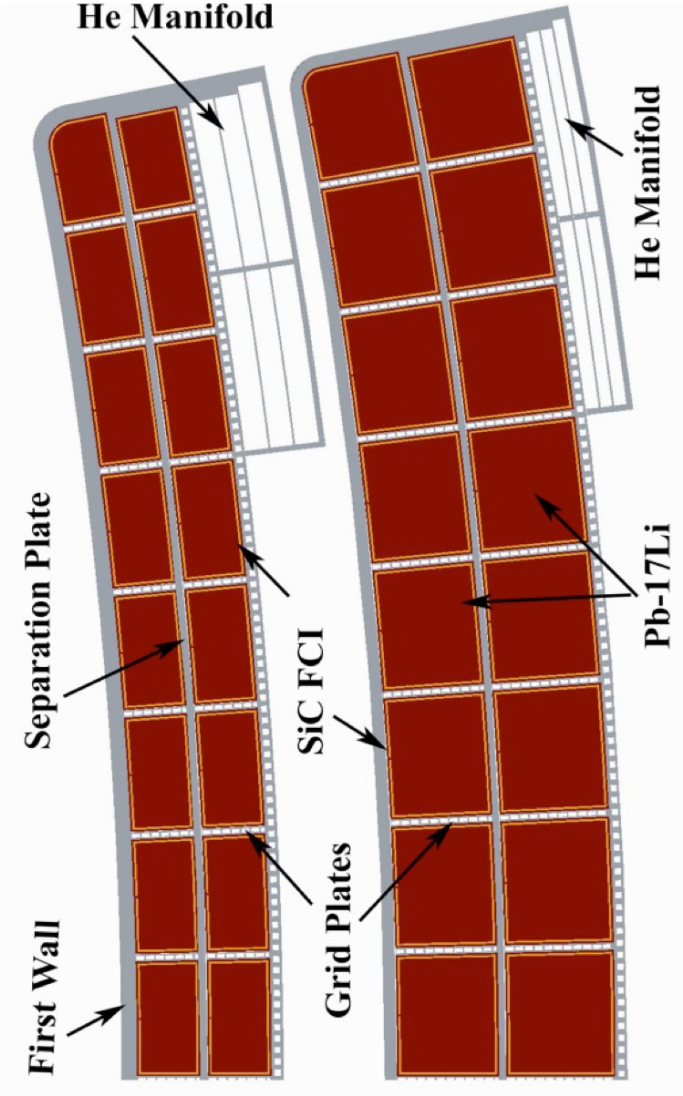
ACT2 uses traditional ARIES full-sector maintenance concept: components contained in a structural ring



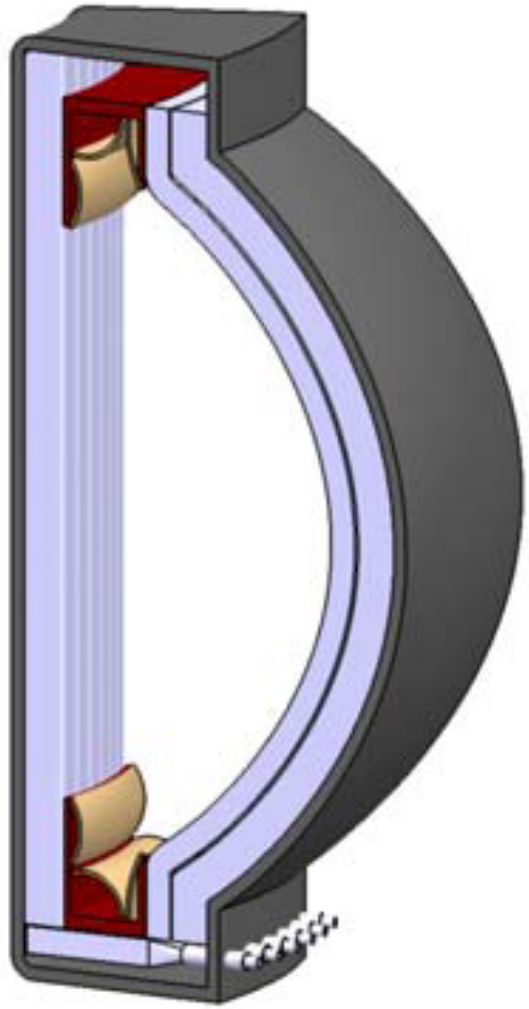


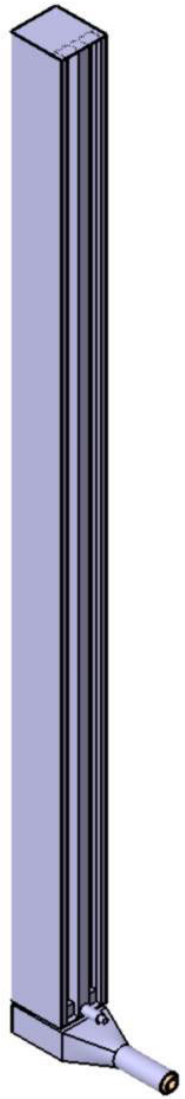
The reference blanket is related to ARIES-ST

- 550°C limit for steel, 500°C limit for steel/PbLi interface.
- 8 MPa He cools the FW toroidally (385-436°C) and grid plates vertically (470°C).
- 0.28 MW/m^2 peak heat flux and 2.2 MW/m^2 peak wall load result in low thermal stresses.
- 2 W/mK SiC insulators (FCI's) allow PbLi temperature to exceed 550°C.
- Simple LM flow paths keep primary stresses low.
- Complete thermal, fluid and elastic stress analyses were performed.

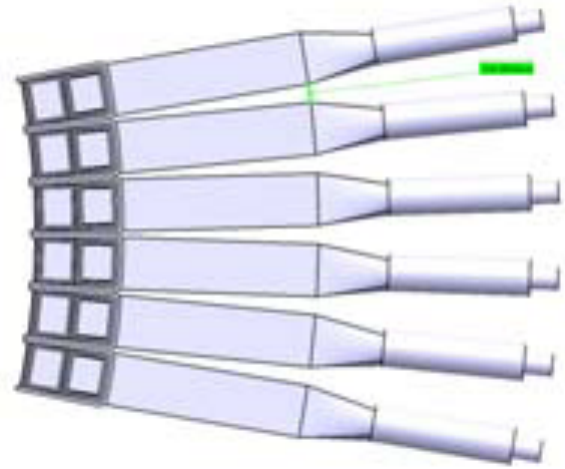


An alternative blanket design concept was explored in an attempt to simplify the manufacturing

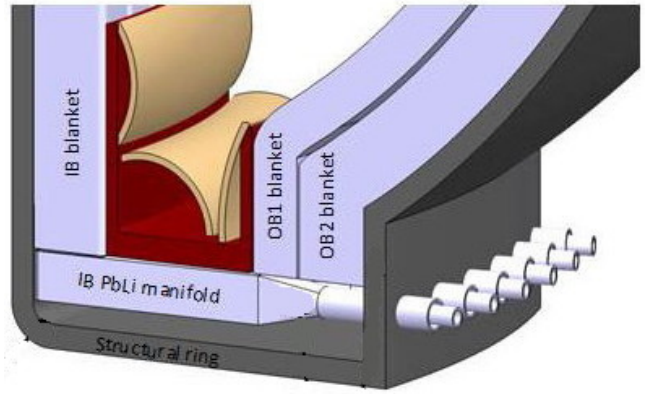




Bottom view



each module is fed by one Pb-Li access pipe



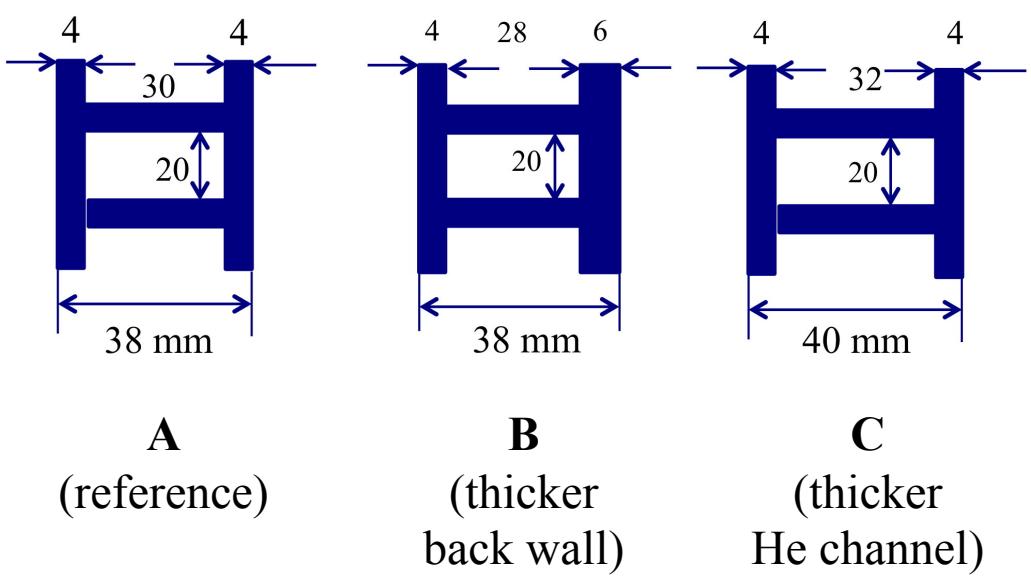
Comparison of reference design and small-module design

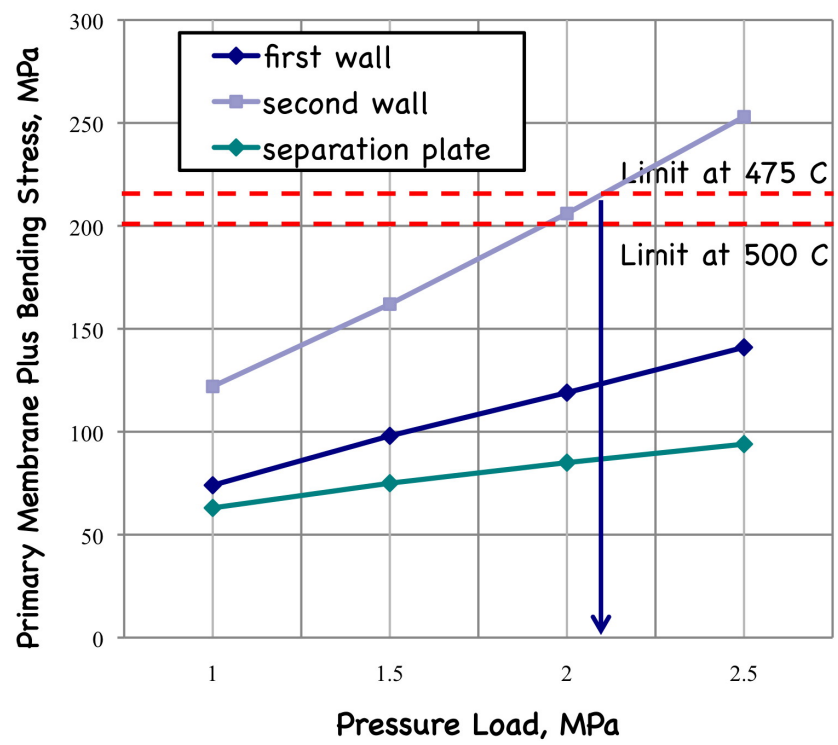
- The main penalty of the small-module design is increased steel fraction (and reduced PbLi), requiring adjustments to maintain TBR.
- Modifications to the FW design allowed us to use 6-module concept.

	ARIES-CS (2m x 2m module)	ACT2 DCLL (Sector)	ACT2 DCLL (6 Modules-A)	ACT2 DCLL (6 Modules-B)	ACT2 DCLL (6 Modules-C)	ACT2 DCLL (8 Modules)
First Wall 3.8 cm	8% ODS FS 27% F82H 65% He	5.3% ODS FS 28.4% F82H 66.3% He	35.5% F82H 64.5% He *(4/30/4 mm)*	39.3% F82H 60.7% He *(4/28/6 mm)*	37.3% F82H 72.8% He *(4/32/4 mm)*	35.5% F82H 64.5% He
Breeding Zone 58.2 cm	**77% LiPb** 7% F82H 3.7% SiC 12.3% He	**79.2% LiPb** 6.1% F82H 6.2% SiC 8.5 % He	**72.3% LiPb** 8.7% F82H 5.3% SiC 13.7 % He	**72.3% LiPb** 9.5% F82H 5.3% SiC 12.9 % He	**69.8% LiPb** 9.0% F82H 5.2% SiC 15.3 % He	**65.5% LiPb** 10.9% F82H 5.8% SiC 17.8 % He
Back Plate 3 cm	80% F82H 20% He	84.1% F82H 15.9% He	35.6% F82H 64.4% He	37.9% F82H 62.1% He	36.8% F82H 63.2% He	35.6% F82H 64.4% He
Max. Pr Load, MPa	*(PbLi pressure not considered in ARIES-CS)*	2.5	1.4	2.1	1.5	2.3

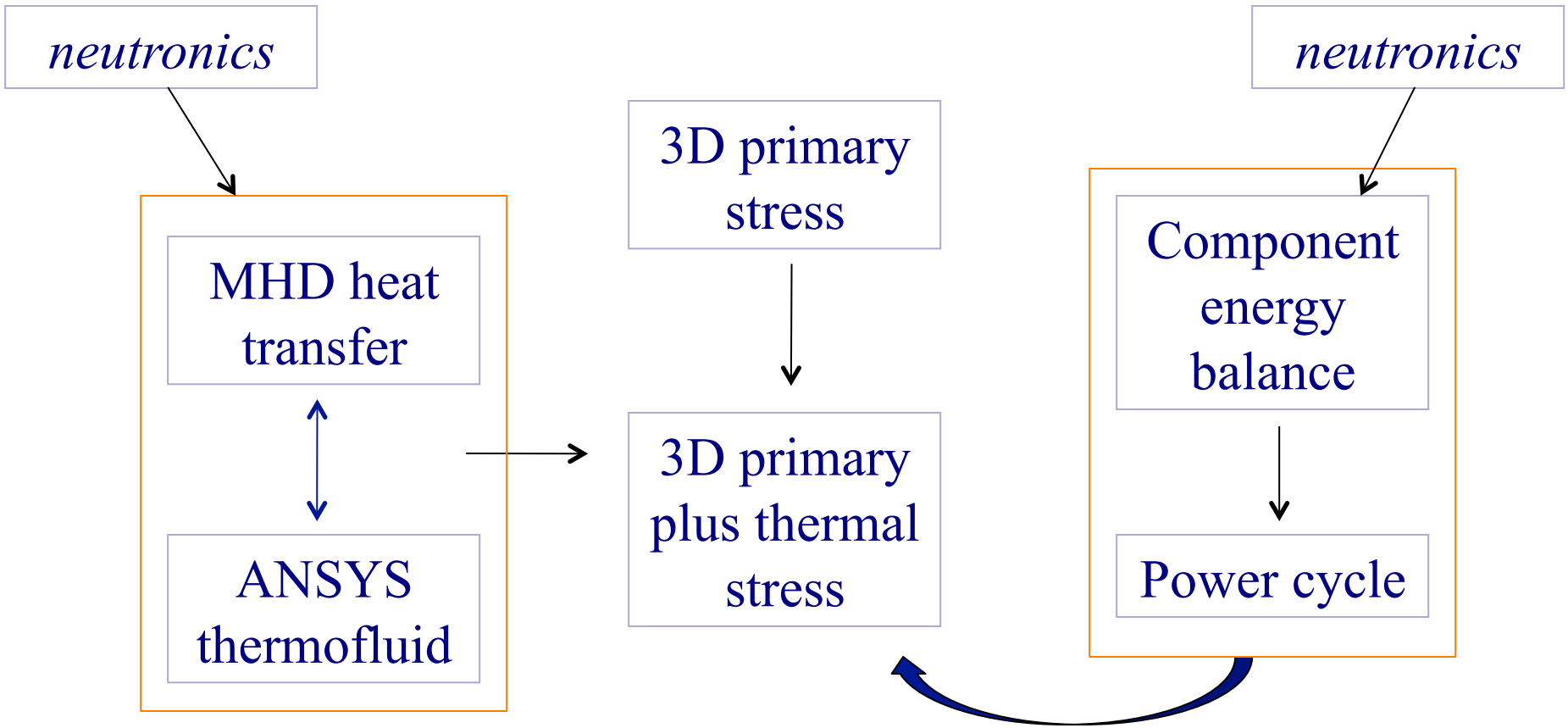
Parametric studies were performed to explore variations of the FW of the alternative design

- 8-module design results in too much steel for TBR
- We attempted to find a solution with 6 modules by adjusting the dimensions of the FW channels
- Option B gave the best results (2.1 MPa max PbLi pressure)



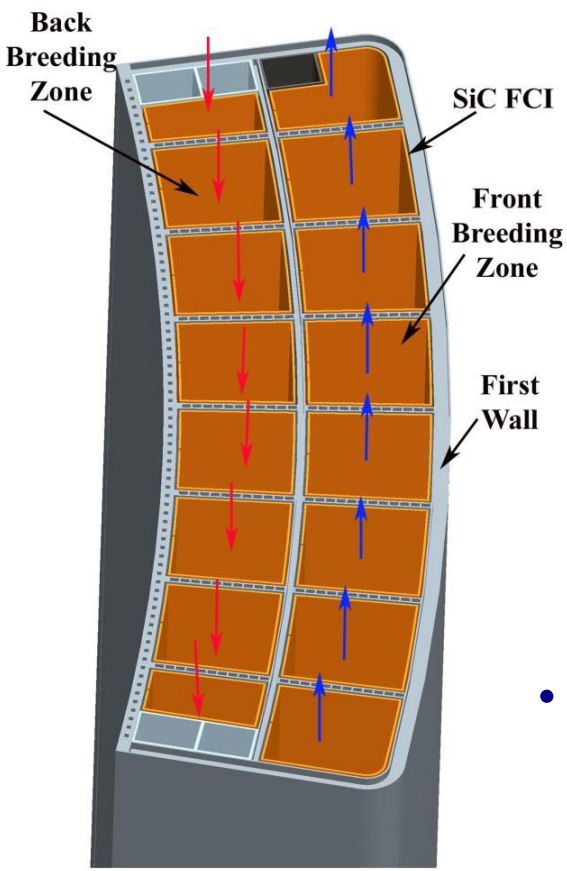


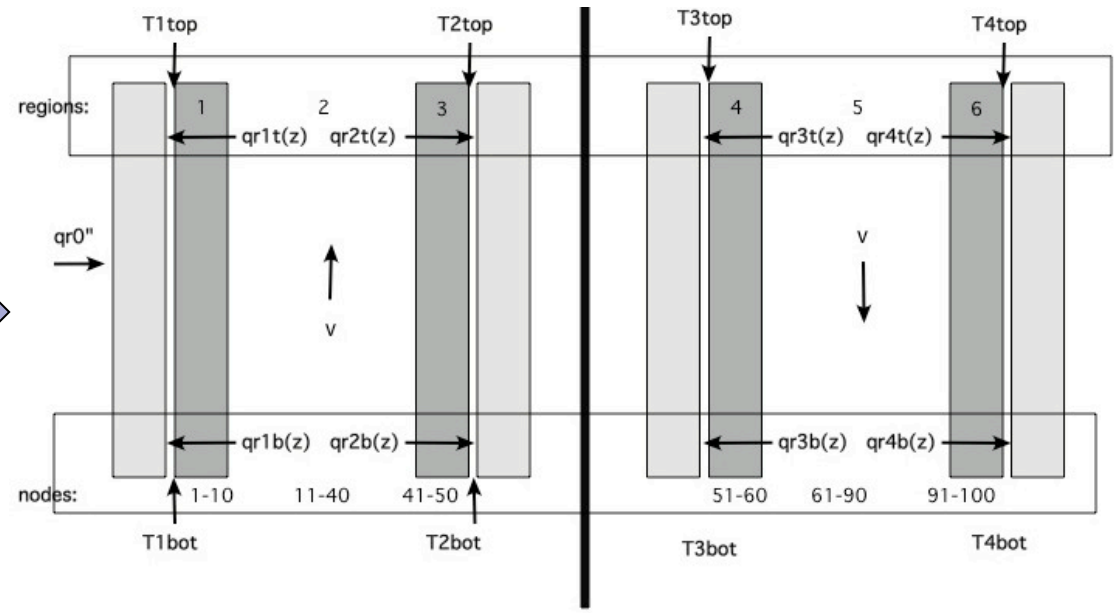
Engineering analysis of the reference blanket



Modeling of MHD heat transfer is needed to provide heat flux boundary conditions into steel structures

- 2D radial/vertical geometry modeled, including PbLi and SiC
- Boundary temperatures provided by ANSYS; heat fluxes solved iteratively for use in thermal and thermal stress analysis at blanket top and bottom

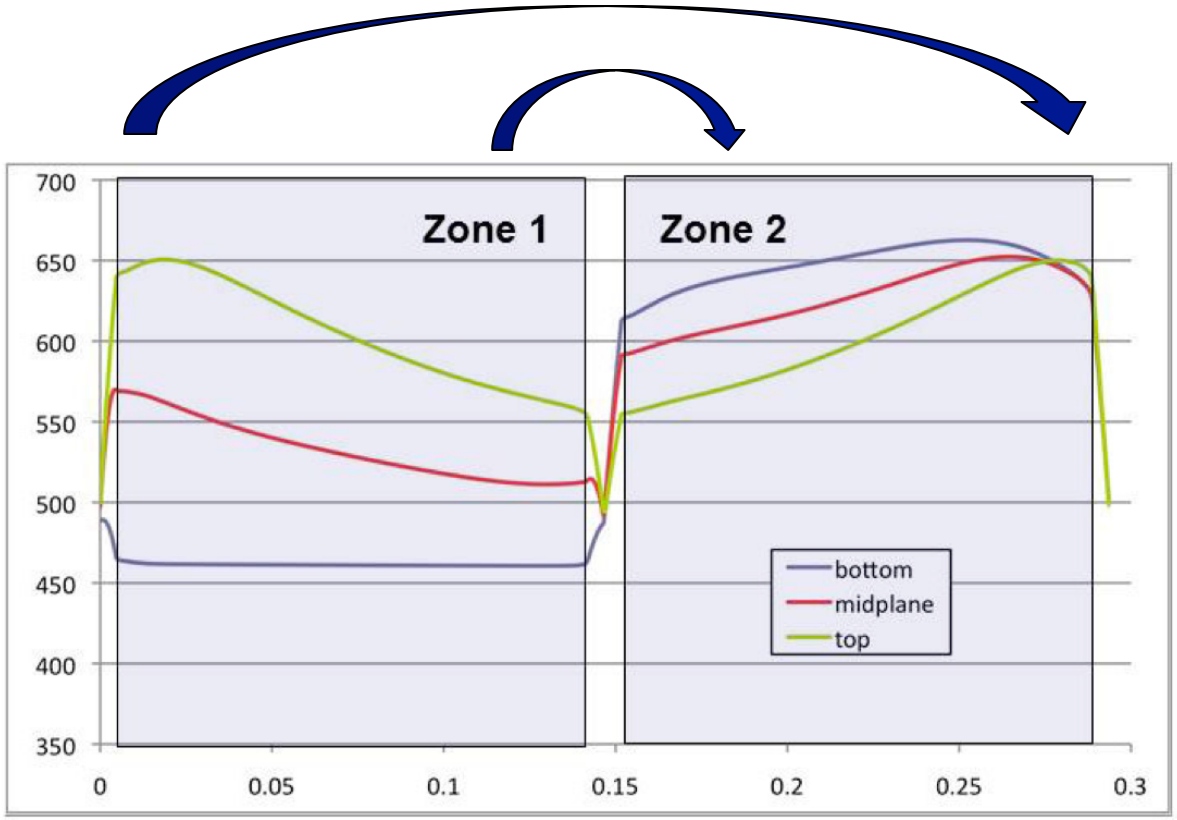




- Iterative solver used previously for ACT1:

$$\frac{de}{dt} = k\frac{\partial^2 T}{\partial x^2} + Q - u\frac{\partial e}{\partial z} = 0$$

Structures remain within their limits, with a modest variation from front to back

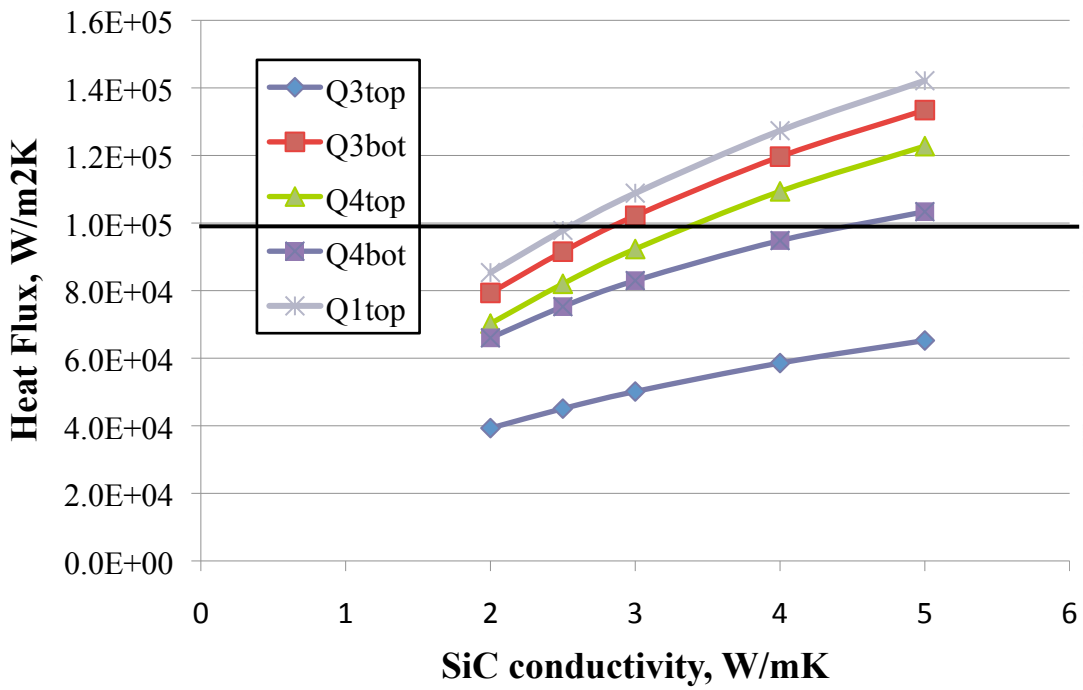


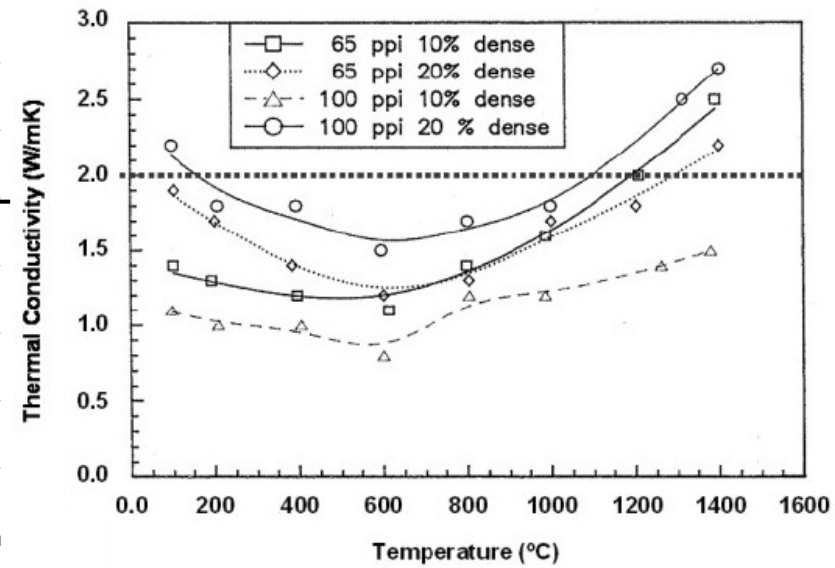
From ANSYS

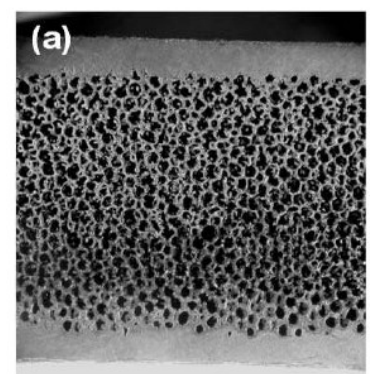
T1top	491 C
T1bot	488 C
T2top	491 C
T2bot	488 C
T3top	491 C
T3bot	495 C
T4top	491 C
T4bot	495 C

- Assumed flow "inverts" due to U-bend at top

The highest leverage on grid plate heat flux comes from k_{SiC}







- $q > 10^5$ W/m^{2}K can cause difficulty maintaining steel within acceptable temperature range
- k = 2 W/mK provides acceptable temperatures
- Recent R&D (Ultramet, Sharafat) shows this is achievable

Load conditions and design limits for primary stress

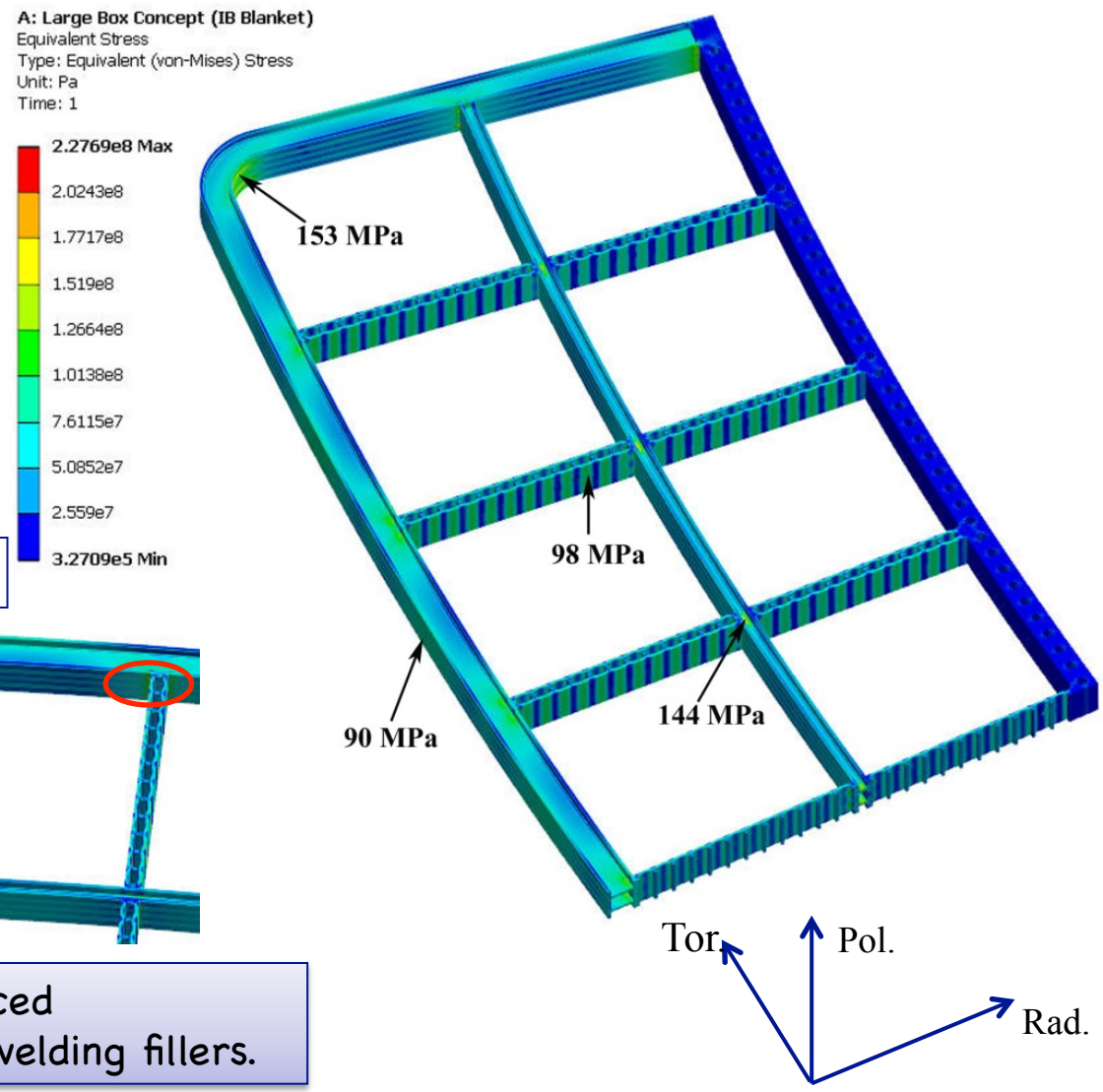
- Helium operating pressure is 8 MPa
- Pb-17Li static pressure at bottom: ~1.6 MPa front, ~1.5 MPa back
  (MHD pressure drop of 0.1 MPa was assumed)
- Stress allowables for F82H steel:
  - Average membrane stress < 1 S_m
  - Primary membrane plus bending stresses < 1.5 S_{mt}
    (2/3 of min. creep stress to rupture)
  - Thermal stresses < 1.5 S_{mt}
  - Combined primary and secondary stresses < 3 S_m

Allowable stress for RAFS (F82H) steel (S_t at t=100,000 h)

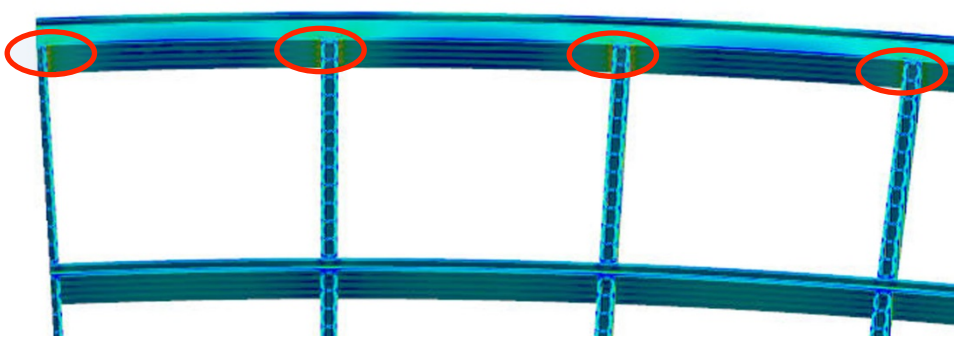
	S_m, MPa	S_t, MPa	1.5 S_{mt}, MPa
425 °C	152	204	228
450 °C	148	180	222
475 °C	144	157	216
500 °C	139	135	203
525 °C	133	112	168

Inboard blanket primary (membrane + bending) stress using 1.6 MPa in PbLi, 8 MPa He

location	σ, MPa
maximum	228
first wall	90
second wall	153
separation plate	144
grid plate	98
back plate	45



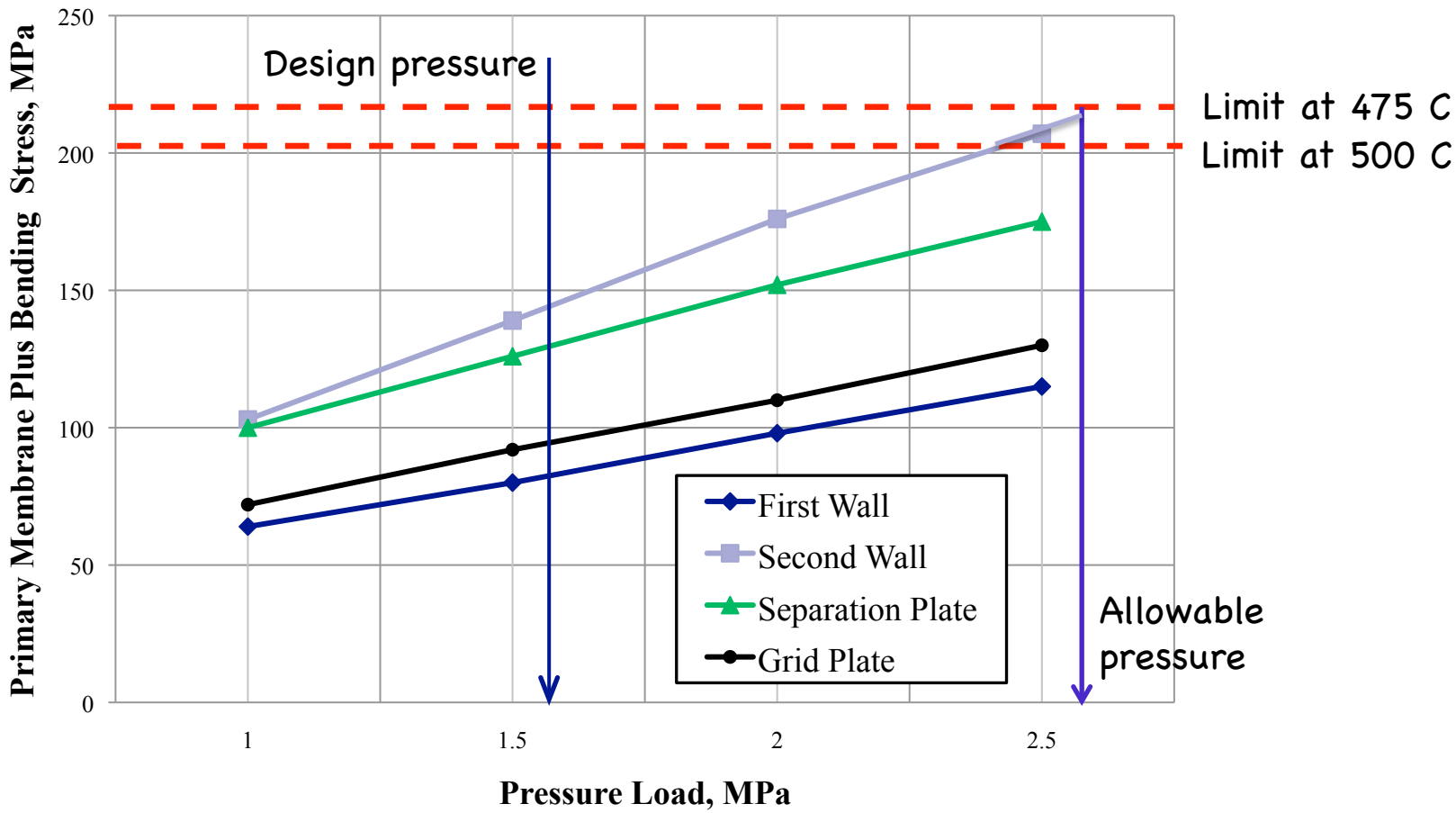
Peak stress concentration ~228 MPa



We assume local stress can be reduced (below 216 MPa @475°C) by adding welding fillers.

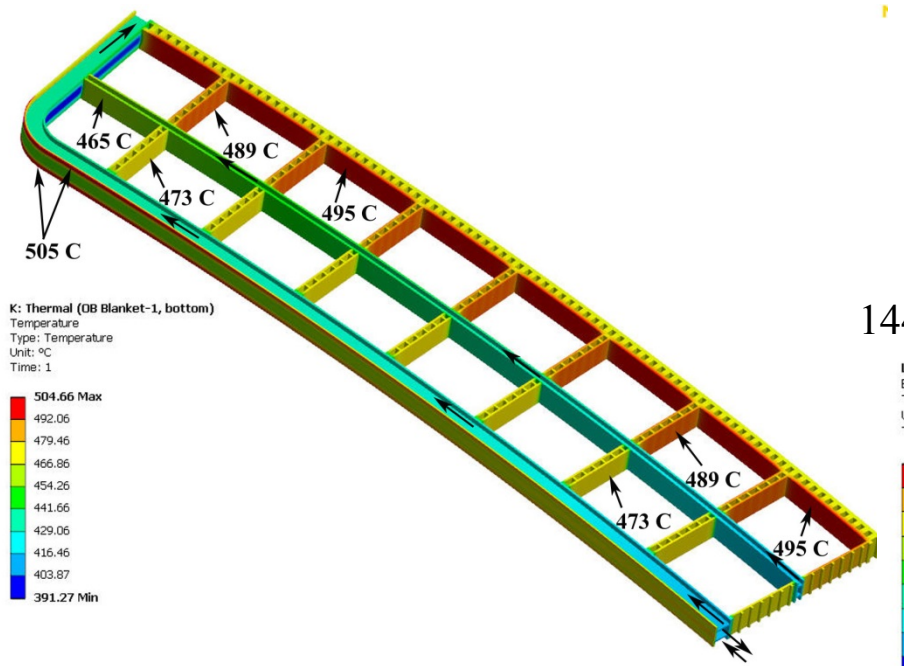
Excluding local concentrations, the *inboard blanket* can accommodate internal pressure up to 2.5 MPa

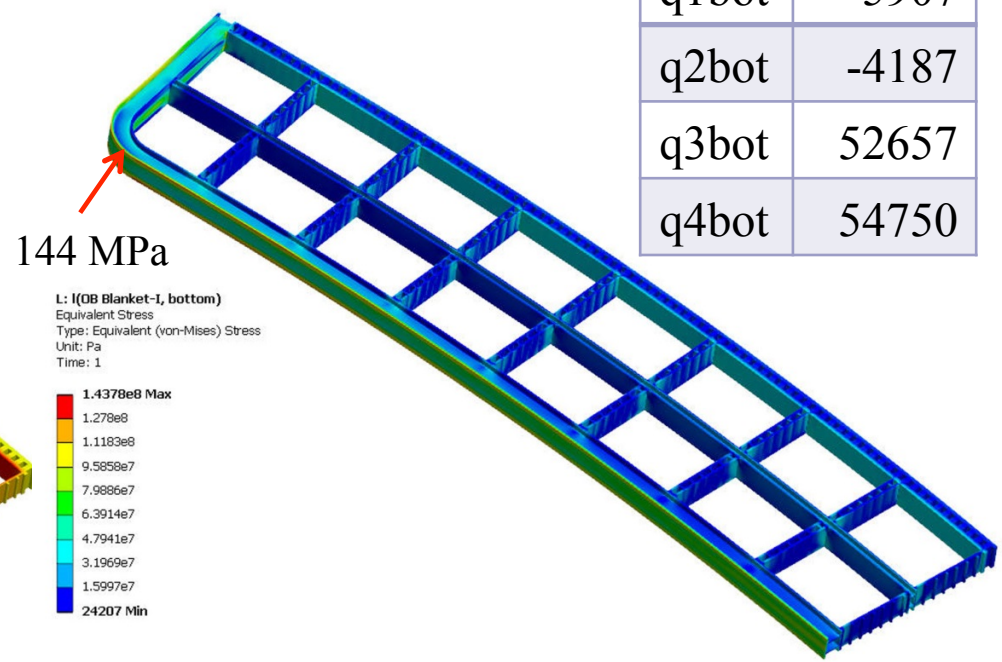
Peak stresses away from local concentrations
(that we believe can be easily fixed)



Thermal stress analysis of OB Blanket-I at **bottom section** shows requirements are met (k_{SiC} = 2 W/mK)

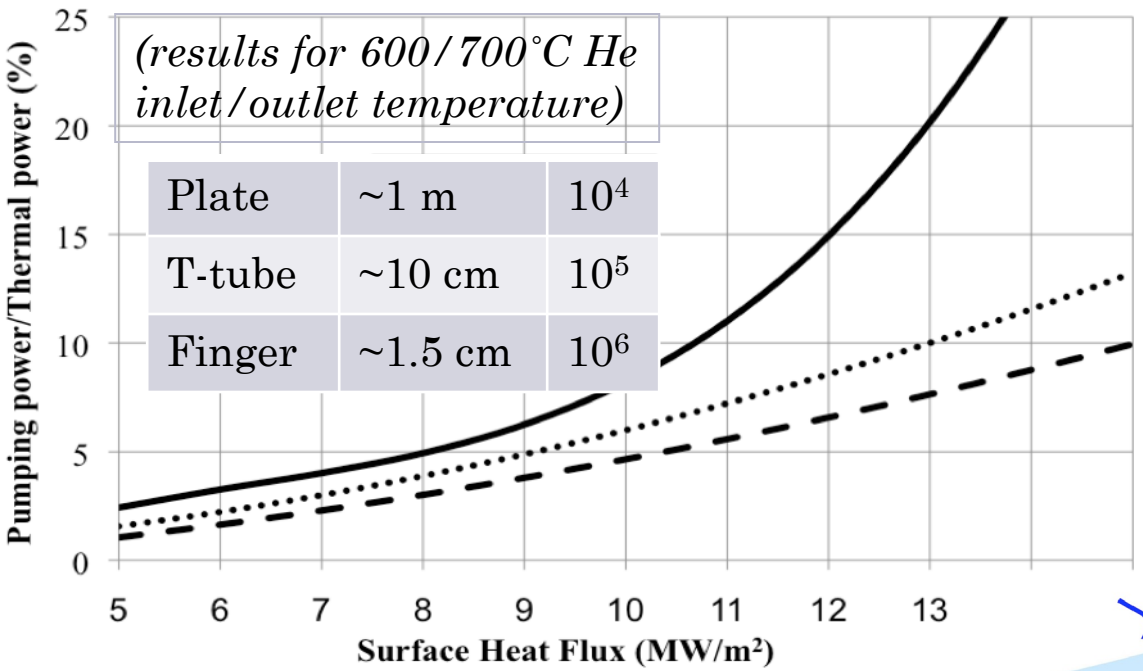
	W/m^2
q1bot	5907
q2bot	-4187
q3bot	52657
q4bot	54750

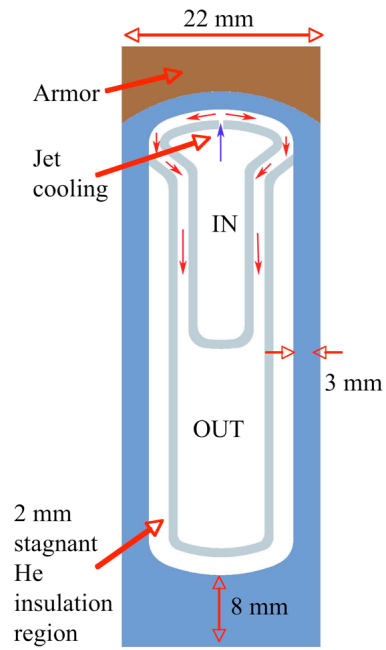


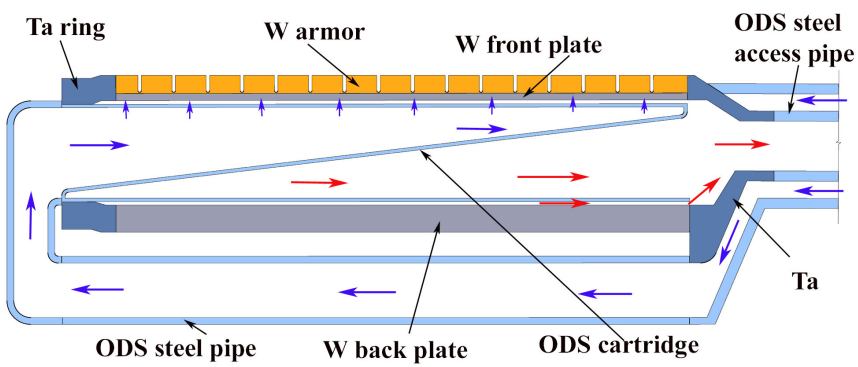


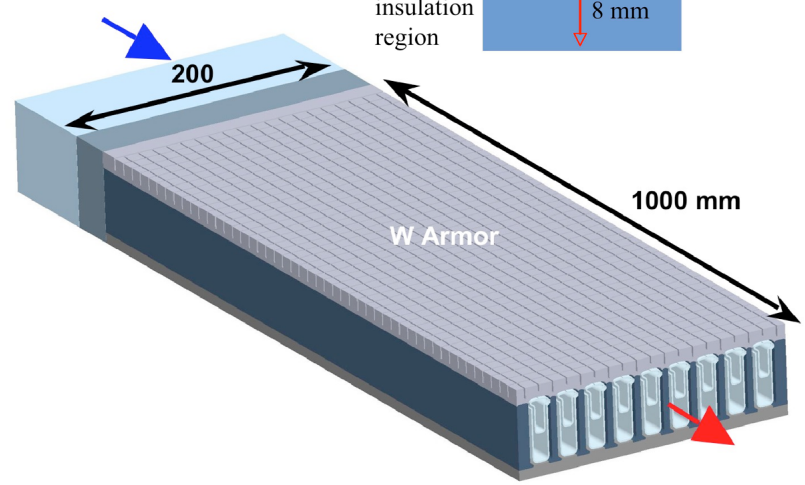
- Maximum FW temperature is well below 550°C limit.
- Maximum LiPb/F82H interface temperature ~495 C (within design limit of 500°C).
- Maximum thermal stress is ~144 MPa (1.5 S_{mt}=203 MPa at T=500°C)
- Similar results at top and mid-plane

The plate divertor concept provides acceptable performance with mimimum complexity

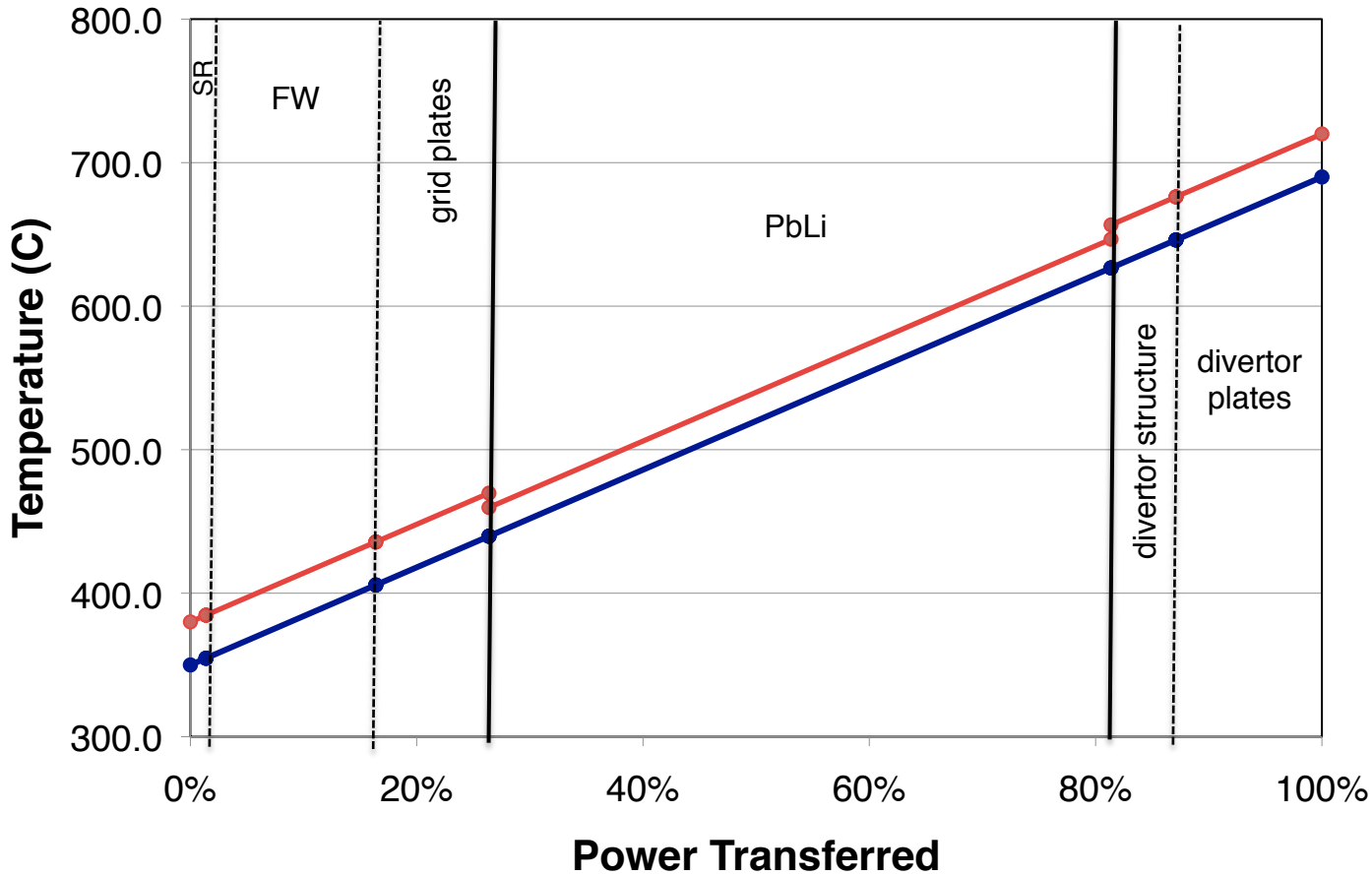




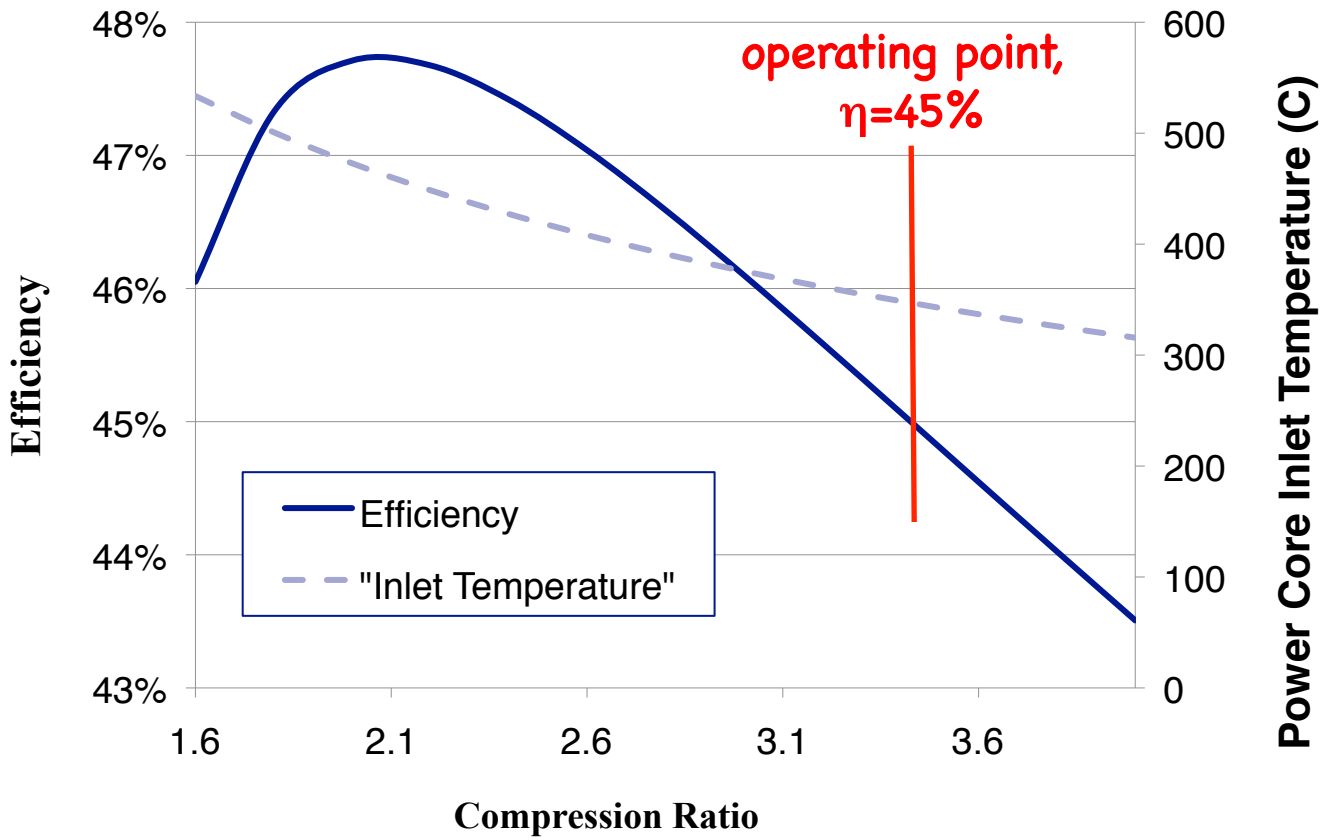




Power flows and HX temperatures are consistent with all power core inlet/outlet temperatures



Brayton cycle efficiency is degraded 2.5% due to the low inlet temperature required to maintain steel/PbLi interface below 500 C



Summary and Conclusions

- The modest loading conditions in ARIES-ACT2 allow the DCLL blanket to easily satisfy materials requirements. **However,** *PbLi technologies must be further developed and demonstrated.*
- The moderate divertor loading allows us to use the simpler He plate-type divertor. **However,** *W-alloy development is a critical issue. Advanced (high temperature) steel alloys are also needed.*
- An alternative, "small module" design was proposed. **However,** *further studies are needed to demonstrate fabricability (including manifolds) and acceptable performance.*
- Much progress has been made on design details. **However,** more effort will be needed on design detauils and fabricability in order to implement in a next-step device such as FNSF.
- The ACT2 power core is a reasonably conservative design that meets the design requirements and provides an attractive 45% conversion efficiency.