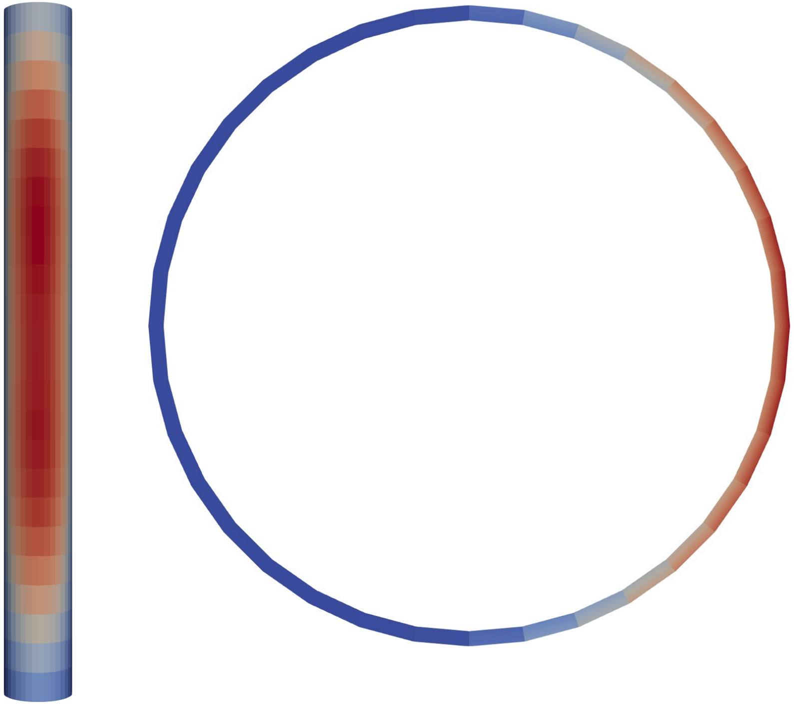
WE START WITH YES.

STRUCTURAL CHALLENGES FOR HIGH TEMPERATURE RECEIVERS



MARK MESSNER
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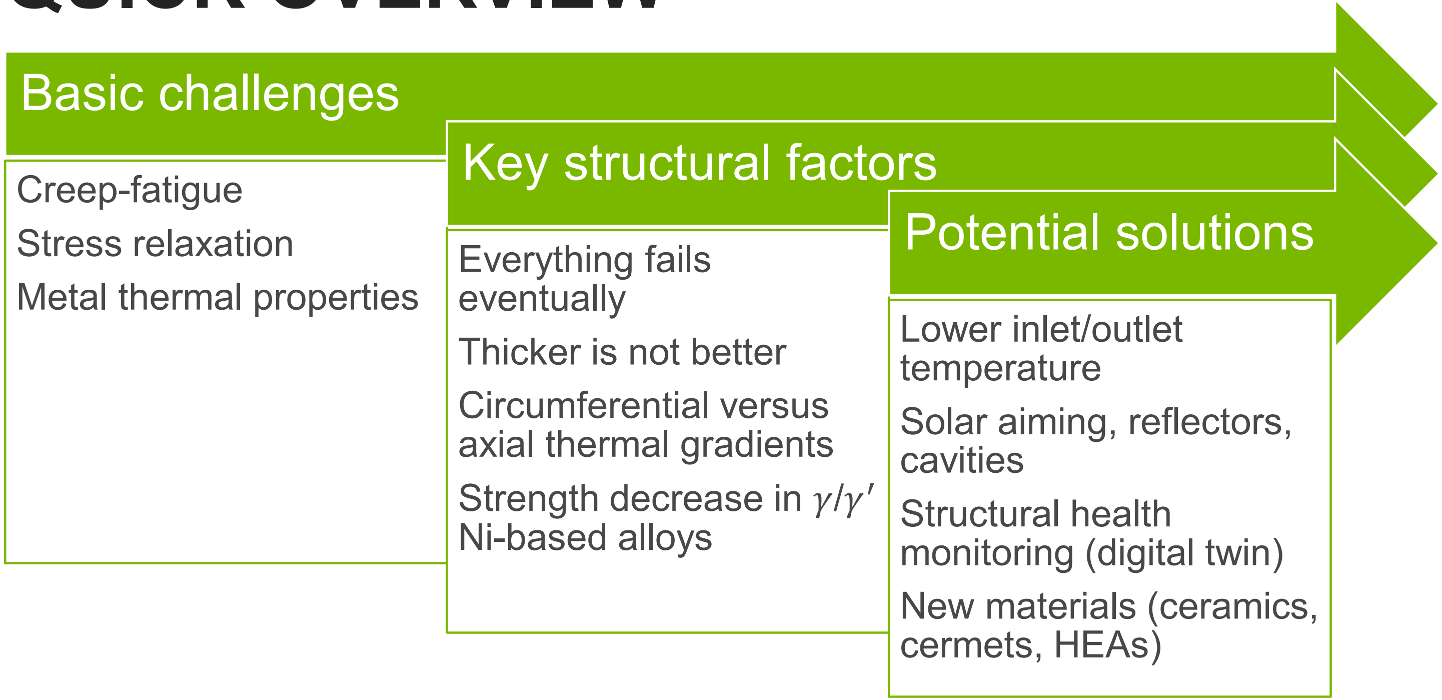
2020 Next Generation Receivers Workshop

QUICK OVERVIEW



Basic challenges

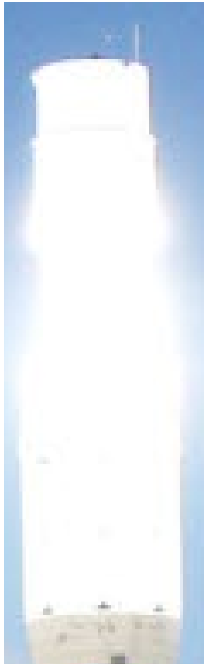
- Creep-fatigue
- Stress relaxation
- Metal thermal properties

Key structural factors

- Everything fails eventually
- Thicker is not better
- Circumferential versus axial thermal gradients
- Strength decrease in γ/γ' Ni-based alloys

Potential solutions

- Lower inlet/outlet temperature
- Solar aiming, reflectors, cavities
- Structural health monitoring (digital twin)
- New materials (ceramics, cermets, HEAs)

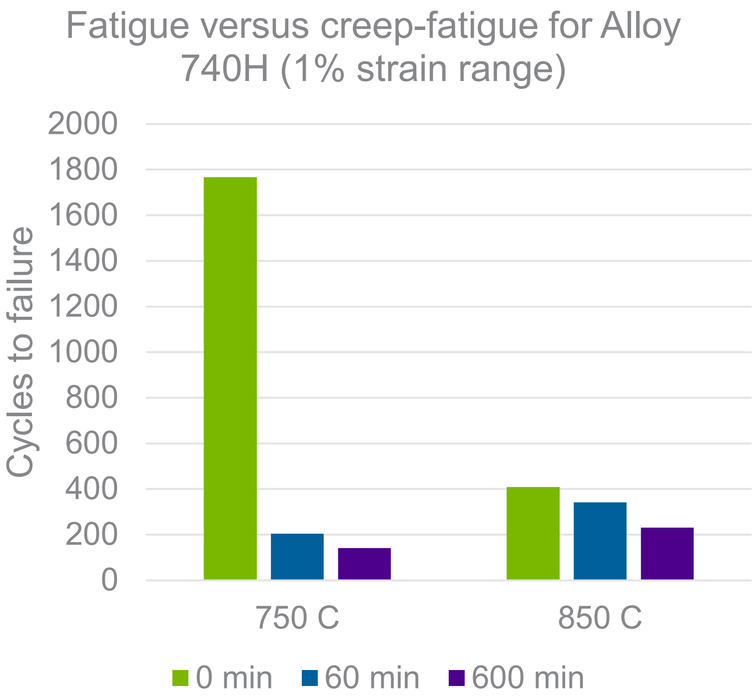


NREL/TP-5500-57625

Caveats: focus here on structural damage (versus environmental) and on tubular receiver designs
Many of these lessons-learned apply to other types of designs, but coolant compatibility is a key factor in selecting a receiver material

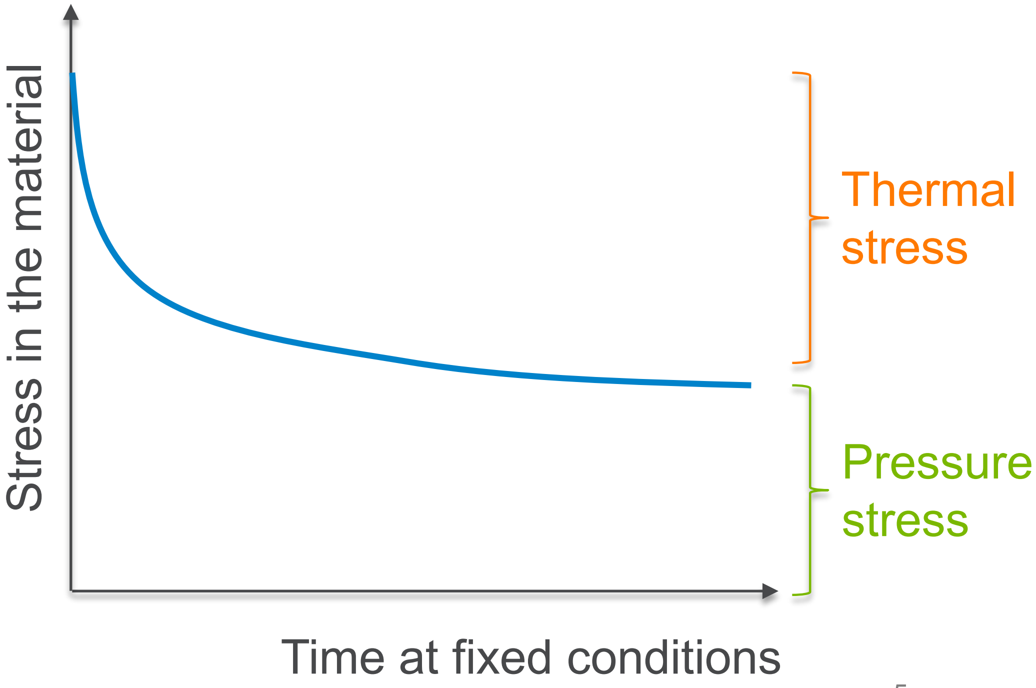
BASIC CHALLENGES

CREEP-FATIGUE IS THE DOMINANT FAILURE MECHANISM FOR HIGH TEMPERATURE RECEIVERS



- At high temperatures the combination of creep and fatigue is much more damaging than each individually:
  - Fatigue: failure under cyclic load
  - Creep: failure under steady load
  - Creep-fatigue: combination of cyclic load + holds at steady conditions
- ***Designing to the fatigue diagram can underpredict life by an order of magnitude***

CREEP AND STRESS RELAXATION OCCUR AT HIGH TEMPERATURES, REQUIRING TIME-DEPENDENT ANALYSIS



- Material deforms over time even at fixed load (creep deformation)
- Structural analysis must be transient/time-dependent (or at least account for creep)
- Creep relaxes high stresses – both a material and a structural effect
- We worry about two “types” of stresses:
  - Stress from pressure: can’t be relaxed
  - Thermal stress: can relax away with time
- Creep deformation can be a good thing if you believe damage ~ stress!

METAL AND WORKING FLUID THERMAL PROPERTIES CONTROL THE MAGNITUDE OF THE THERMAL STRESS FOR FIXED FLUX

Increasing the following does what to the thermal stress?

Increases thermal stress

- Thermal expansion coefficient
- Thickness
- Elastic stiffness

Decreases thermal stress

- Thermal conductivity

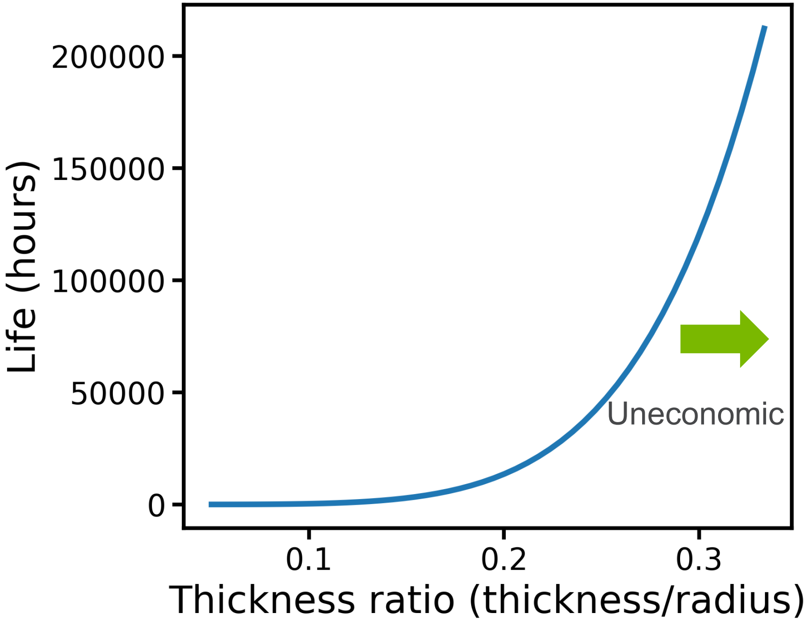
Increasing convection with the fluid decreases the maximum metal temperature

KEY OBSERVATIONS ON STRUCTURAL DESIGN

EVERYTHING FAILS EVENTUALLY

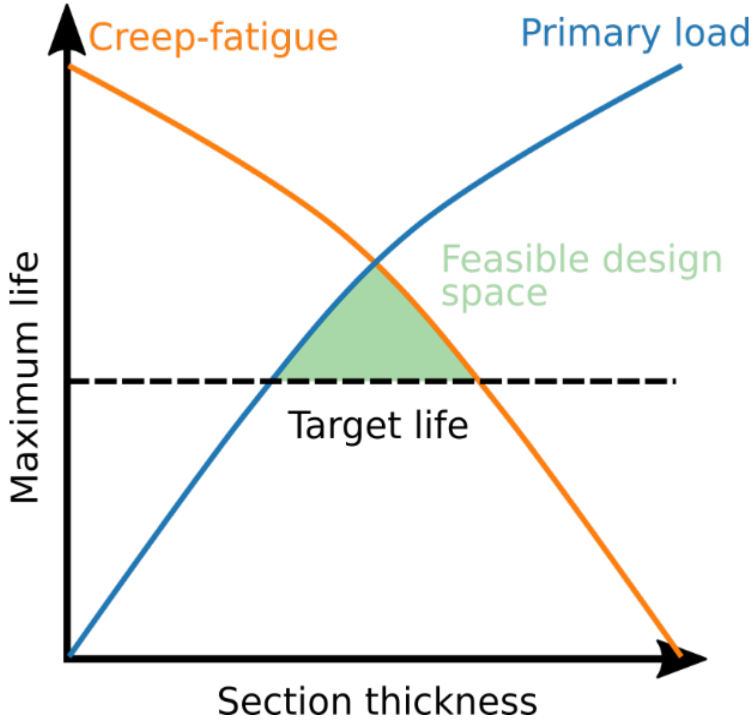
Key difference from low temperature design

A740H, 820° C, 20 MPa internal pressure, 1 in radius tube



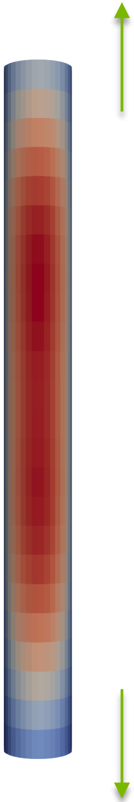
- Low temperature design: structure designed to withstand the load
- High temperature design: structure designed to resist the load for a certain period of time
- Example: creep life at fixed temperature
- Subtle point about Section I/VIII ASME design: typically assume 100,000 hour properties but do not explicitly consider a design life

THICKER IS NOT BETTER

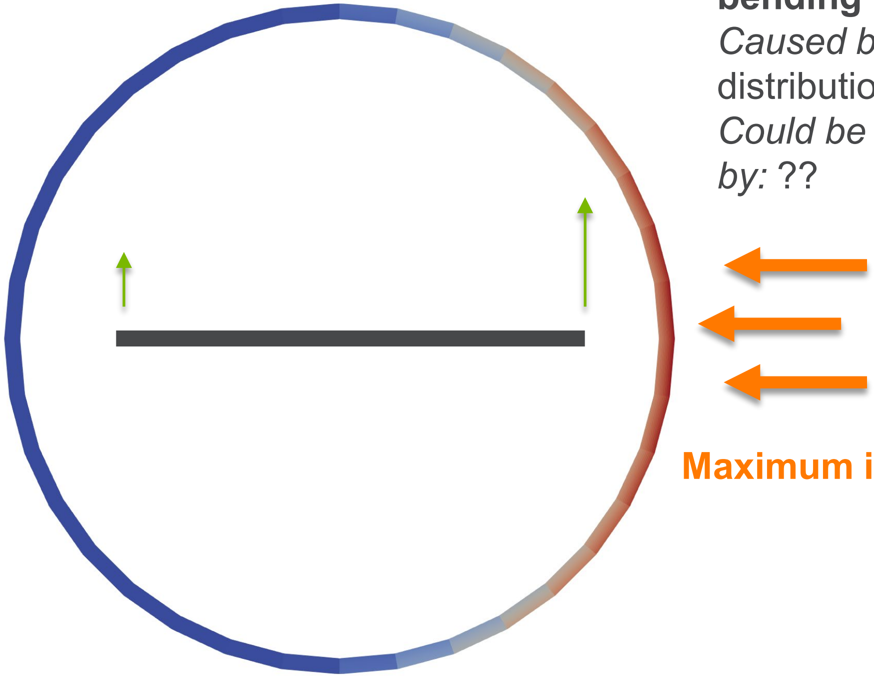


- Unlike low temperature design based on pressure only you can't design your way out by increasing the section thickness
- **Two competing design limits:**
    - *Pressure*: **increasing** thickness improves creep rupture/plastic collapse
    - *Thermal stress:* **decreasing** thickness improves fatigue/creep-fatigue

CIRCUMFERENTIAL THERMAL GRADIENTS ARE WORSE THAN NET THERMAL EXPANSION



Net axial expansion
Caused by: net tube temperature increase
Could be alleviated by: bellows



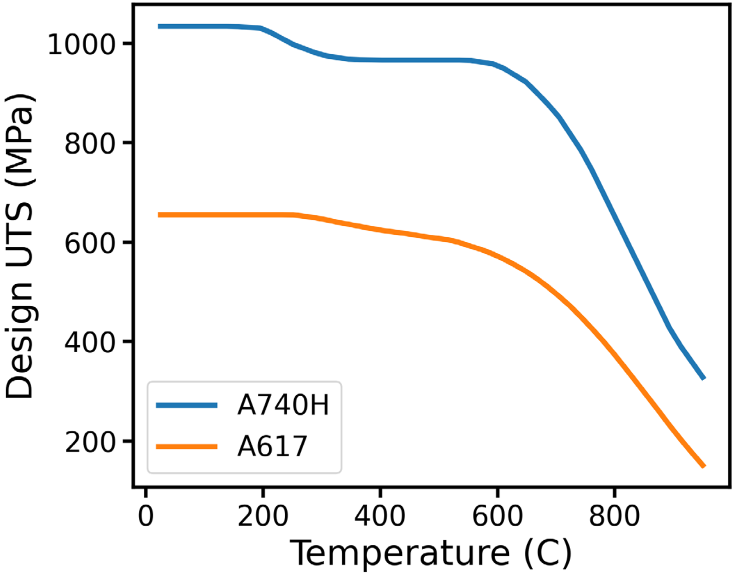
Circumferential bending
Caused by: flux distribution
Could be alleviated by: ??

Maximum incident flux

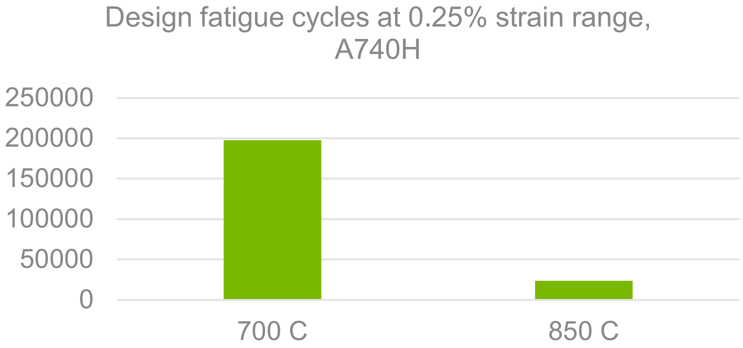
In our experience circumferential bending is much more challenging than net tube expansion

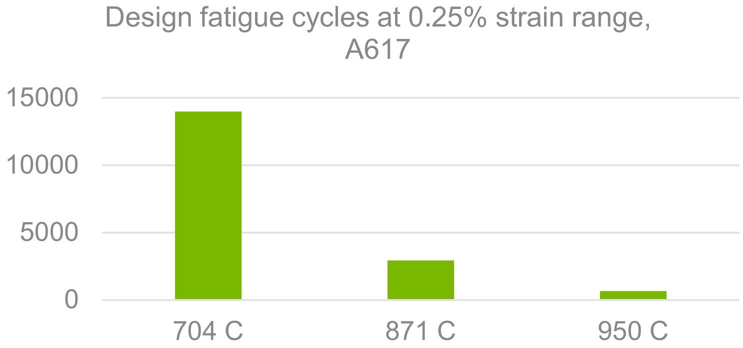
THE STRENGTH OF NI-BASED ALLOYS DROPS OFF PAST $\sim 775℃$

Shift in precipitation kinetics significantly reduces γ' phase nucleation and growth



Change associated with shift from work hardening to perfectly-plastic behavior



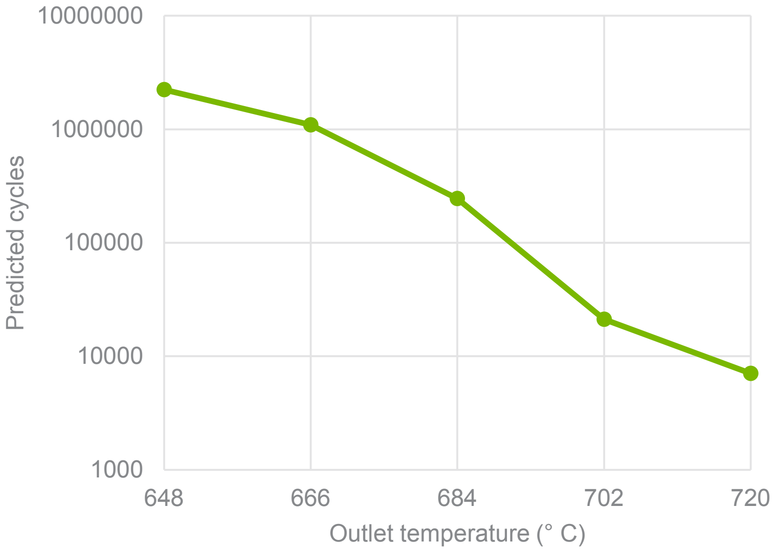


POTENTIAL SOLUTIONS

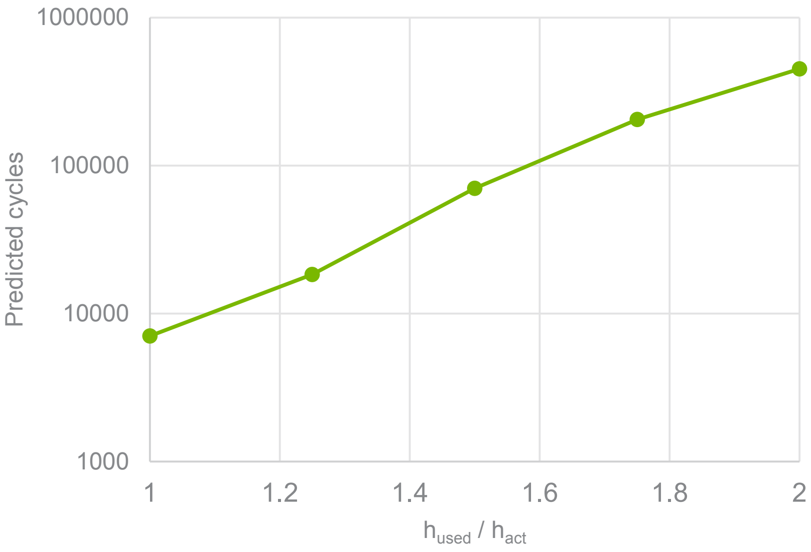
ACCEPT A LOWER OUTLET TEMPERATURE OR USE A “BETTER” WORKING FLUID

Not an ideal solution, but certainly feasible

Reference A740H salt receiver as a function of outlet temperature (fixed flux, 1D analysis)

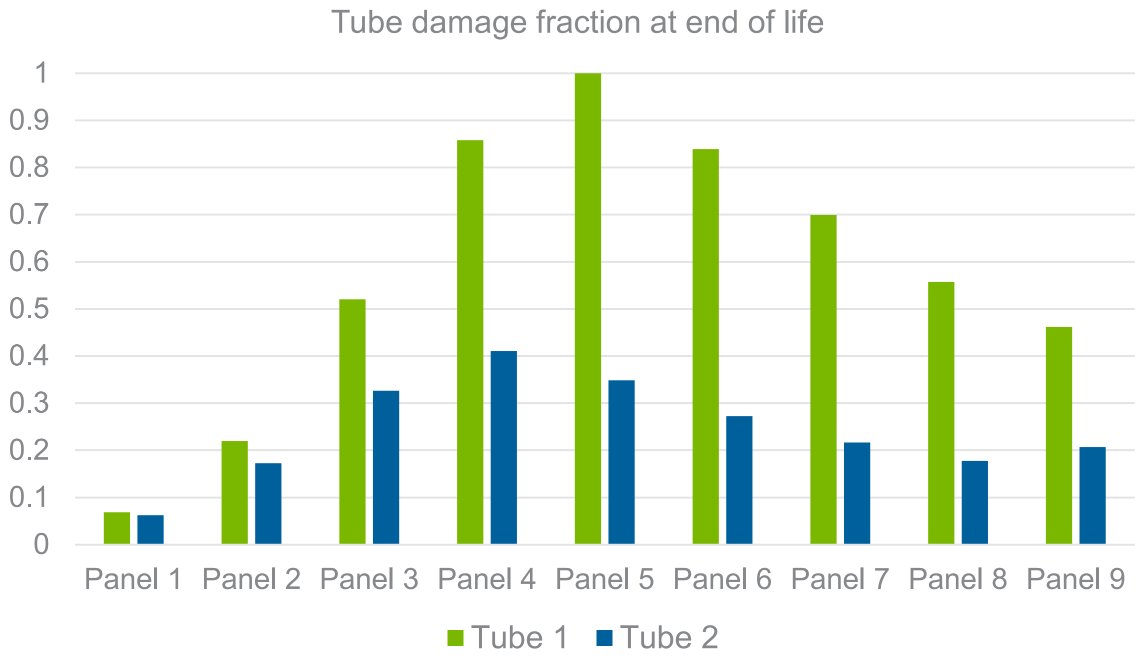


Reference A740H salt receiver as a function of working fluid convective heat transfer coefficient (fixed flux, 1D analysis)



DISTRIBUTE THE DAMAGE MORE UNIFORMLY

Repair and replace tubes, structural health monitoring



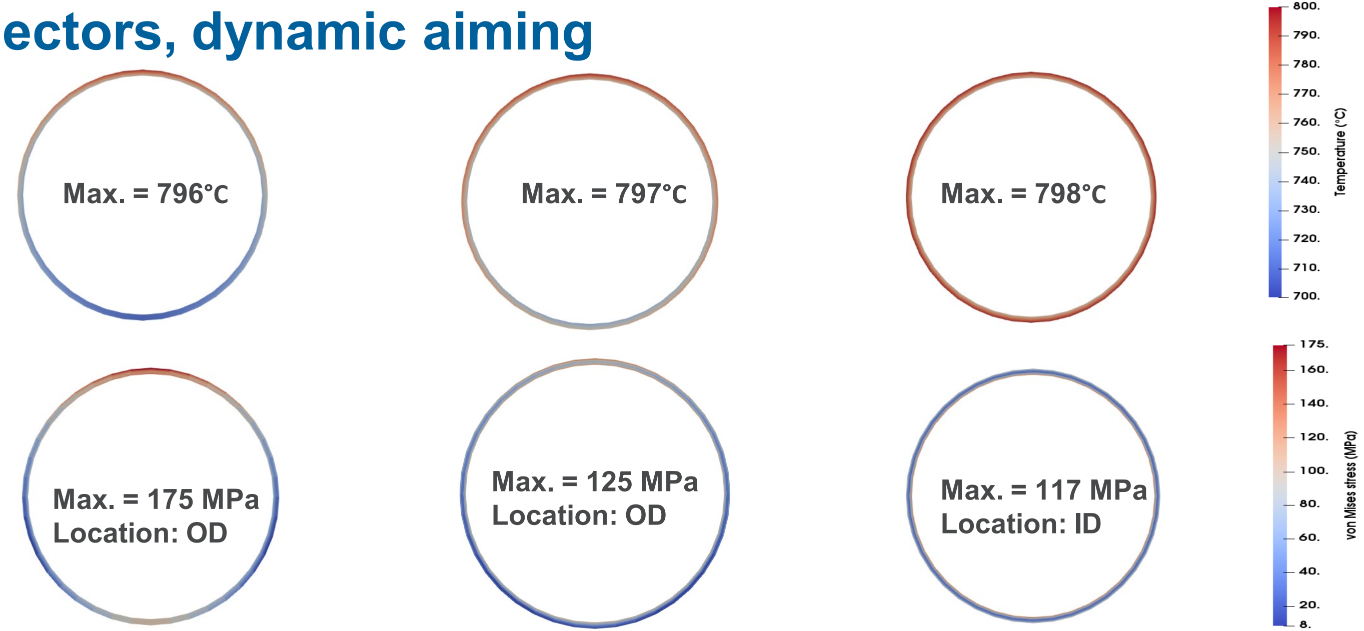
- Peak damage occurs only in a limited number of tubes in the receiver
- Remaining tubes have substantial residual life
- Take advantage of that:
    - Monitor development of damage in tubes
    - Repair/replace when required
- Design changes to accommodate this strategy?
- In situ health monitoring (digital twin)?

DISTRIBUTE THE FLUX MORE UNIFORMLY

Cavities, reflectors, dynamic aiming

Temperature

Von Mises stress



Case:1

- *Maximum circumferential flux variation (e.g. a typical external receiver)*
- *Creep-fatigue life = **61 days***

Case:2

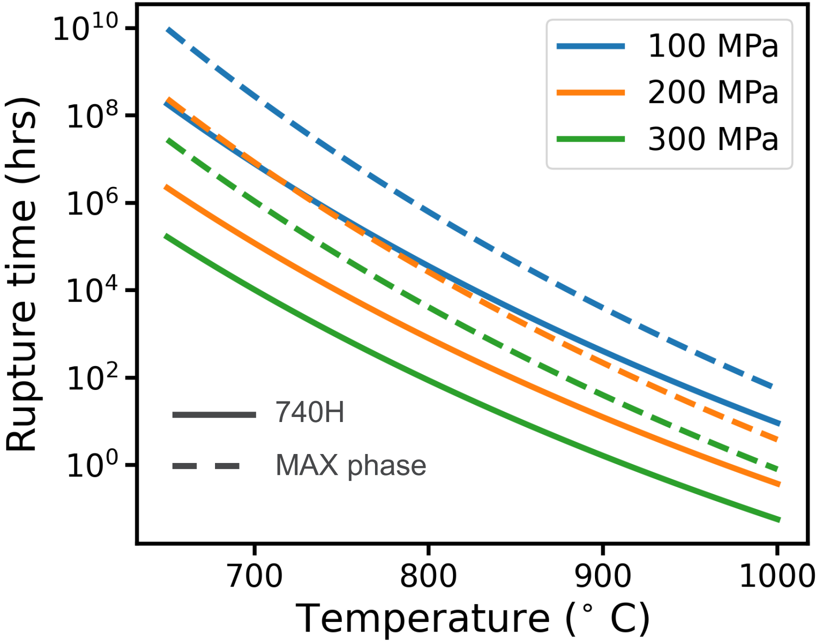
- *Reduced circumferential flux variation (e.g. a cavity receiver, an external receiver with reflectors at the back of the tubes)*
- *Creep-fatigue life = **377 days***

Case:3

- *No circumferential flux variation (e.g. an ideal cavity receiver)*
- *Creep-fatigue life = **4877 days***

USE NEW MATERIALS WITH BETTER CREEP/CREEP-FATIGUE RESISTANCE AT TEMPERATURE

- Ceramic based-materials maintain creep strength to much high temperatures, when compared to Ni-based superalloys
  - Creep strength fairly well established (albeit at higher temperatures)
  - *Creep-fatigue (or fatigue) strength less studied*
- There are other candidate metallic material systems:
  - HEAs
  - ODS alloys
  - Co superalloys
- Substantial practical challenges:
  - Forming (AM?)
  - Joining
  - Thermal properties (for *some* ceramics)
- Additional challenge: design practices for non-ductile materials



Projected creep-rupture comparison between Ni-based Alloy 740H and MAX phase material