# Thermostructural Analysis of the SOFIA Fine Field & Wide Field Imagers Subjected to Convective Thermal Shock

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# Overview

- SOFIA Overview
- The Thermostructural Concern
- Determination of Governing Parameters
- FEM Model Development
- Results
- Conclusions

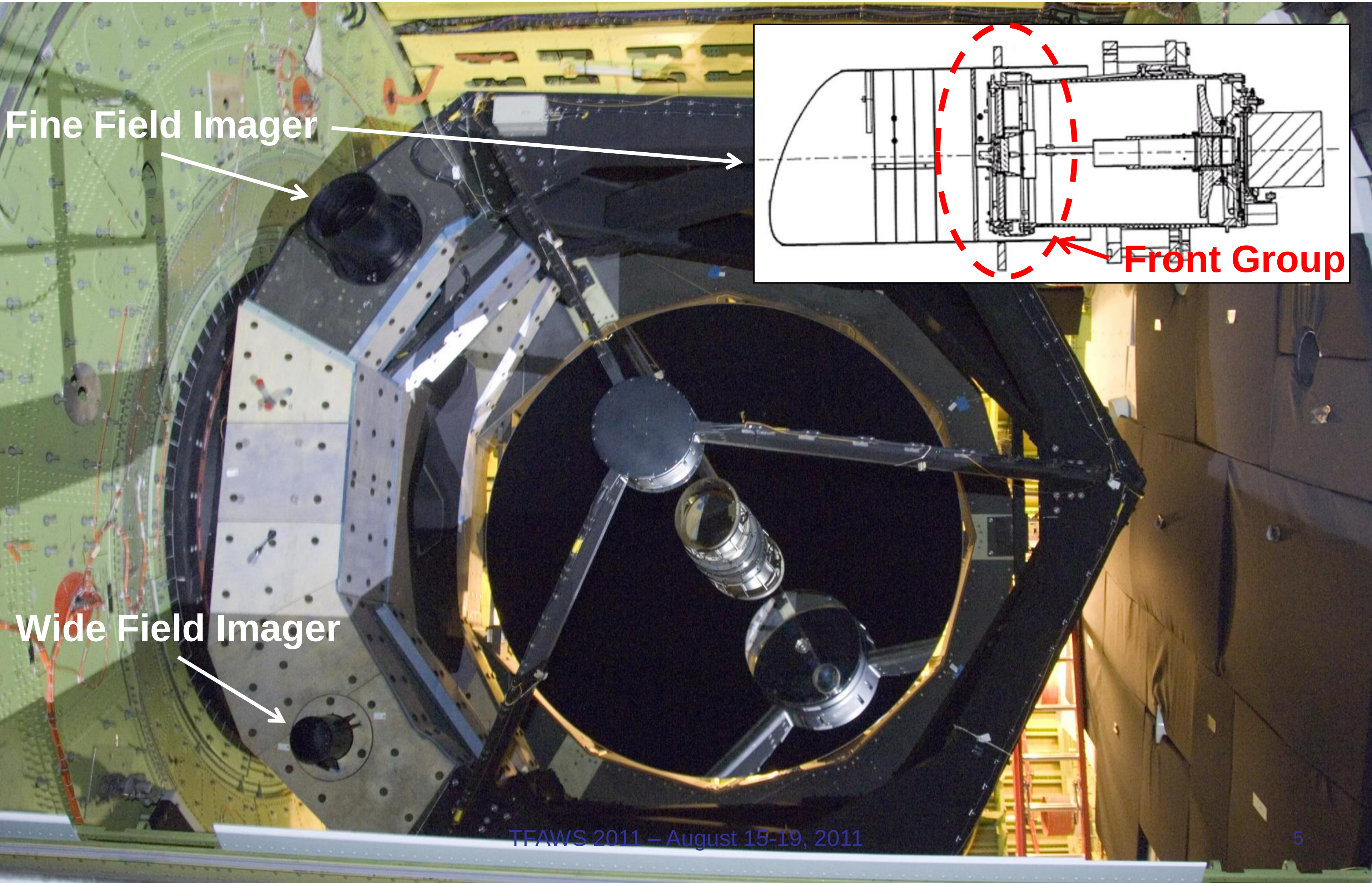
# Stratospheric Observatory For Infrared Astronomy

- Highly Modified Boeing 747-SP
- 17-ton Infrared Telescope:
  - Primary Mirror: 2.5m diameter
  - Optimized for infrared wavelengths that cannot be accessed by any ground telescope or current space telescope
- Max Opening (shown): 58°
- Mobile observatory platform (anywhere, anytime)
- Envelope expansion complete, science flights begun

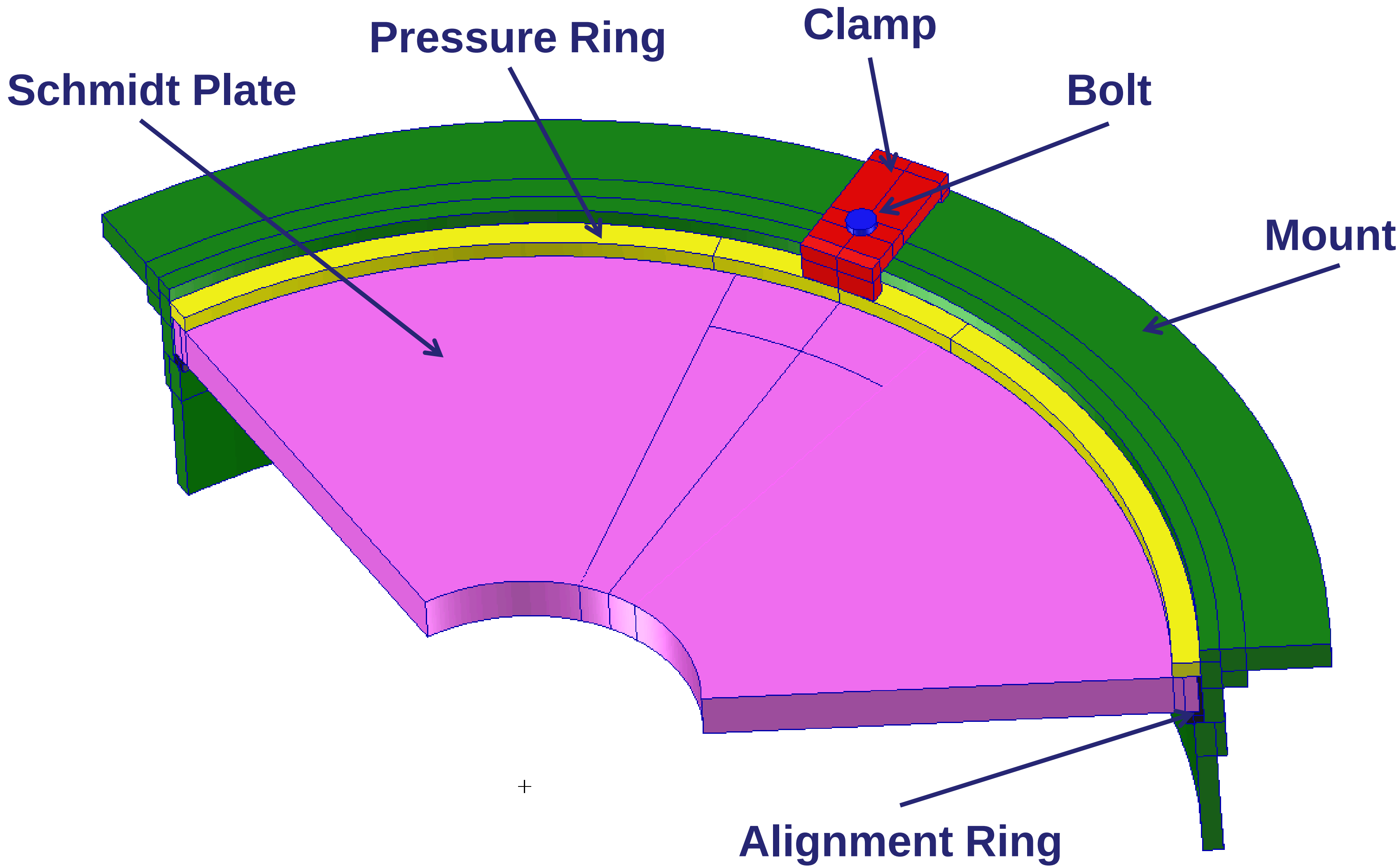

# The Thermostructural Concern

- **Primary:** Original SOFIA design included telescope cavity ground pre-cool, and for various reasons needed to consider flight testing without
  - Would door opening at altitude result in a thermal-shock strong enough to damage imager optics?
- **Secondary:** Some parties concerned that flight test with original design would still have unsafe thermostructural loading due to air temperature change along flight path (will not fly isothermal flight path)
- **Tertiary:** CTE mismatch, already mitigated by ground testing of imagers
- 4 different optical components identified
  - FFI (Fine Field Imager)
    - Schmidt Plate (higher concern)
    - Achromat
  - WFI (Wide Field Imager)
    - Achromat 1 (higher concern)
    - Achromat 2
- FFI Schmidt Plate analyzed, none others due to results of analyses and different fixture comparison (clamps vs. fixing rings)

# Telescope Assembly



# FFI Front Group



# Determination of Governing Parameters

- Determination of physics to be modeled
  - ★ Convection-induced thermal gradient (thermal stress)
  - ★ Bolt pre-load induced stress (and CTE mismatch +/-)
  - ★ Circumferential clamping (CTE mismatch)
  - 🚫 Vibratory stress
  - 🚫 Acoustic pressure
  - 🚫 Max flight load

- Determination of domain
  - Relatively thermally isolated front group containing Schmidt Plate was clear choice for geometry

*Already mitigated by ground test of imager

# Determination of Governing Parameters

- Determination of model key result(s) & acceptance criteria
  - Glass is much stronger in compression than tension
  - Tensile strength strongly dependent upon surface finish
  - Glass manufacturer (Schott) TIE-33 “Design strength of optical glass and ZERODUR”
    - Low stress level allowable for infinite part life (8 MPa and 10 MPa allowable for optical & ZERODUR, respectively)
    - When application requires higher stresses, statistical approach provided, characteristic strength values for zero failure probability all > 20 MPa even for the worst surface finishes – this part is optically finished
    - So $\sigma_{p1}$ < 8-10 MPa adopted as target value rather than requirement based upon strength data available, but 20 MPa would be seen as conservative benchmark value for margin determination
    - These are low values: model aggressively conservative and if no positive margin then refine conservativism
  - Due to clamping mechanism & ground test, in addition to determining stress level it was important to determine stress composition
  - Because of uncertainty in some inputs, a parameter sensitivity study would have to be performed to make this analysis complete

# Determination of Governing Parameters

- Determination of material properties
  - Materials known, no batch properties, combination of manufacturer supplied and database, if “pencil sharpening” required then examine more closely (along with other layers of conservativism)
- Determination of structural loading
  - Loading due to bolt pre-load in clamping mechanism
  - Agreed upon value of bolt pre-load range 2-3 kN (3 kN value seems strongly conservative)
- Determination of thermal loading
  - Instead of working up cooling rate range, assume limiting scenario of convective thermal shock
  - 3 Governing parameters for convective thermal shock: initial temperature ($T_i$), fluid temperature ($T_R$), convection coefficients (h)

# Determination of Governing Parameters

- Determination of thermal loading (cont'd)
  - Initial temperature: 20°C reasonable assumption given onboard aircraft systems
  - Fluid temperature:
    - Airflow ingested into telescope cavity, into FFI Baffle, impinging/over external surface of Schmidt Plate
    - Not freestream temperature, but recovery temperature of fluid
      - Determined using the isentropic, subsonic compressible flow equation, but modified to assume non-zero flow at Schmidt Plate surface

$$T_R = \left[1 + R\frac{\gamma - 1}{2}\left(M_\infty - M_{res}\right)^2\right]T_\infty$$

Where $T_R$ is the recovery temperature, R is a factor (0.9) to compensate for the process not being perfectly adiabatic, $M_\infty$ and $T_\infty$ are freestream values, and $M_{res}$ is the residual flow velocity (a max value for the whole cavity being ≈0.1)

    - This leads to a conservative value of $T_R$ = -40°C for max door-opening altitude
    - The resulting shock value ($T_i$ – $T_R$) = 60°C
    - This is conservatively the worst possible scenario, there can only be less severe than this (finite air temperature cooling rate, smaller $\Delta$T, etc.)

# Determination of Governing Parameters

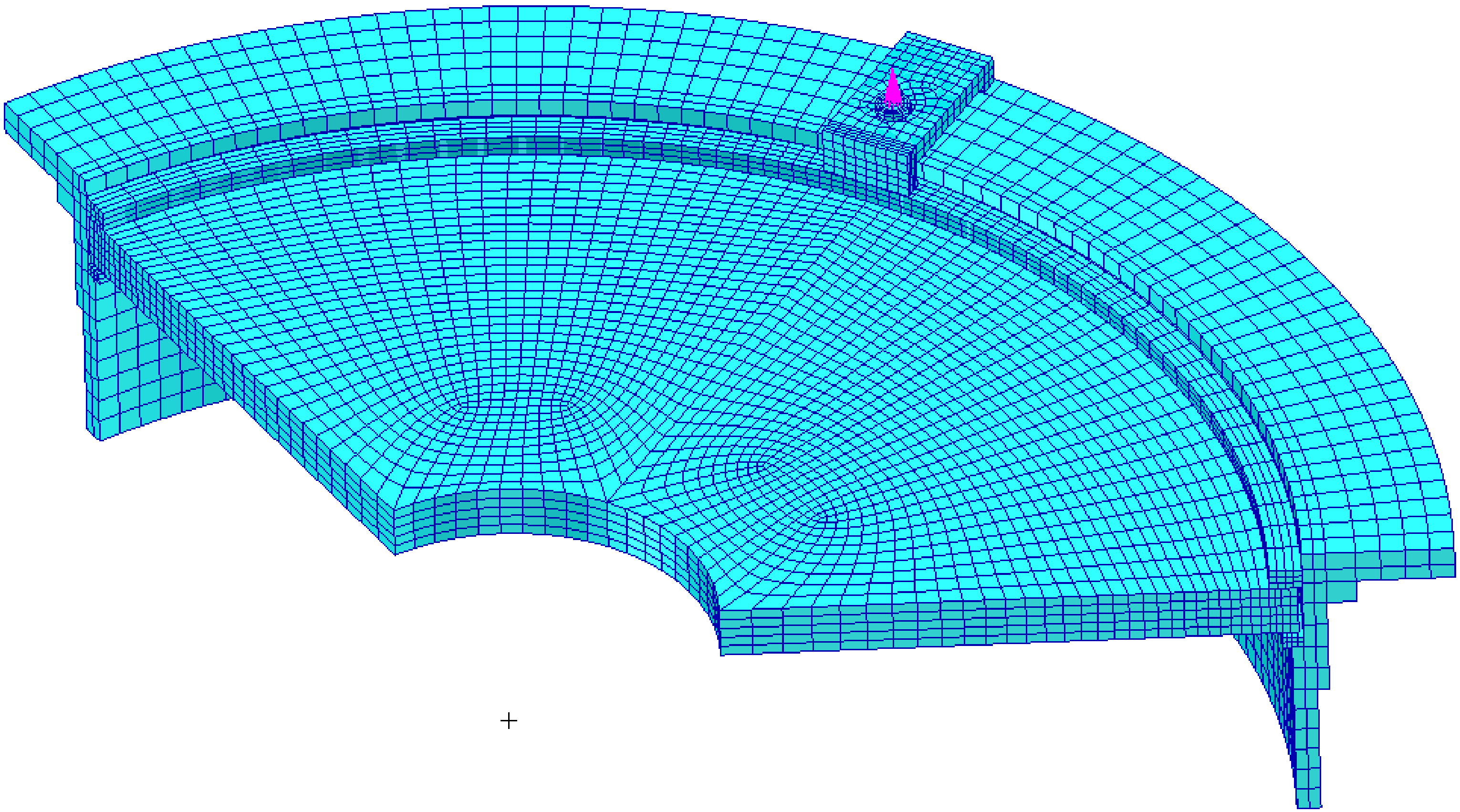
- Determination of thermal loading (cont'd)
  - Convection coefficient
    - Dependent upon geometry and flowfield
      - Used CFD results for velocity range
      - Calculated several correlations, subsonic stagnation point @ 15 kft (lowest door-opening altitude) was the highest, used conservative velocity, h = 60 $W/m^2K$
      - Flow around the body behind the headring (low speed/free, h = 5 $W/m^2K$)
  - It should be noted that a physically impossible $\Delta T$ & h combination (from different altitudes) leads to a very conservative analysis

# FEM Model Development

- Began with hand calc $\sigma = E\,\alpha\,\Delta T$ (35 MPa) for bounding value for model results
- 2D structural model to look at mesh density for solution convergence to this idealization
- 2D & 3D transient thermal models to investigate thermal response between components & $t_{max\ grad}$
- 3D coupled thermal-structural transient FEM with structural and thermal contact (to allow DOFs between plate and fixture)
  - Mesh refinement to allow contact calculations to run without physically impossible load concentrations
- Working model ~16,000 hex elements using 21,800 nodes, ~1 day runtime
- Model used to iterate on 4 key input parameters to investigate sensitivity to uncertainty
  - Clamp pre-load
  - Friction coefficients
  - Convection coefficients
  - Shock strength
- Epiphany: another mesh refinement (in contact region) to determine convergence

# FEM Model Development

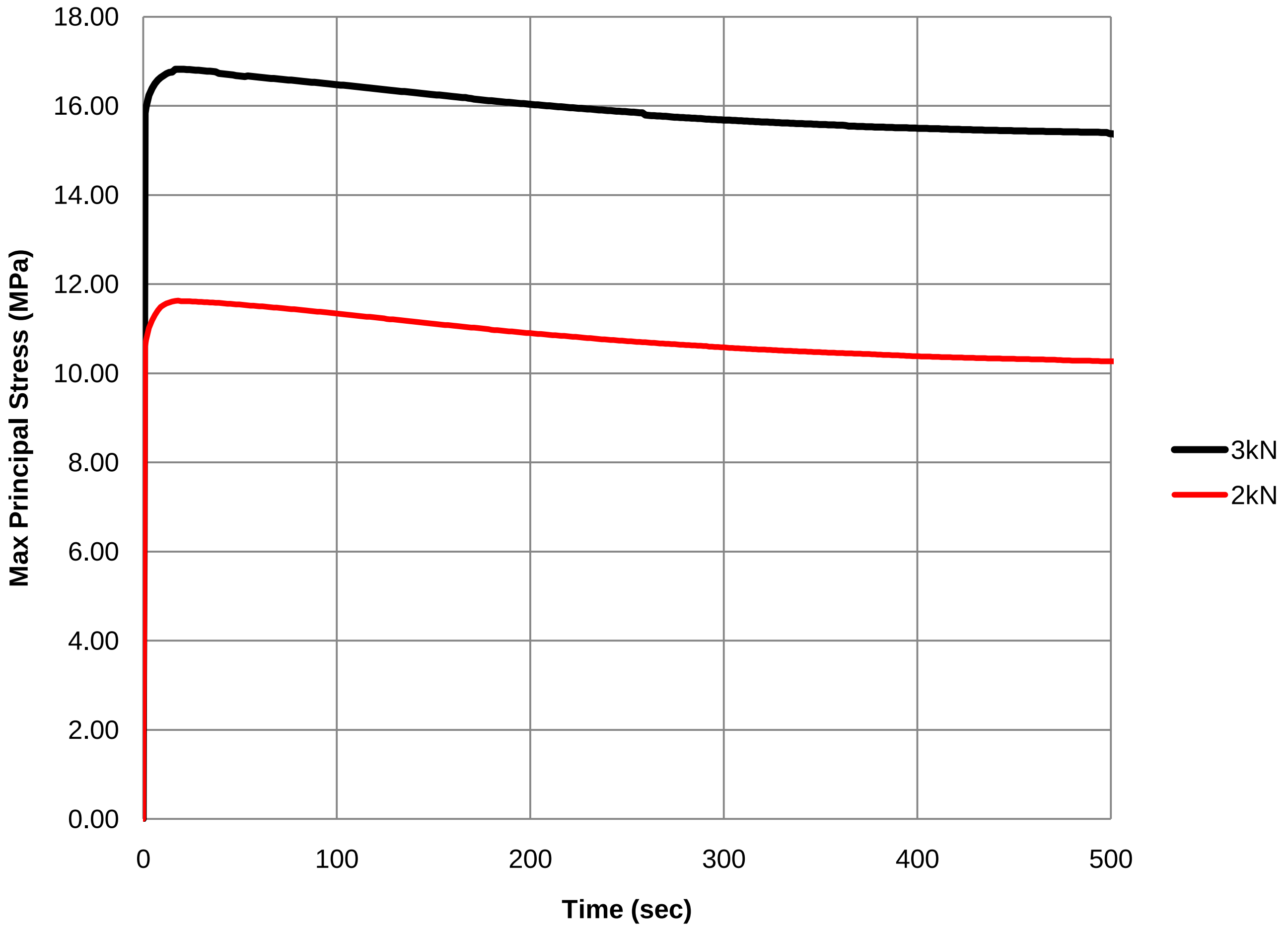
## Coarse Working Mesh



# FEM Model Development

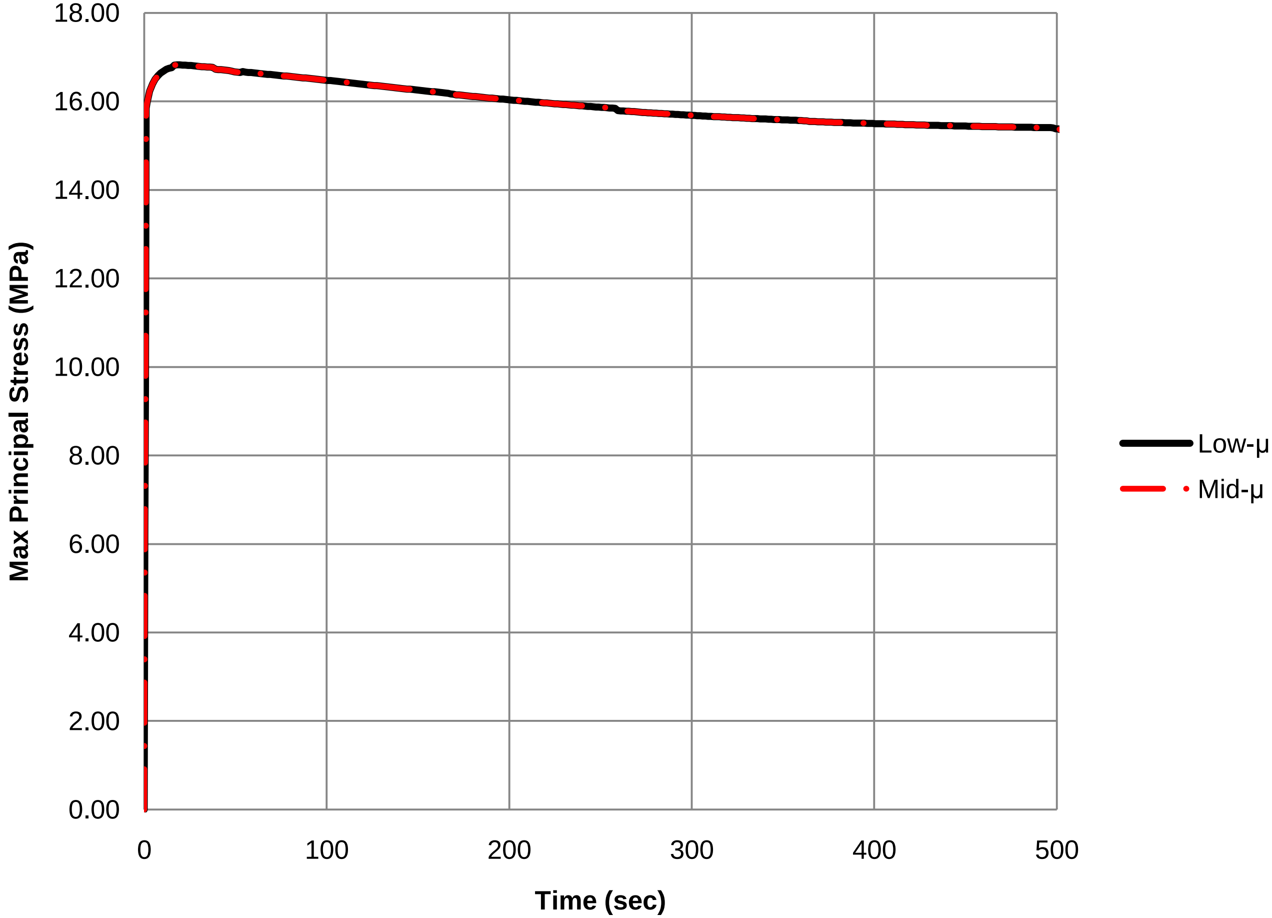
- MSC.Patran pre/post processor, MSC.Marc solver
- Loading separated for stress composition determination

# Results: Max Principal Variation with Pre-Load



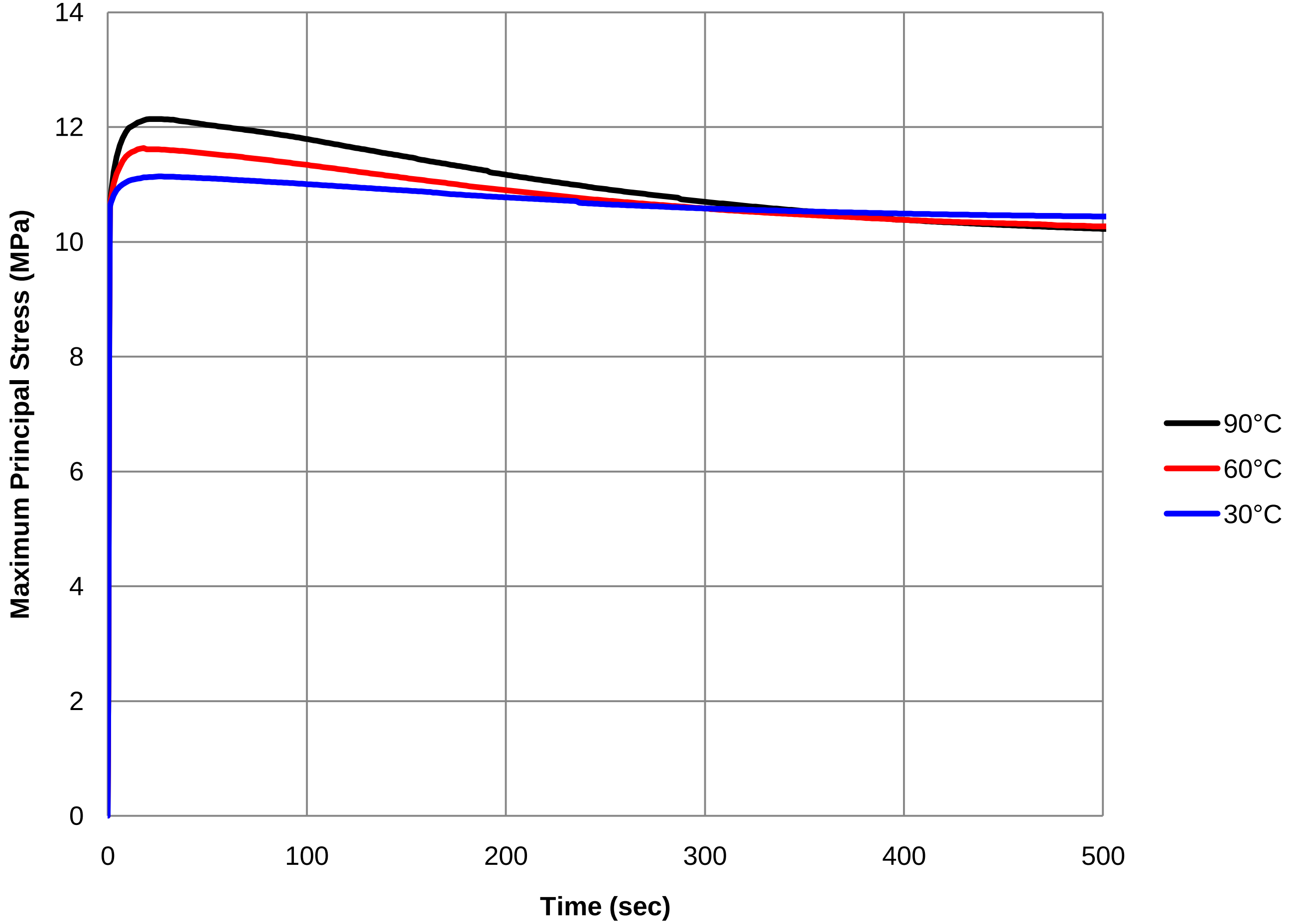

- Very conservative (physically impossible) combination of $\Delta T = 60°C$, and $h = 60\ W/m^2K$ produced only small increase in maximum occurring $\sigma_{p1}$ over clamp pre-load induced level (pre-load > 90% of max occurring)

# Results: Max Principal Variation with Friction



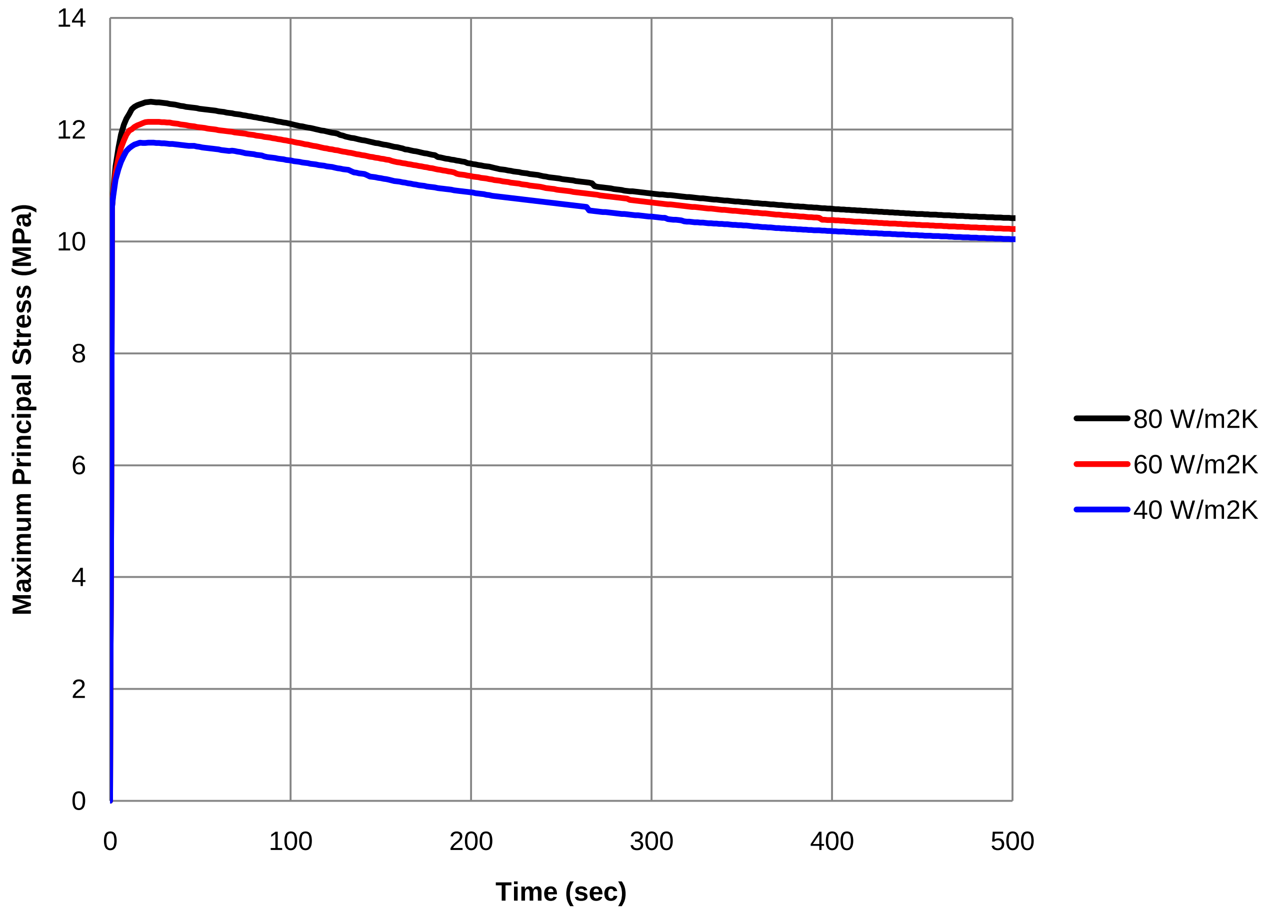

- 3 kN pre-load, h = 60 W/m$^2$K, $\Delta$T = 60 °C
- Friction coefficients variation did not effect Schmidt Plate stress state
- High-μ case also run (not plotted) and produced overlapping results

# Results: Max Principal Variation with Shock Strength




- 2 kN pre-load, h = 60 W/m$^2$K, $\Delta T$ = 30/60/90 °C
- For $\Delta T$ = 0-90 °C $\sigma_{p1}$ only 1.5 MPa higher
- This would be less given a more realistic convection coefficient

# Results: Max Principal Variation with Convection Coefficient




- 2 kN pre-load, $\Delta T$ = 90 °C shock, h = 40/60/80 W/m$^2$K
- Higher shock value used to magnify the insensitivity
- For h = 0-80 W/m$^2$K $\sigma_{p1}$ only 1.5 MPa higher with overly conservative 90 °C shock

# Results: Additional Refinement

- Until this point several mesh refinements had been performed (2D thermal, 2D thermostructural, 3D thermal)
- Additionally, there was a mesh densification required in contact regions to protect against false stress concentrations
- The preceding two steps engendered a sense of sufficiency in model development, convergence
- Upon realization that solution convergence needed to be demonstrated with “working” mesh another mesh refinement was done
- Edge length reduction of 40% lead to max $\sigma_{p1}$ dropping from 10.6 MPa to 0.7 MPa, with further edge length reduction providing negligible reduction, proportional reduction in variation due to thermal effects

# Conclusions

- Determined clamp bolt pre-load contributed >90% of max principal stress
- Demonstrated thermally-induced stress variation as insensitive to uncertainty
- Found positive margin for extreme scenarios, no fatigue concerns
- Cleared, by comparison, other components
- Learned valuable lesson – keep careful track of steps taken (and any remaining) to demonstrate solution convergence when performing multi-disciplinary analyses, regardless of whether using home-grown or commercial code
  - Sense of conventional mesh sufficiency may no longer apply

# Questions?