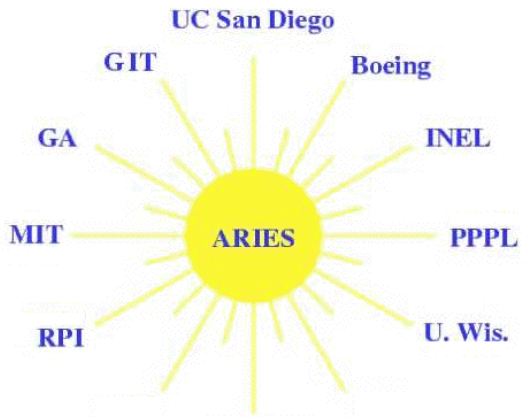
Evaluation of high heat flux components under normal and off-normal conditions



M. S. Tillack

with contributions from
X. Wang, A. R. Raffray,
S. Malang, H. Chitalia, J. Burke

UC SanDiego

US-Japan Workshop on Fusion Power Plants
and Related Advanced Technologies
23-24 February 2010

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Background

- **Significant progress has been made in the past decade developing high-performance divertor concepts with W alloy and He cooling**
  - *W is used for high conductivity and high-temperature strength*
  - *He is used for high cycle efficiency and materials compatibility*
  - *Typical steady-state heat flux limits are ~10 MW/m^2*
- **The behavior of these designs under *off-normal* conditions has not been well characterized** (*e.g.*, the effect of ELM's, VDE's, disruptions)
  - *Scoping studies are discouraging*
- **However, heat flux limits are usually based on conservative design rules**
  - *How much higher heat flux could be handled using "design by analysis" instead of "design by rule"?*
- **In the current ARIES study we will perform detailed, nonlinear, time-dependent elastic-plastic analyses of components, from fabrication to failure, to refine our understanding of their behavior and limitations**

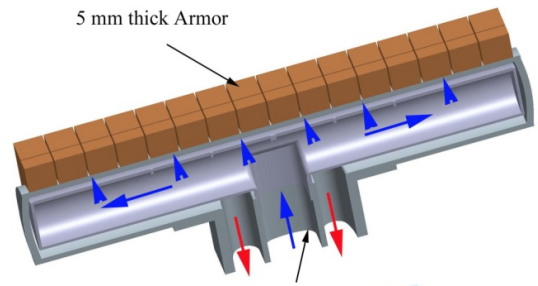
Several He/W design concepts are under investigation in the ARIES Team

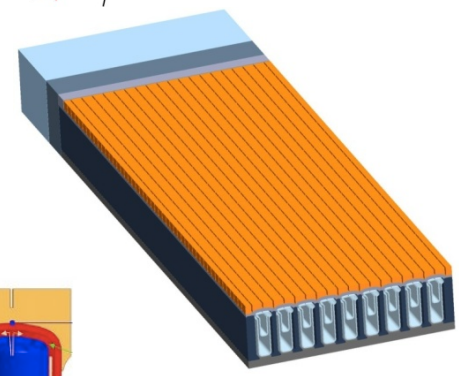
- **T-Tube**: ~1.5 cm diameter x 10 cm long
- Impinging slot-jet cooling
- Allowable heat flux >10 MW/m^2
- ~110,000 units for a power plant

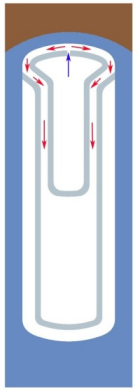
- **Plate**: 20 cm x 100 cm
- Impinging slot-jet cooling
- Allowable heat flux ~10 MW/m^2
- ~750 units for a power plant

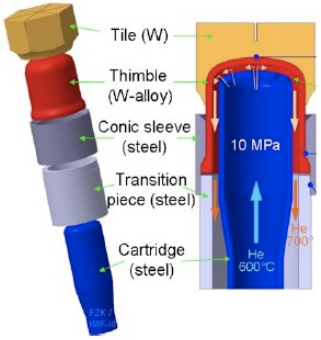
- **EU finger**: 2.6 cm diameter
- Impinging multi-jet cooling
- Allowable heat flux >10 MW/m^2
- ~535,000 units for a power plant

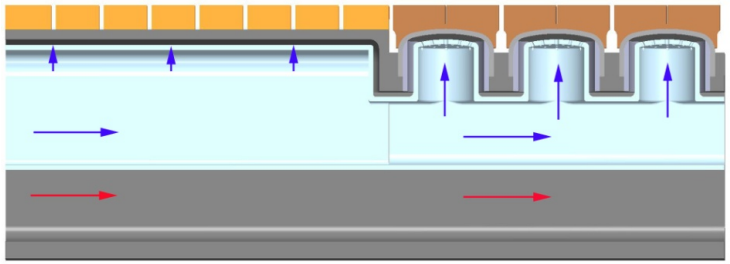
- **Combined plate and finger**
- Fingers for q>8 MW/m^2
- Plate for q<8 MW/m^2
- Increased design margin in exchange for more finger units, ~89,000





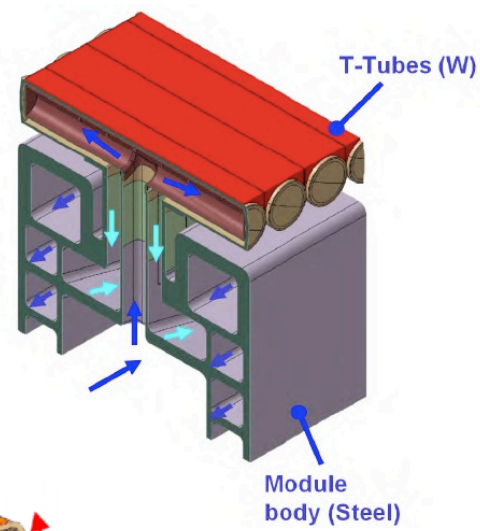


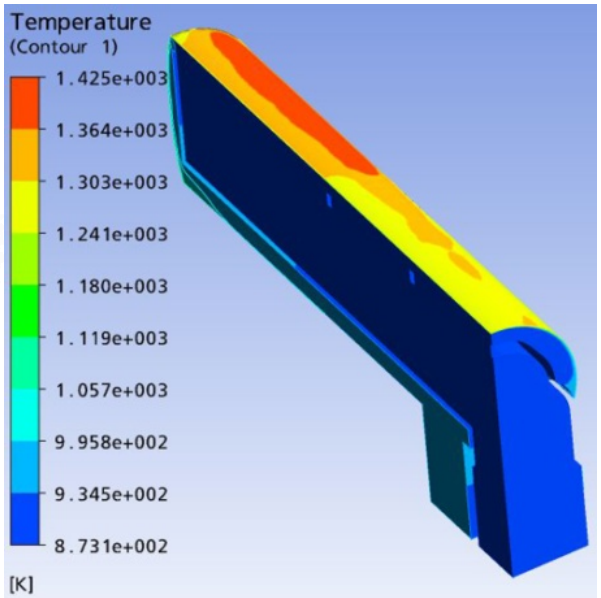


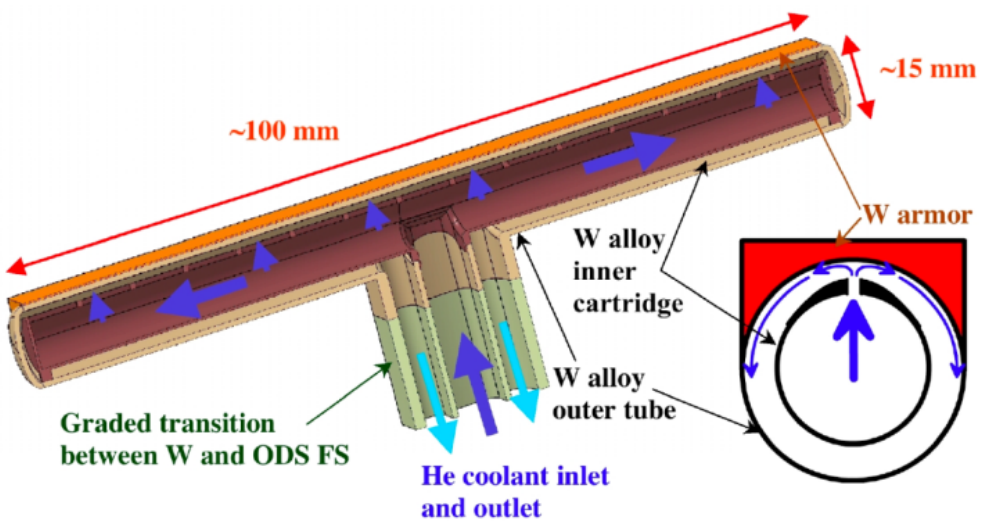


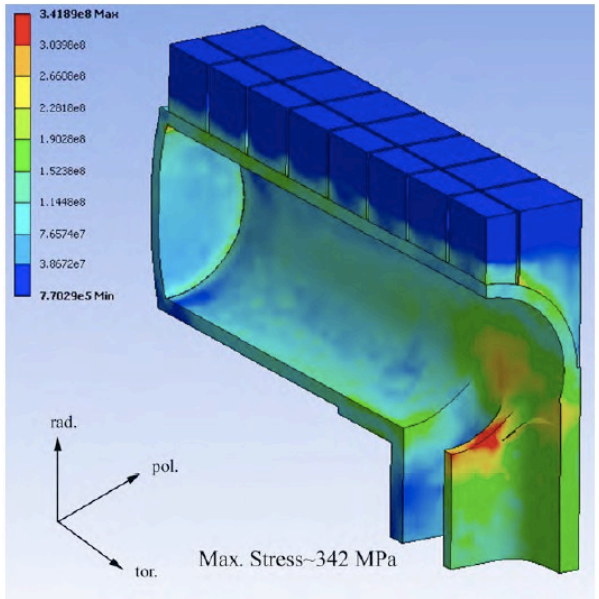
T-tube divertor

- The T-Tube divertor was designed to accommodate a surface heat flux of 10 MW/m^2 for ARIES-CS (by Thomas Ihli)
  - T_{max}=1300 ˚C
  - $3S_m$=752 MPa@750 ˚C
- It was modified for tokamaks to accommodate two heat flux zones without changing configuration, except for the W armor thickness.



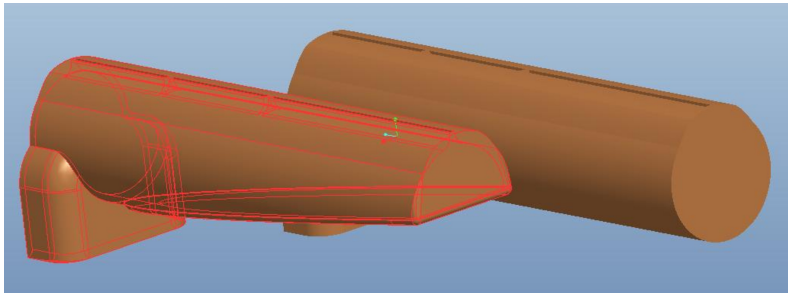


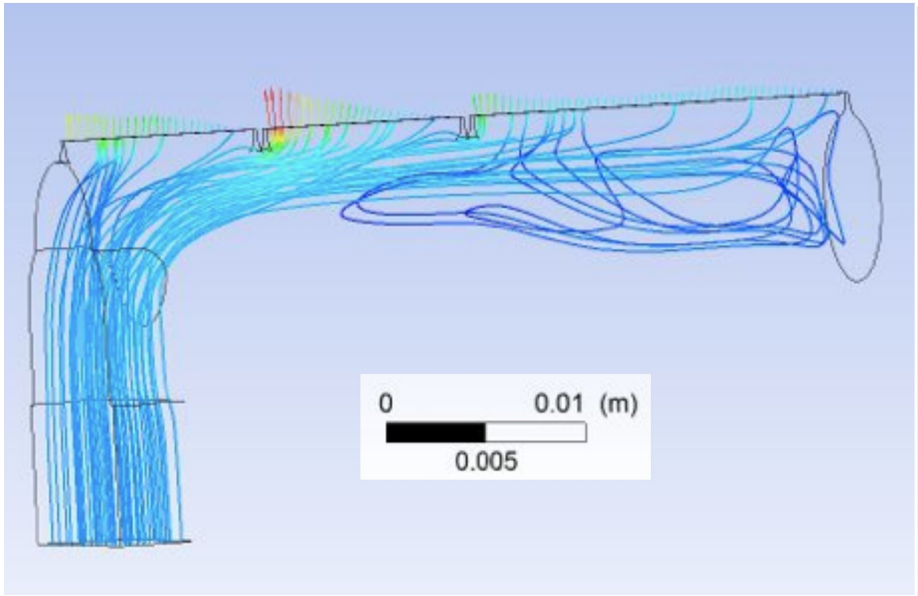




The T-tube design can be further optimized by tailoring the inlet channels

- Tapering reduces eddies
- More uniform slot flow results
- Further improvement can be found by optimizing the shape





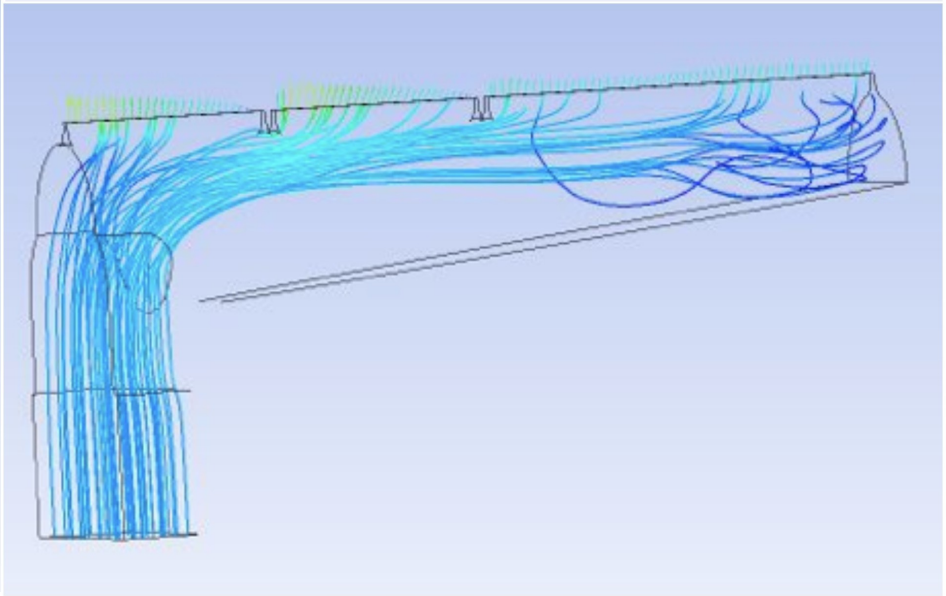


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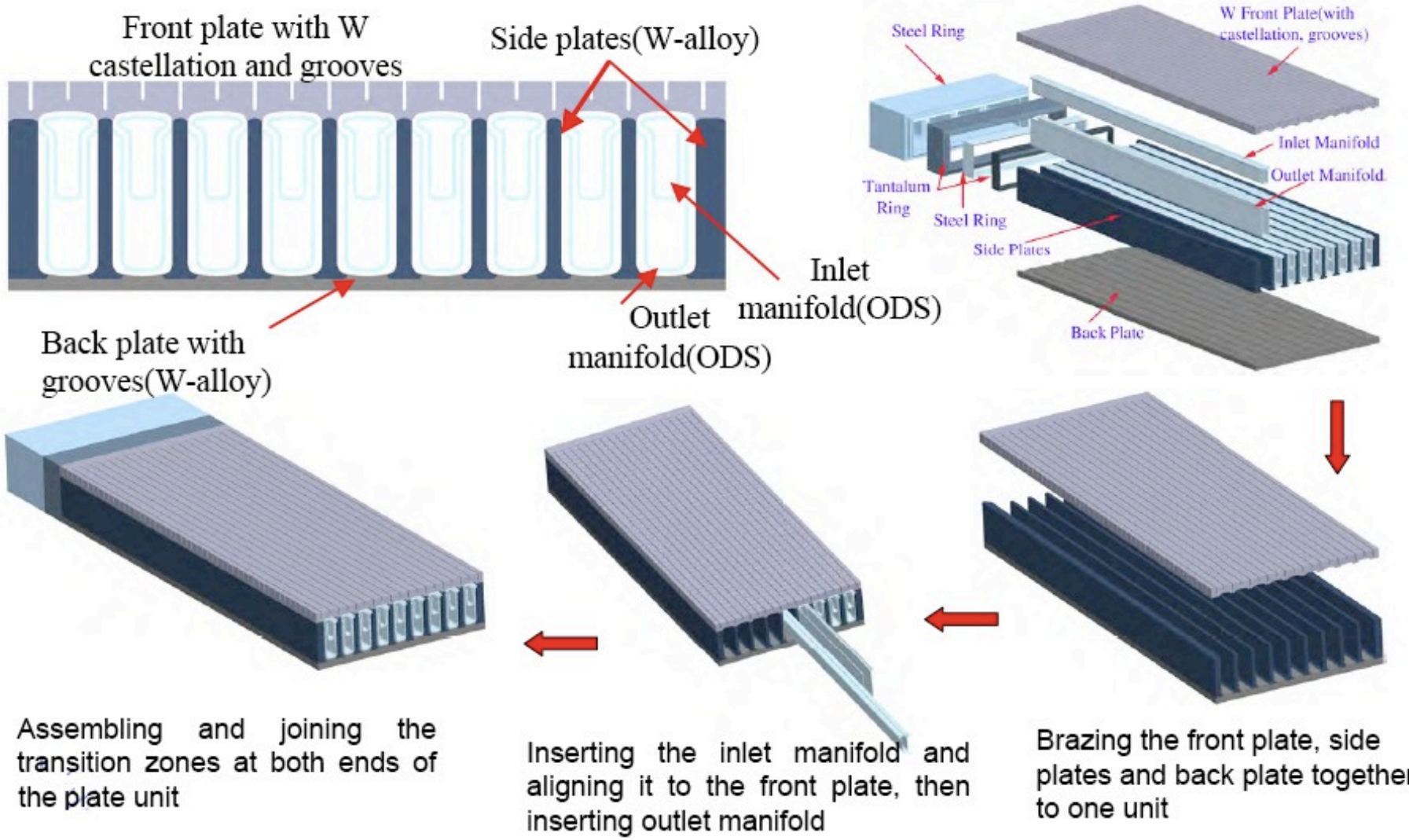
Plate divertor design



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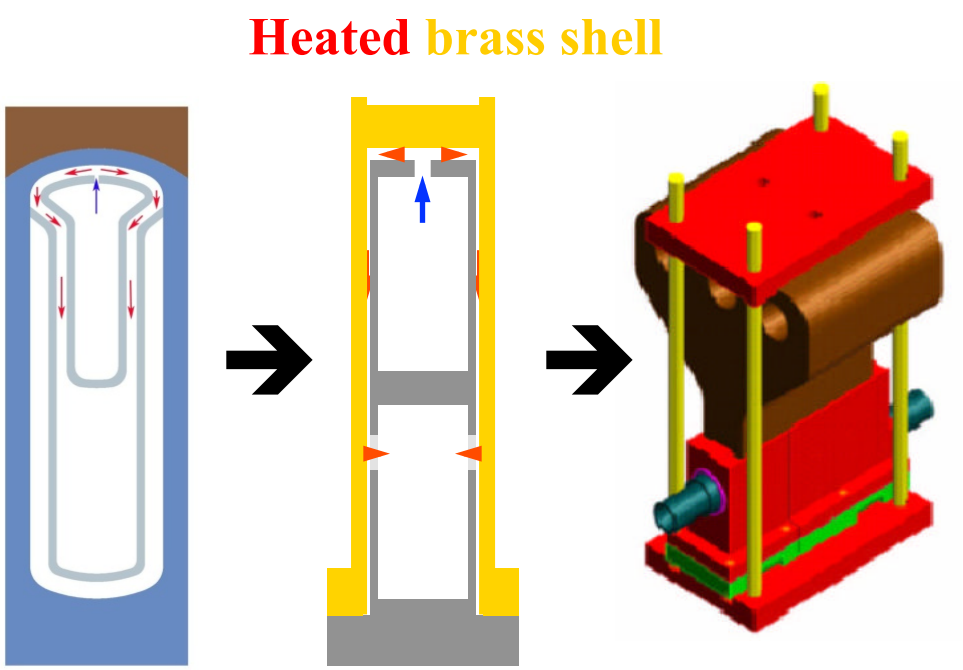
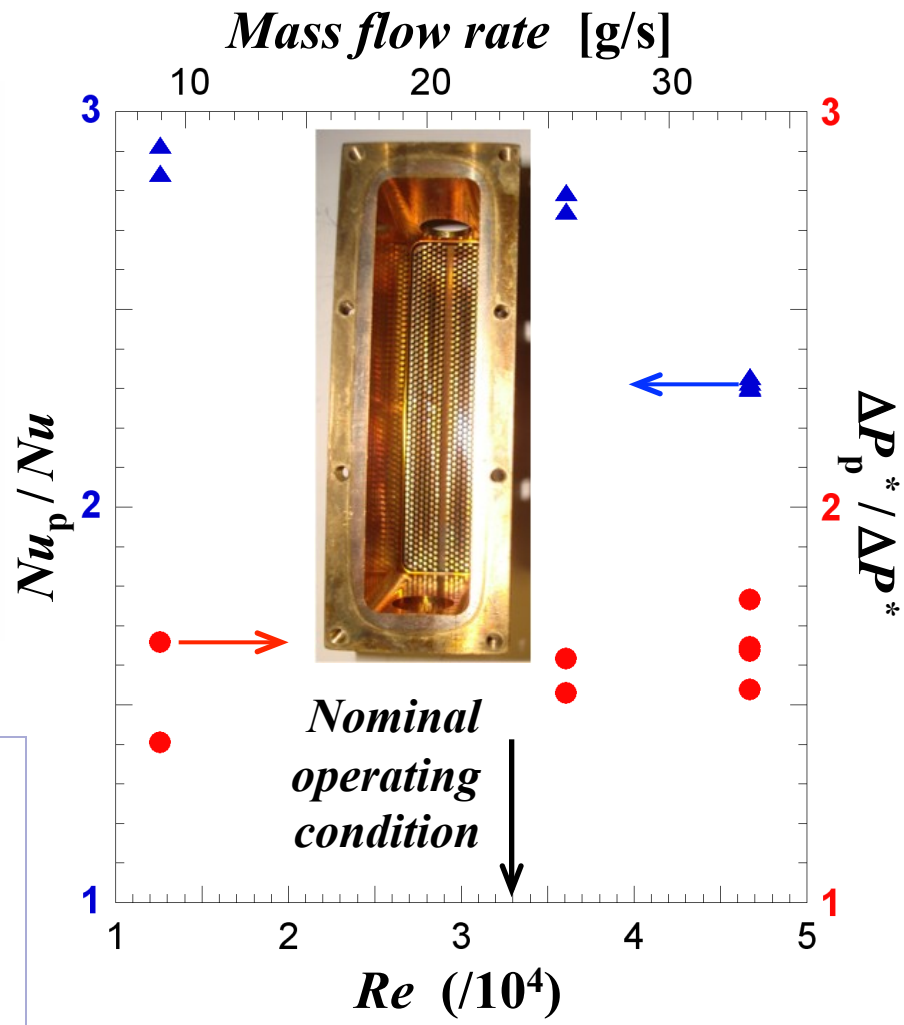
Thermal hydraulic experiments confirm very high heat transfer for slot jet cooling, including pin fins



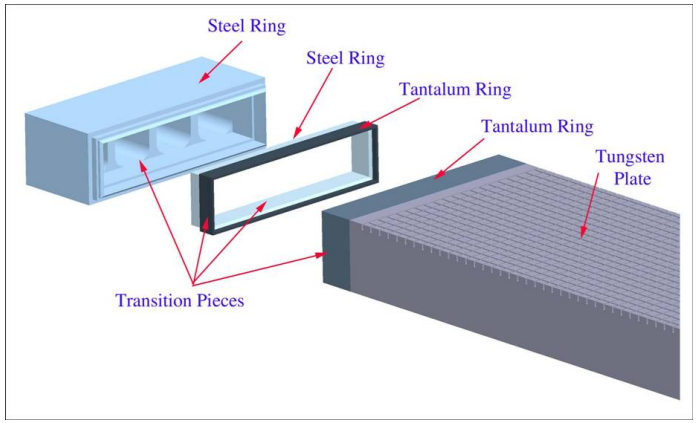


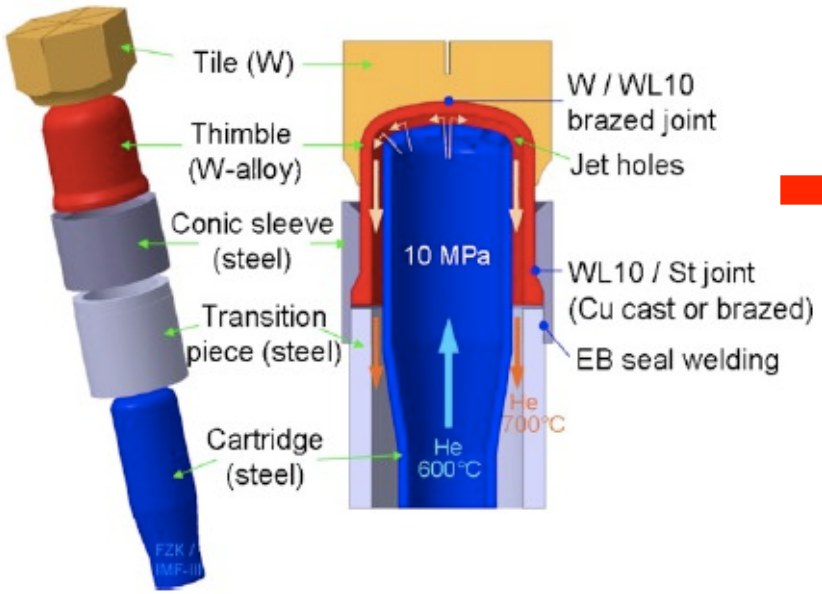
- Pin-fins with ~260% more surface area improve cooling performance by **~150%–200%** while increasing pressure drop by **~40–70%**
- H > 50 kW/(m^2·K) is possible

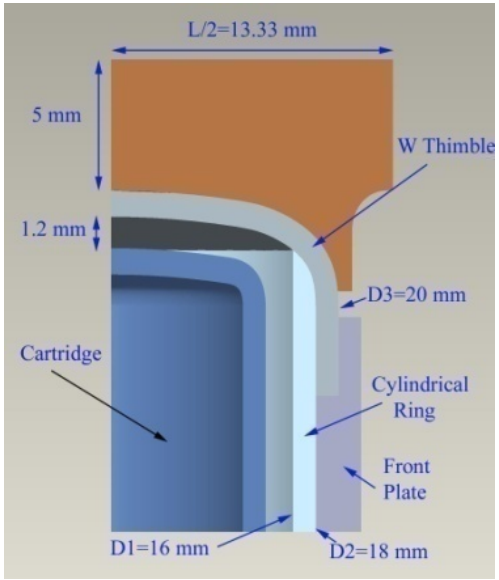
Georgia Institute of Technology

The EU finger design was improved

- No transition joint between W and FS
- Transition is made at the end of the inlet manifold
- We also added a 1-mm inner shell for double containment







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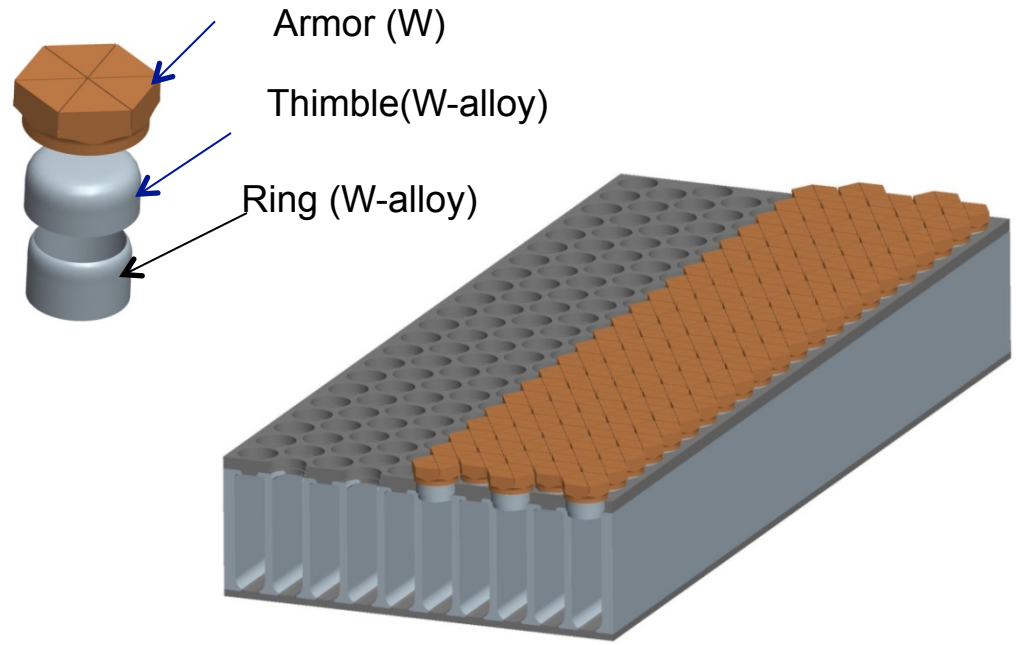
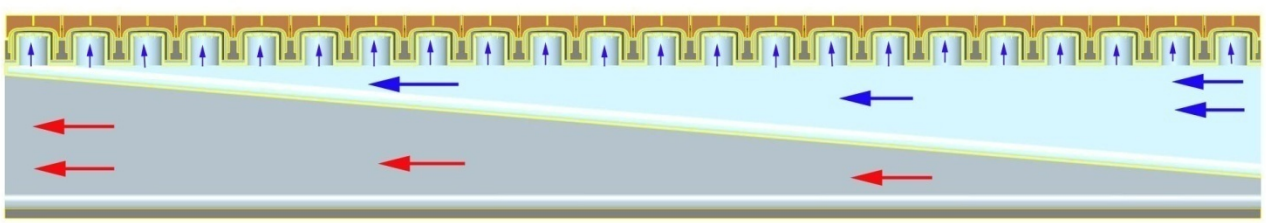
Fingers can be integrated into the plate design to provide localized HHF handling capability with minimum units

- Multiple-jet cooling
- W-base plate fabricated by brazing together front plate, back plate and side walls.
- Small modules on plasma side arranged over the entire plate
- No transition between W-alloy and steel at the modules (in the EU finger design, joints exist between W and steel)



He-cooled W target plate



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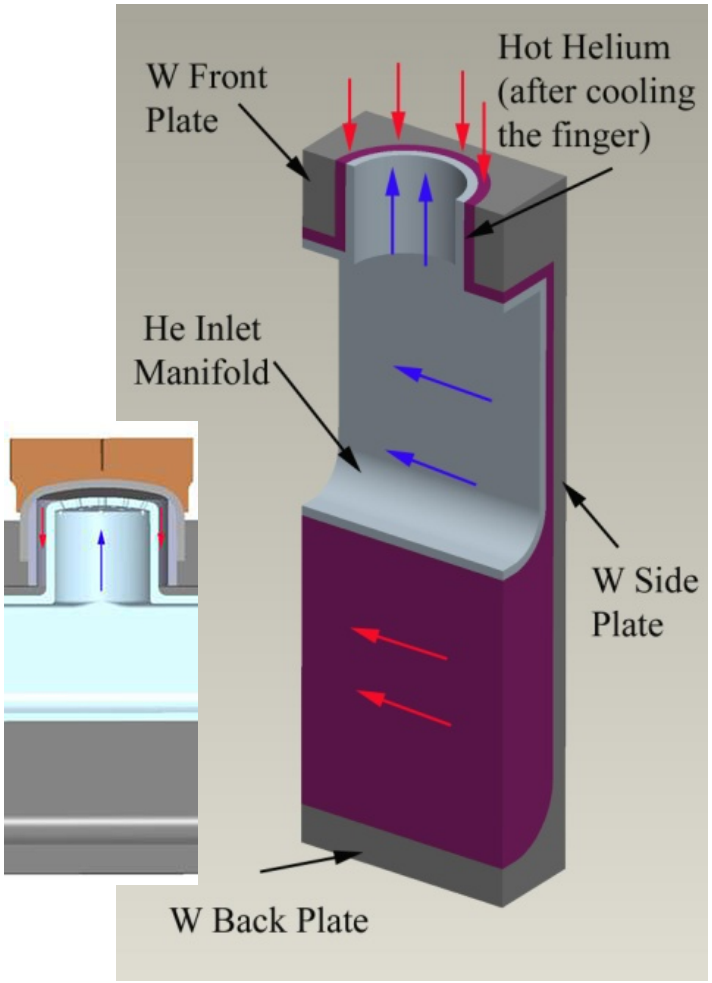
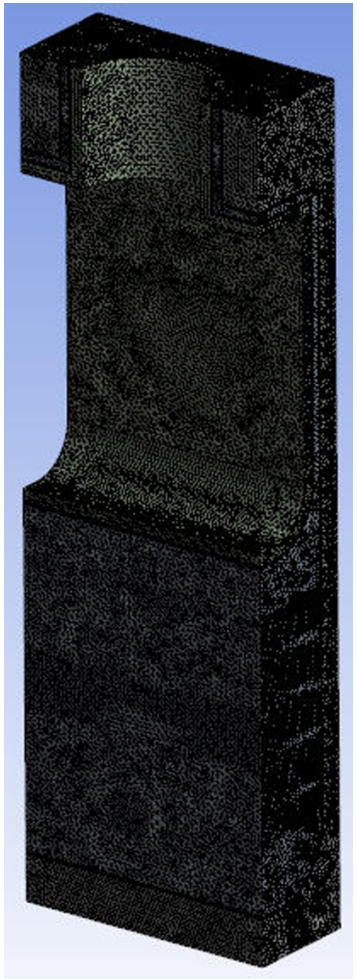
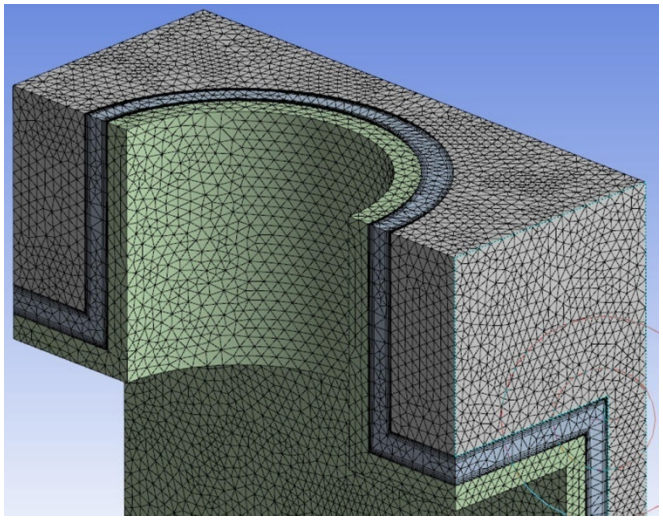
New analysis of the combined plate+finger design now includes the back portions of the unit



CAD model



FEA Model



- 1.8 million tetrahedral elements in CFX model.
- k-ε turbulent model.
- Inlet boundary condition assumed identical to the outlet flow of the finger.

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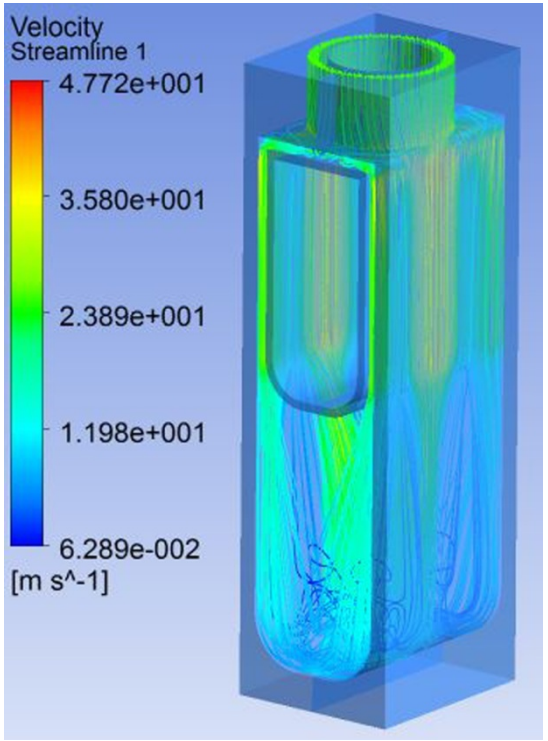
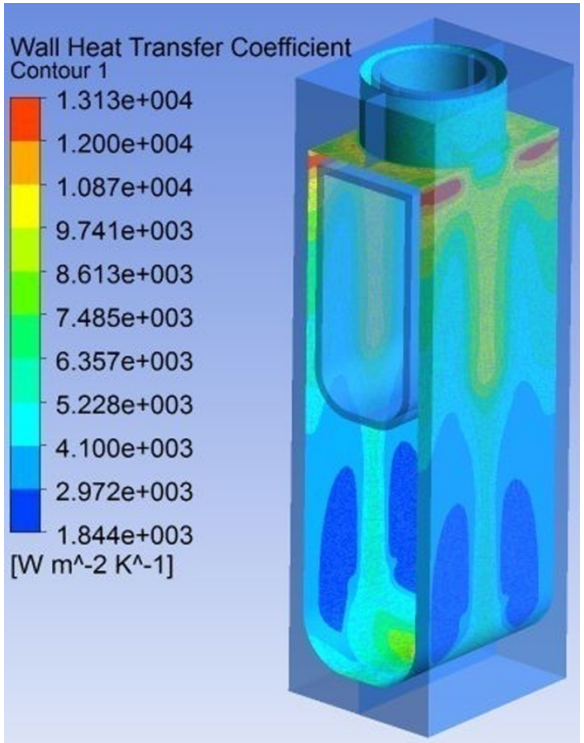
Analysis confirms temperature and stress remain within allowable limits

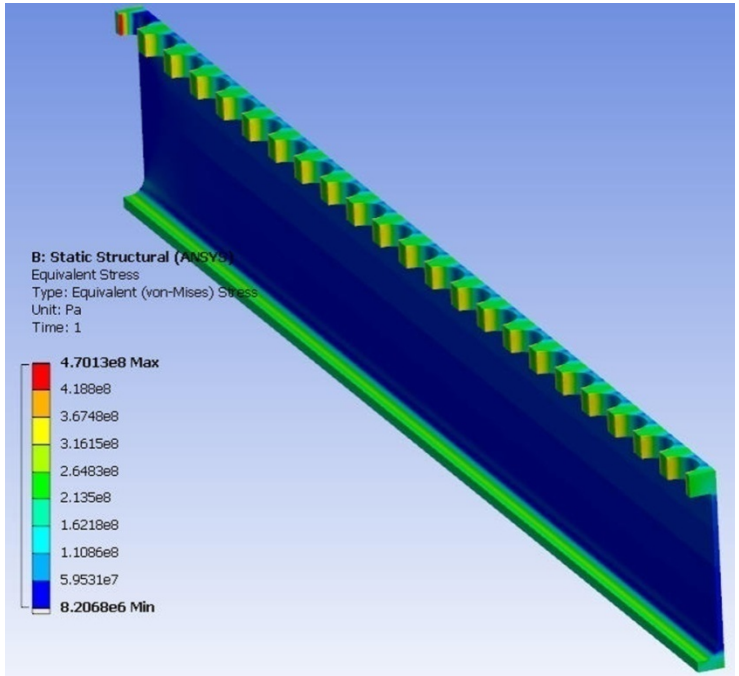
- Maximum combined primary + secondary stress is 470 MPa (< $3S_m$=752 MPa for W temperature T=750°C)
- Maximum total deformation is about 0.4 mm



Velocity



Heat transfer coefficient



Stress

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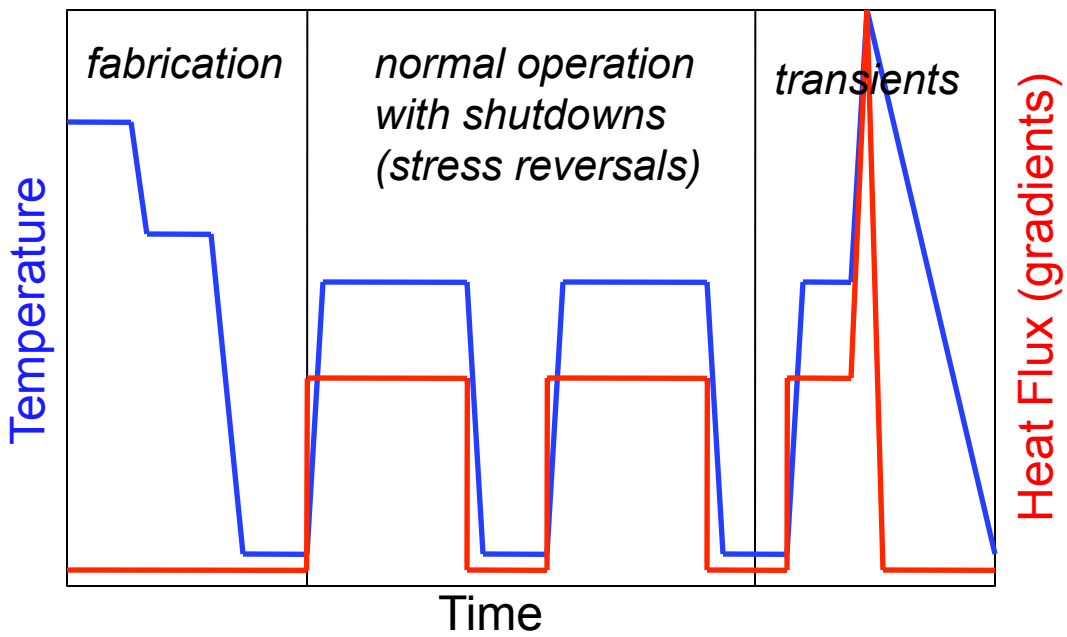
Expanded efforts are underway to improve our understanding of HHF limits

- **Allow local yielding, and consider shakedown, strain hardening, creep and ratchetting phenomena**
- **Analyze a limited number of transient loading conditions**
- **Use "Design by Analysis" rather than "Design by Rule"**



- ASME is conservative; "Design by Analysis" limits may be higher due to stress relaxation, strain hardening, *etc.*
- Extensive modeling and experimental verification are needed

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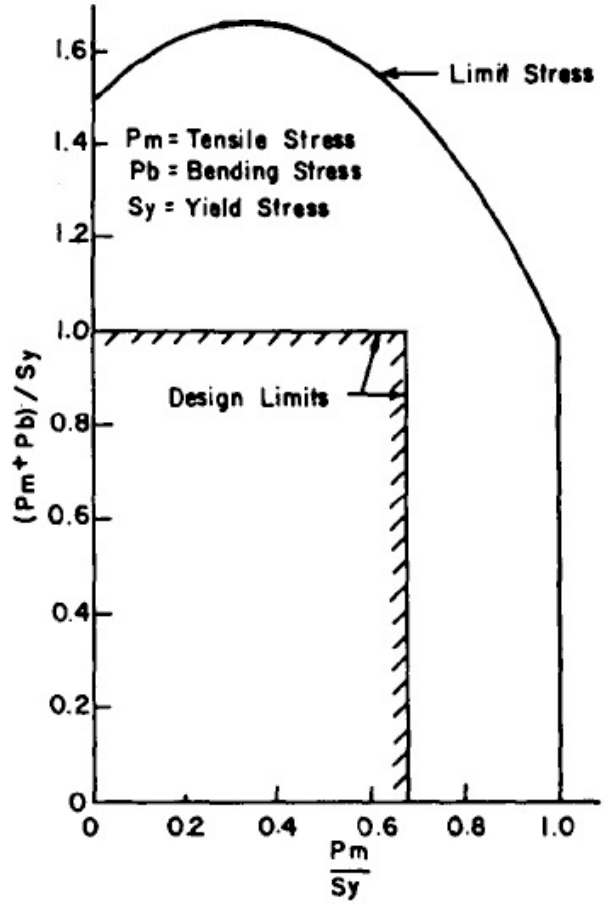
"Design by Code"

- **ASME pressure vessel code** (& Japanese MITI Notification 501) **contain rules for simplified elastic-plastic analyses**
  - These rules are intended to provide conservatism for critical components in applications such as nuclear reactors
- **S_m (for FS and refractories) is the lowest of the following**
  - 1/3 of the minimum **tensile** strength at room temperature
  - 1/3 of the **tensile** strength at elevated temperature
  - 2/3 of the minimum **yield** strength at room temperature
  - 2/3 of the **yield** strength at elevated temperature
- **Code rules ($3S_m$) are intended to prevent…**
  - Bursting and gross distortion from primary (pressure) stress
  - Ratchetting under combined primary + secondary stress, for any number of cycles between room temp. and operating temperature
  - Fatigue failure
- **They do not guarantee survival under all forms of inelastic behavior**

"Design by Analysis" should allow higher heat loads

- Even for pure elastic behavior the code can be conservative
- Secondary stresses are inherently self-limiting; local yielding may be acceptable
- Including creep stress relaxation might extend the design space even further
- Initially we want to answer the question: "how much benefit may be gained if we use 'Design by Analysis'?"



Limit stress for combined tension and bending (from ASME criteria document)

(safety factor of 1.27-1.67)

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Design criteria are needed for "design by analysis"

- **For example, the NET Team used:**

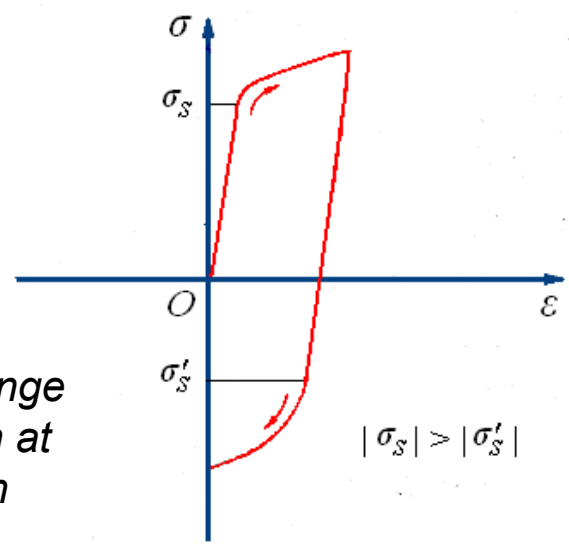
$$\varepsilon_{inelastic}^{principal} < \varepsilon_{allowable}^{BaseMaterial}$$

where $\varepsilon_{inelastic}^{principal}$ is the maximum value of the principal strains accumulated over the operating life,

and $\varepsilon_{allowable}^{BaseMaterial}$ is 1/2 of the uniform elongation.

Analysis methodology using ANSYS

- **Various plastic deformation models exist, e.g.**
  - Bilinear with isotropic hardening (recommended for large strain)
  - Bilinear with kinematic hardening (for small strain), including the Bauschinger effect
  - Multilinear (allows for more temperature-dependent data)
- **Choice of different models may result in different conclusions**
- **Include thermal creep**
- **Include radiation creep**



Bauschinger effect: microscopic change in material increases tensile strength at the expense of compressive strength

Summary

1. Progress has been made on design and analysis of several advanced W/He divertor designs
2. New efforts on elastic-plastic analysis are underway
3. We hope to demonstrate a larger design window for plasma-facing components under “normal operating conditions”
4. We will also quantify the limits under a select number of “off-normal” operating conditions