Concurrent Engineering Works: Thermal Results from an Integrated Structural Thermal Optical (STOP) Analysis Study

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March 11, 2009

Outline

- Introduction
- STOP Analysis Process Overview
- S1 Channel Overview
- Lens 13-16 Thermal Control
- Thermal Analysis Approach
- Thermal Model Inputs
- Thermal Results
- Conclusions

The Aerospace Corporation's STOP Analysis Team

- David Thomas – Team Lead
- Jason Geis - Optics
- Jeff Lang - CAD
- Leslie Peterson - Thermal
- Francisco Roybal - Structures

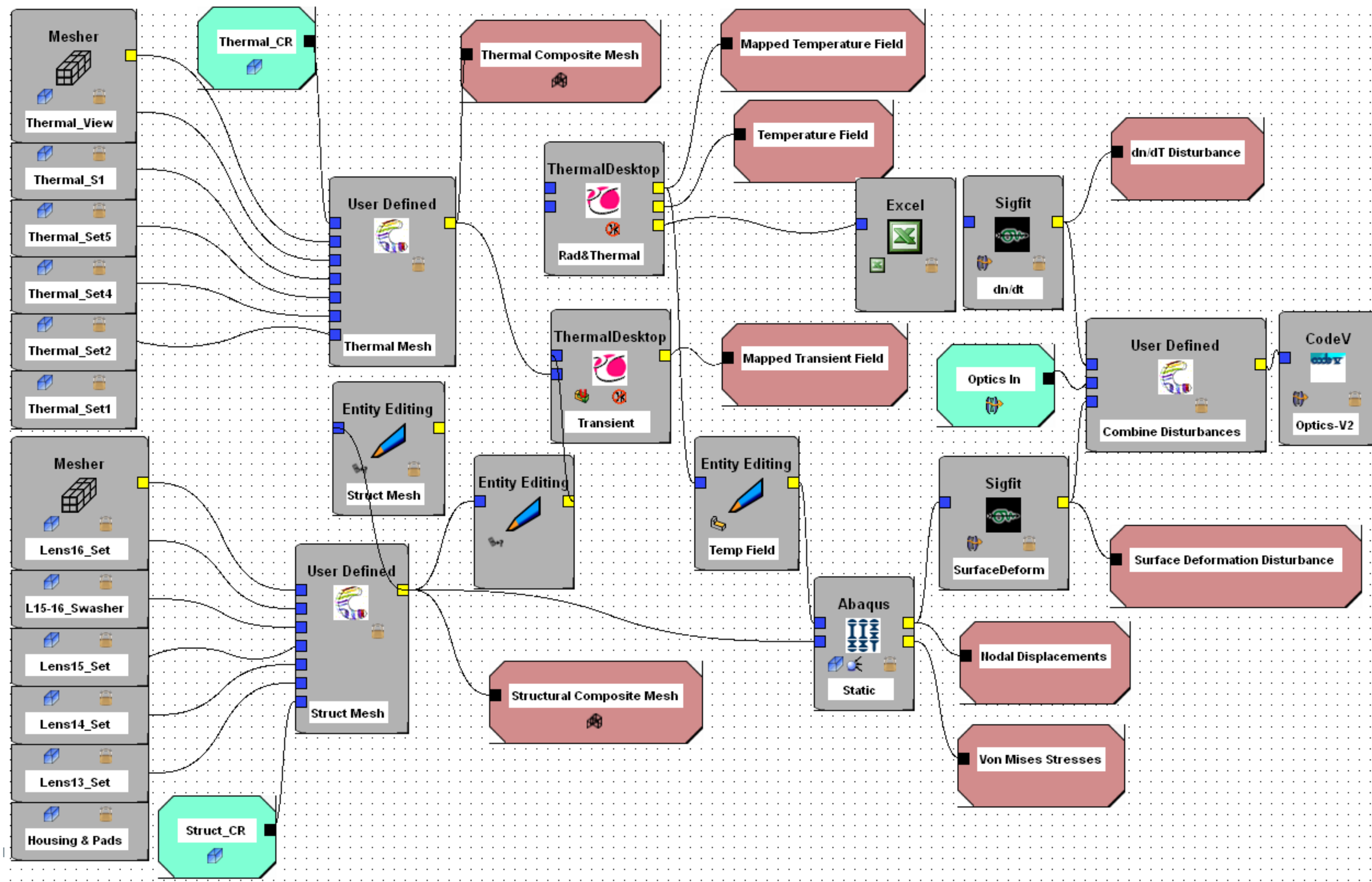
Introduction

- A Structural Thermal Optical (STOP) Analysis model of an optical system was constructed and utilized to simulate the thermal and optical testing of a payload
- The optical bench consists of eighteen lenses; however this study was focused on the S1 channel and in particular the Lens 13-16 assembly
- Analyses were performed using the Comet Solutions Performance Engineering Workspace which ties together various commercial applications including Thermal Desktop

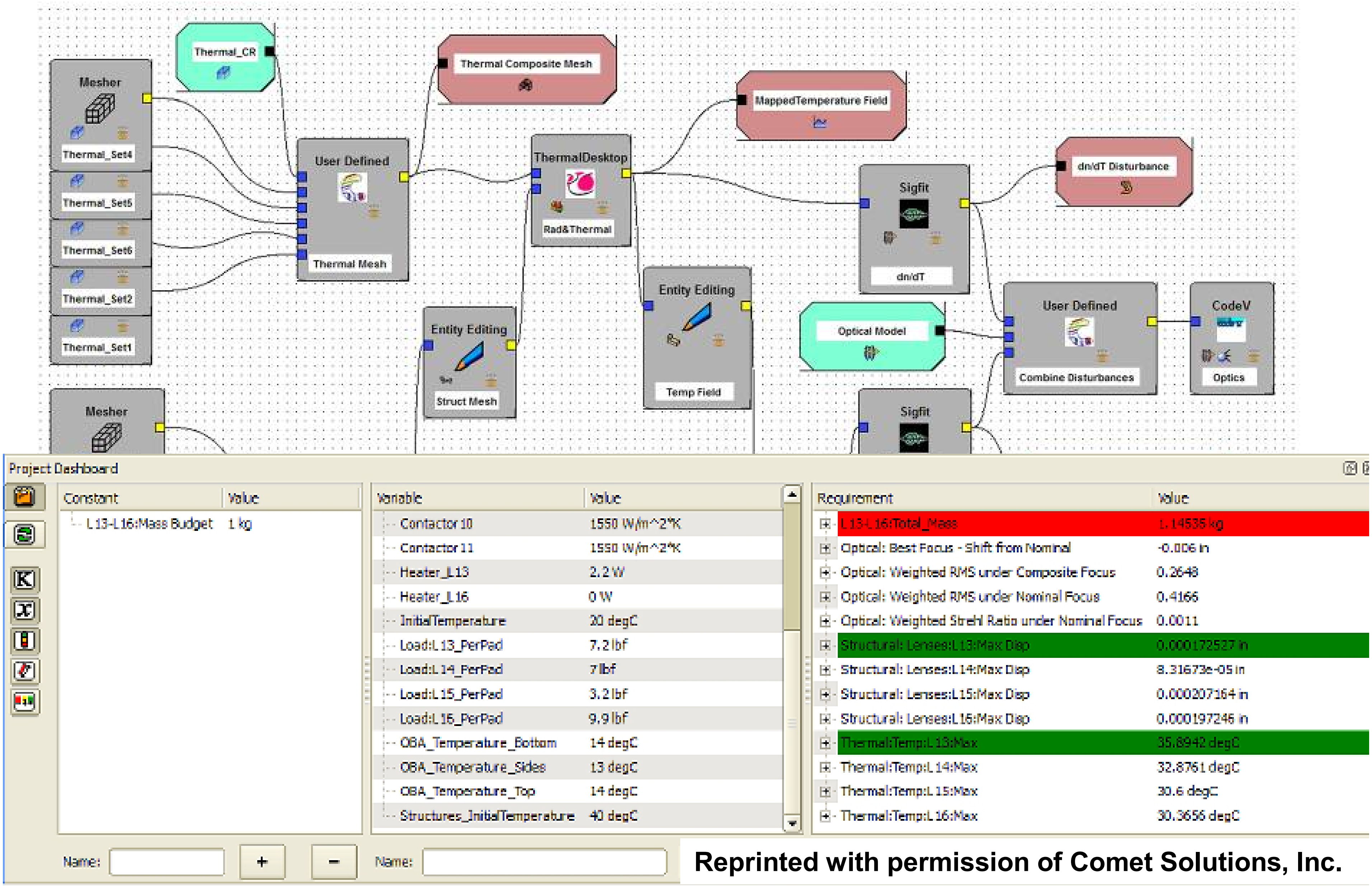
STOP Analysis Process

- The STOP process begins with importing a tagged CAD model of the instrument geometry into the Comet software environment
- Independent thermal and structural meshes are generated
- The thermal mesh is imported into Thermal Desktop for thermal analysis and mapping of temperatures onto the structures mesh
- Thermally induced structural deformations are evaluated in Abaqus
- Thermal and structural results are imported into Sigfit for computation of wavefront errors due to refractive index changes (dn/dt) in the lens components and deformations of the lens surface figures
- Sigfit creates a modified L13-16 optical prescription that is imported into Code V for evaluation of optical performance impacts

STOP Analysis Process



Structural/Thermal/Optical Performance (STOP) Process Enhanced by Abstract Modeling



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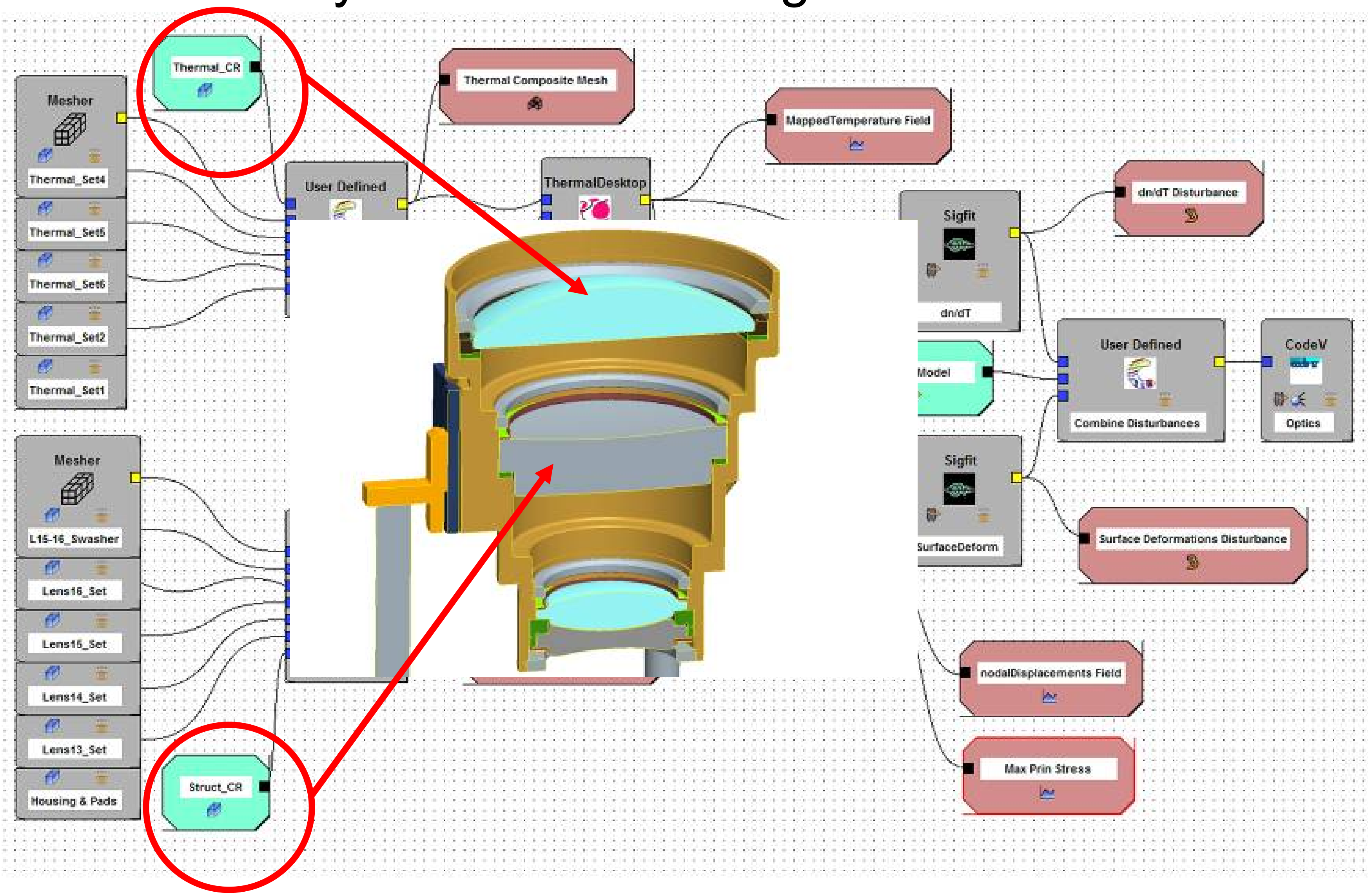

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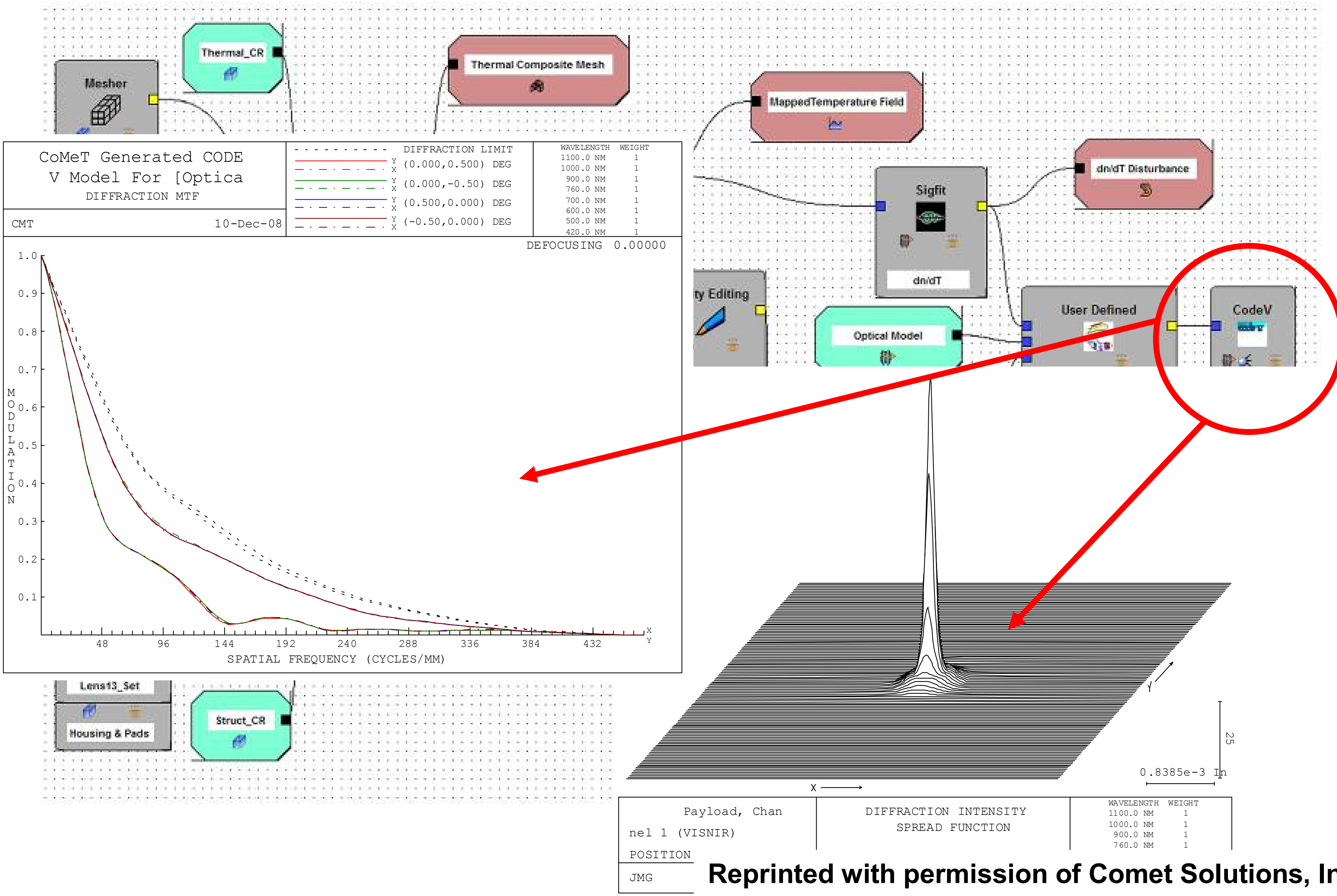

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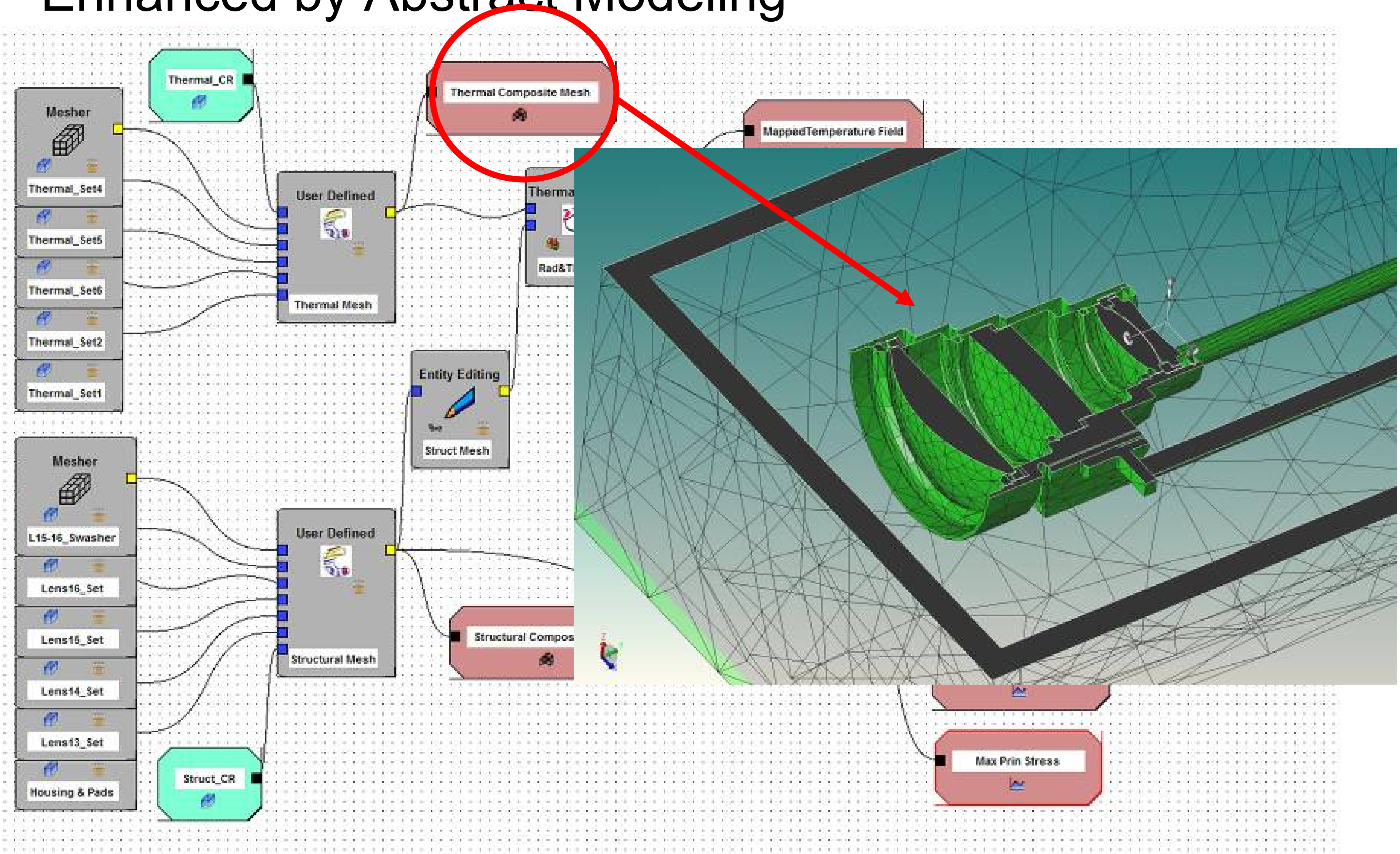

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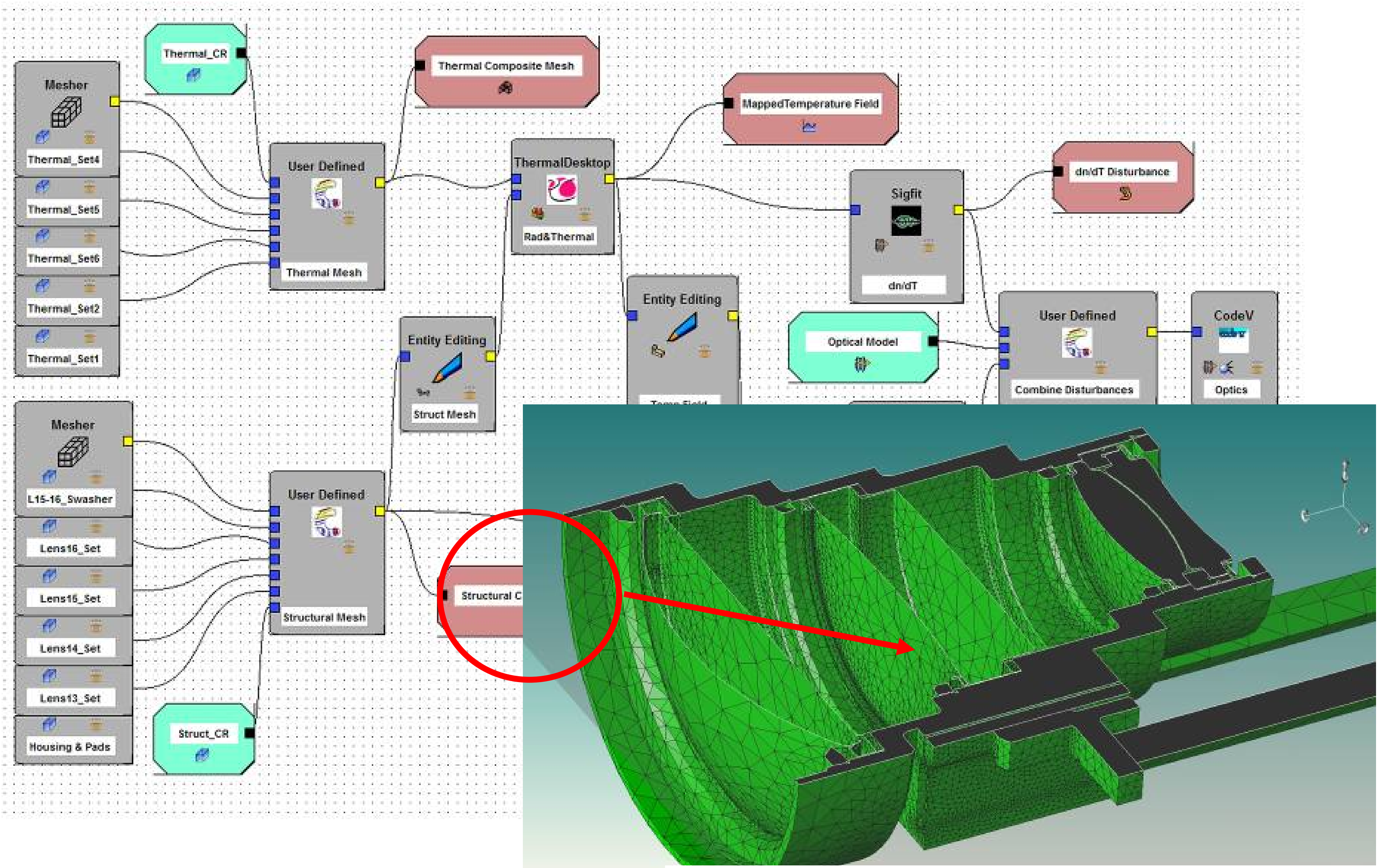

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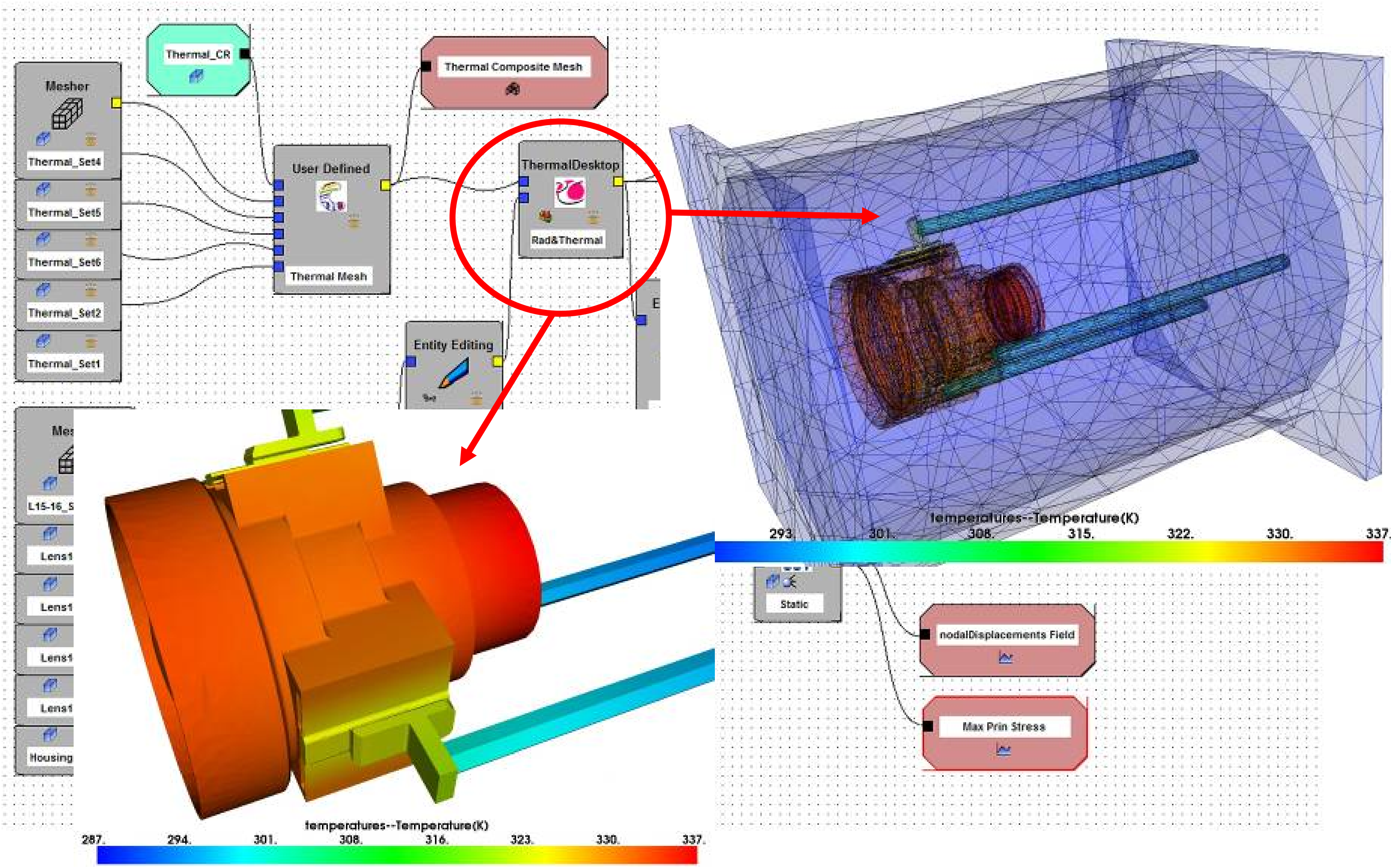

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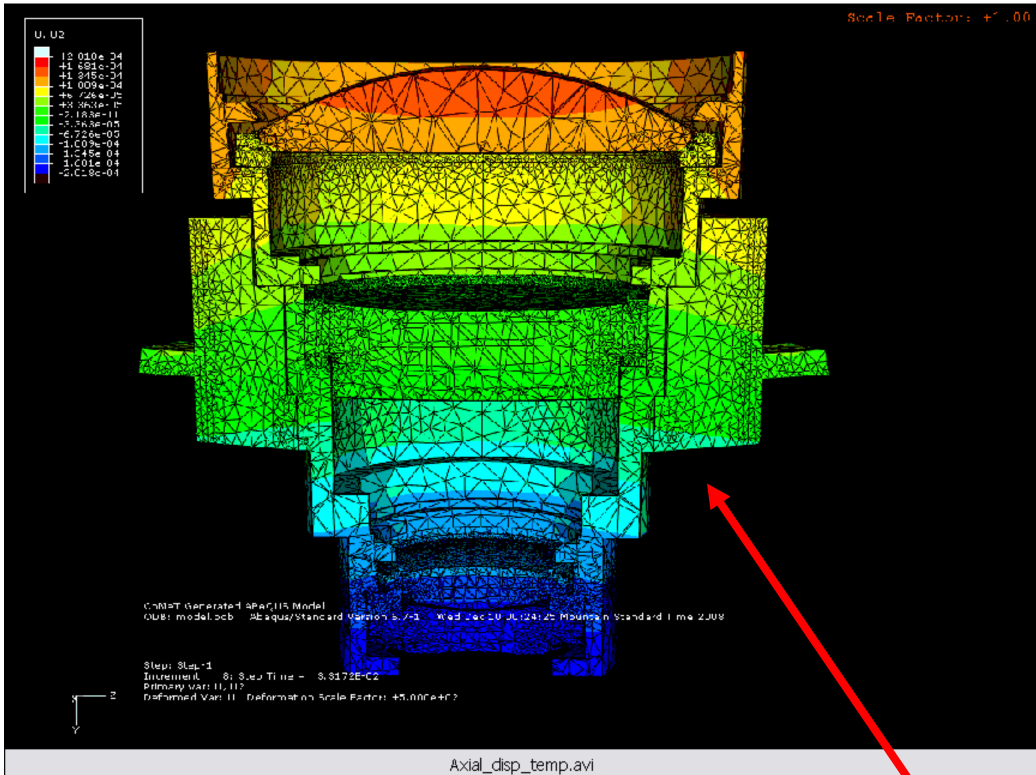

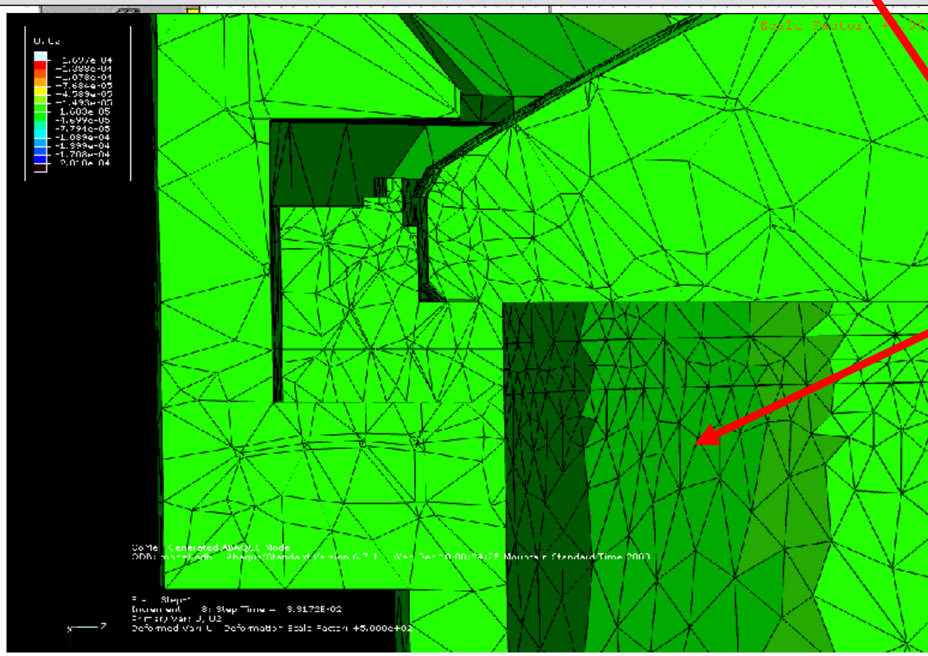

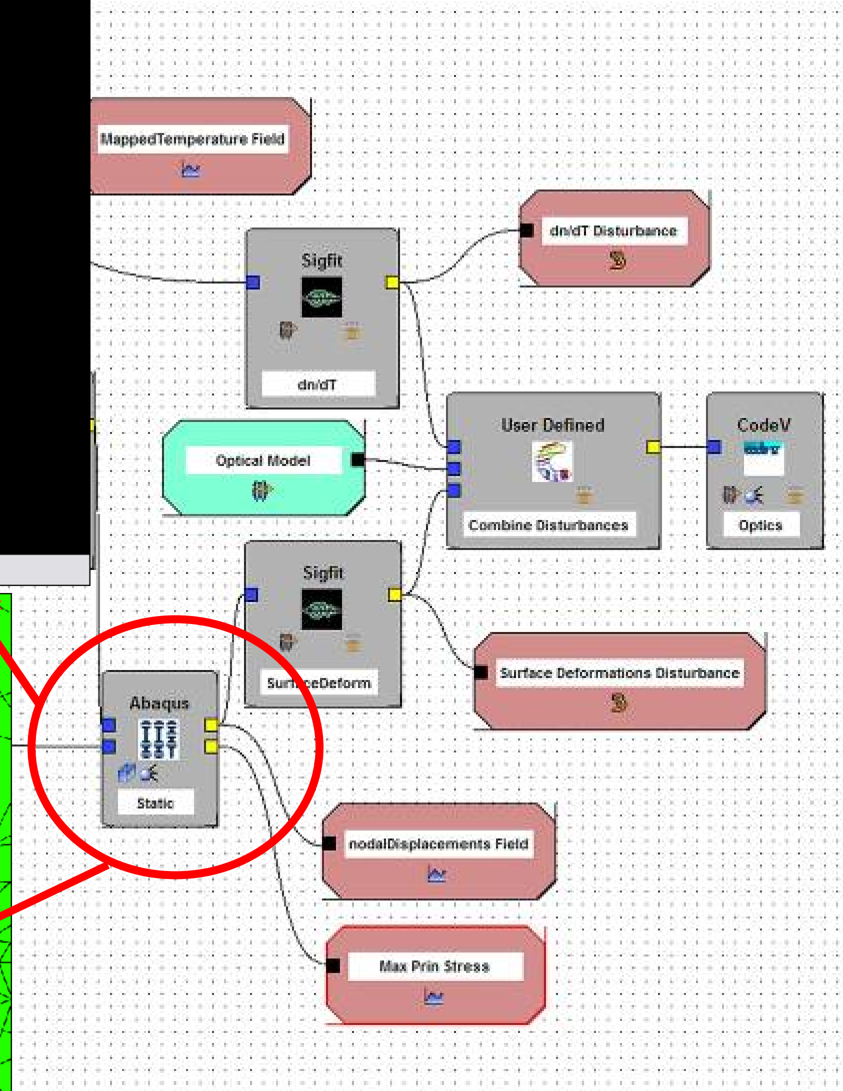

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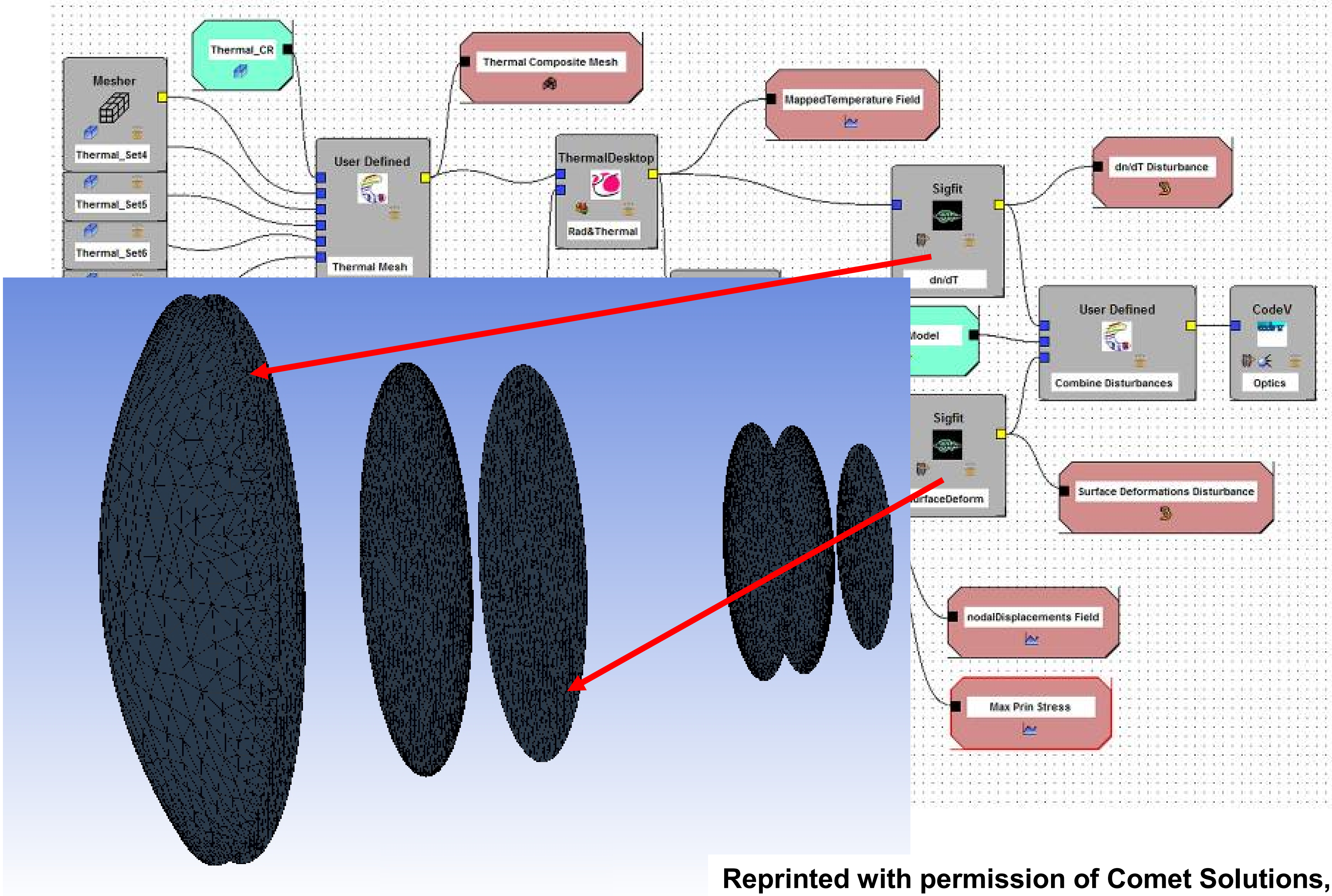

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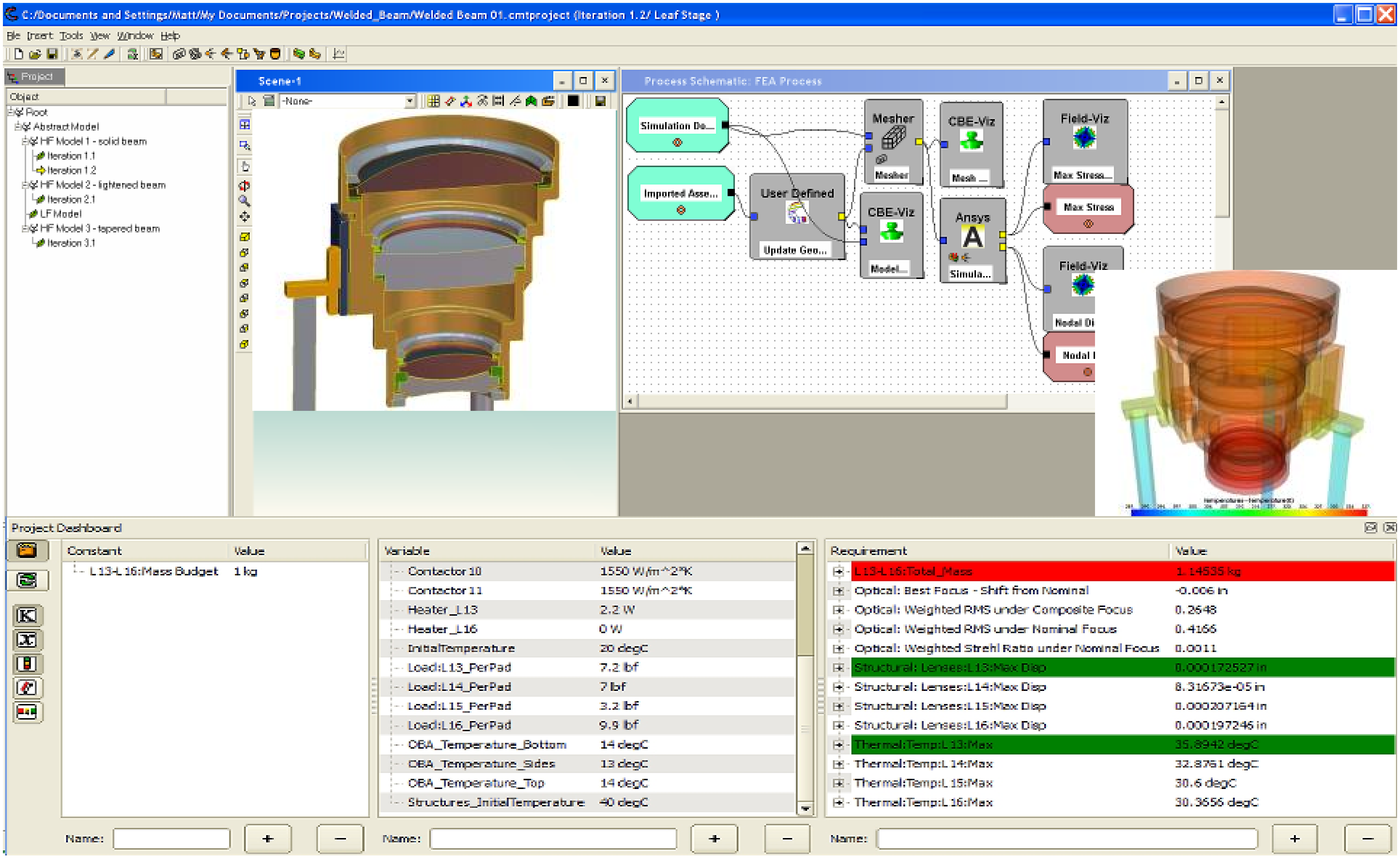
The Performance Engineering Workspace



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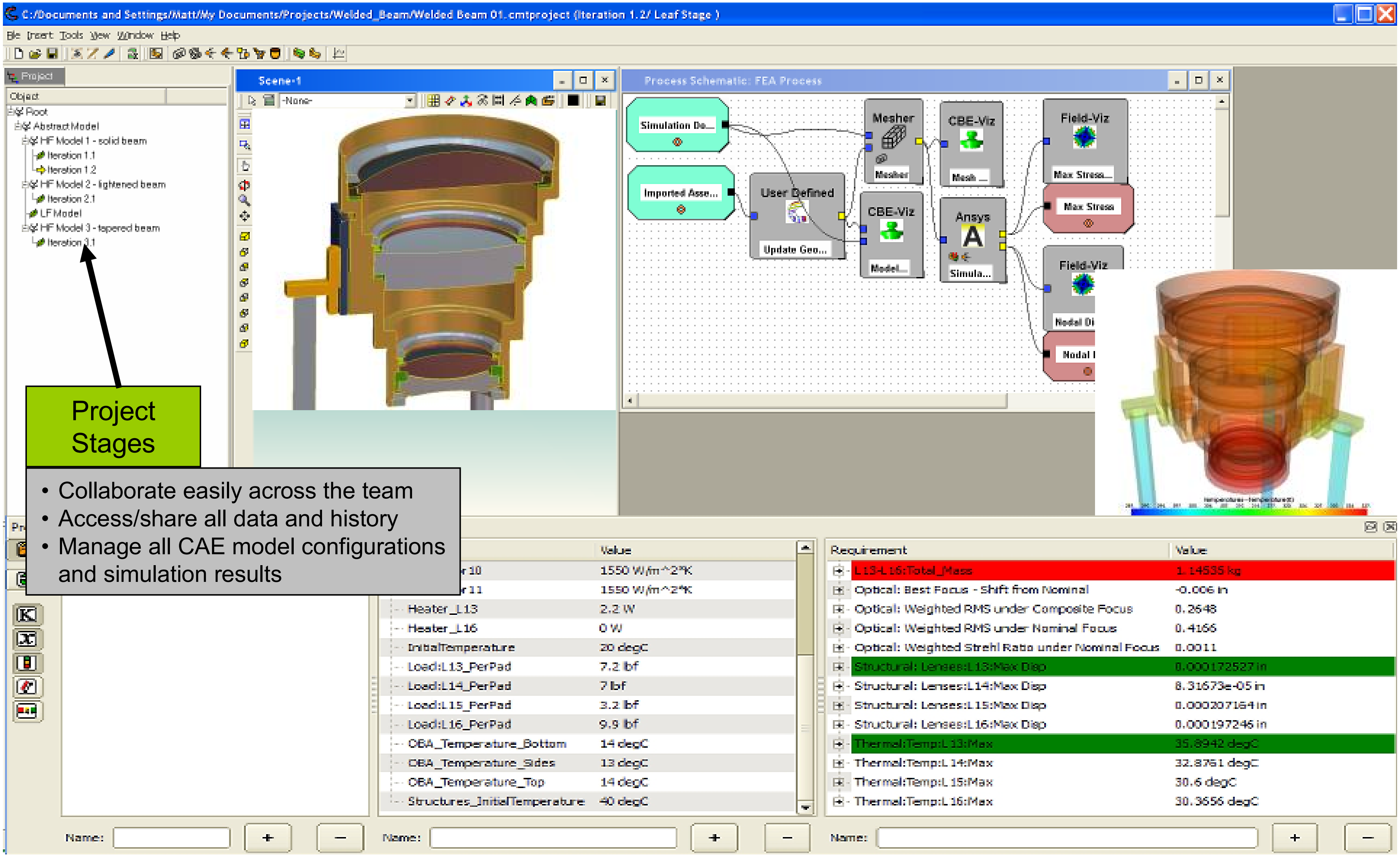

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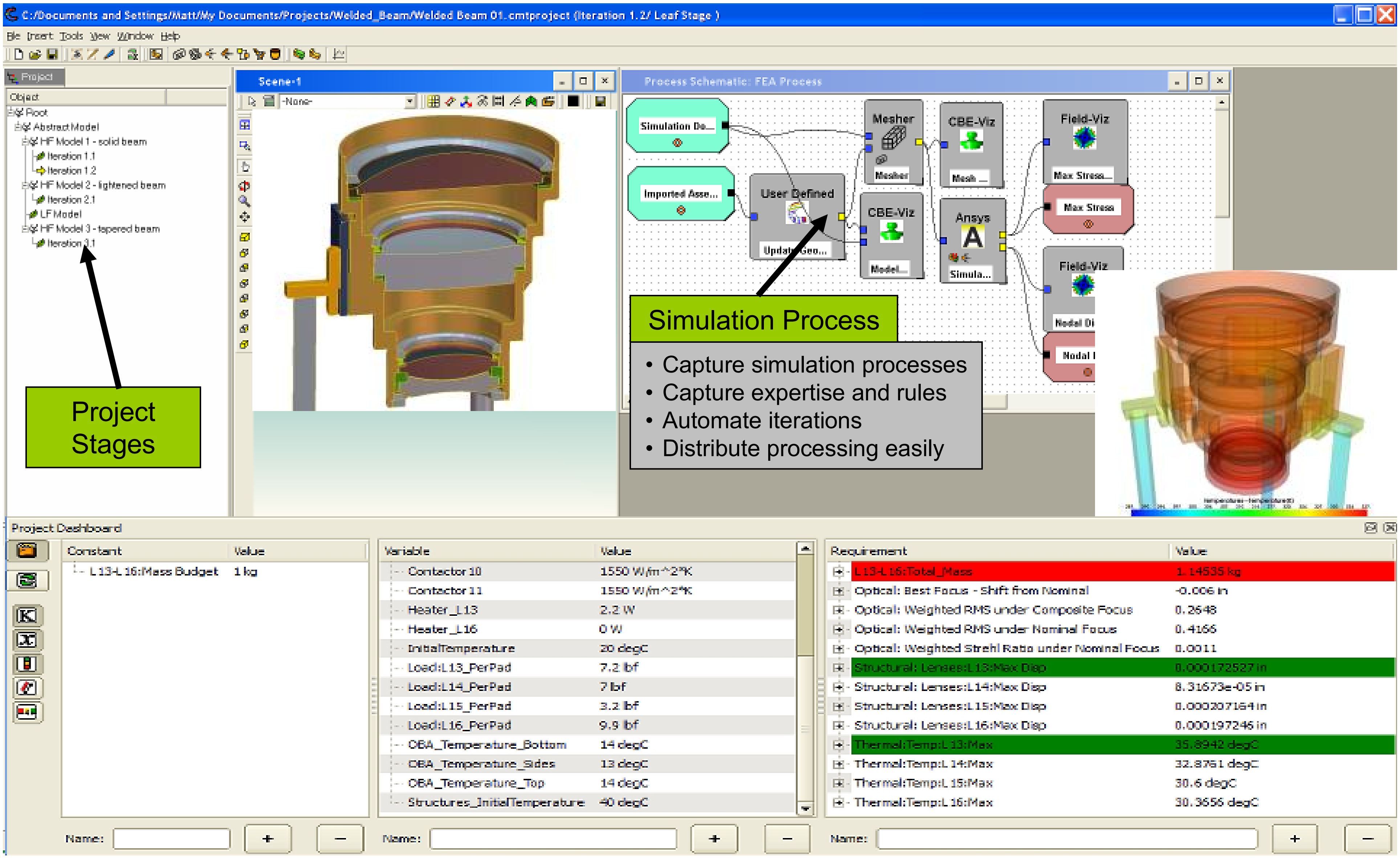
The Performance Engineering Workspace



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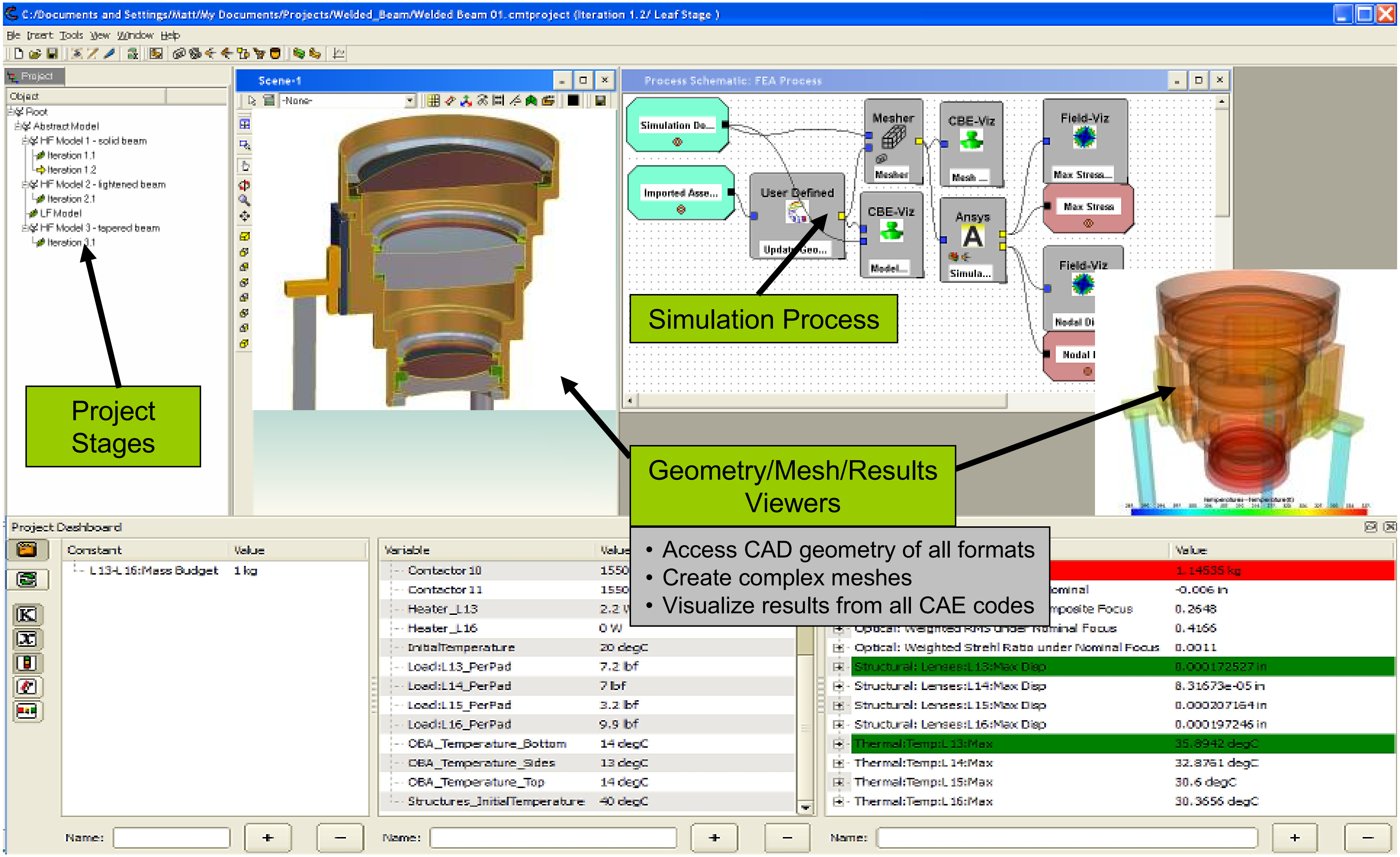

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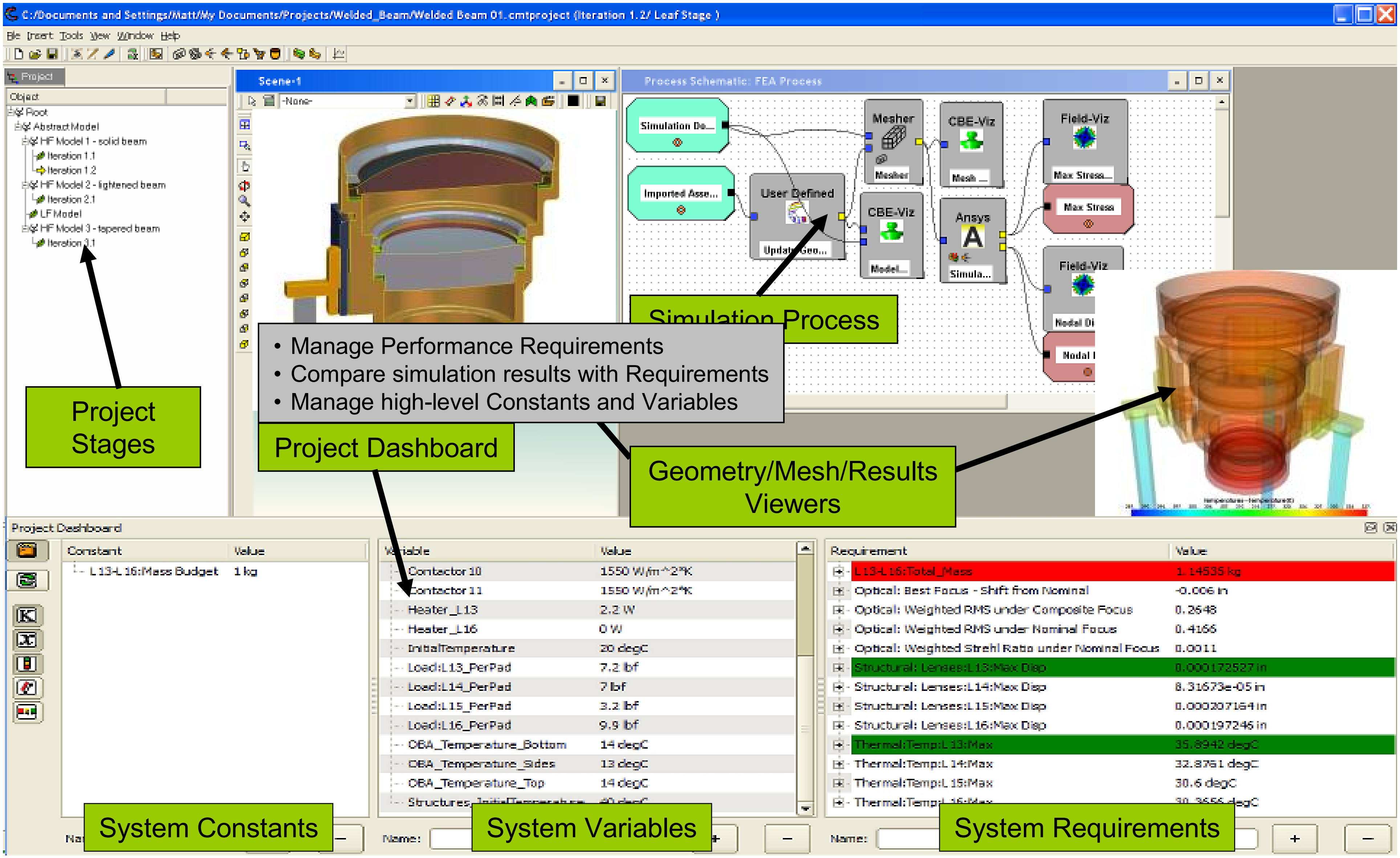

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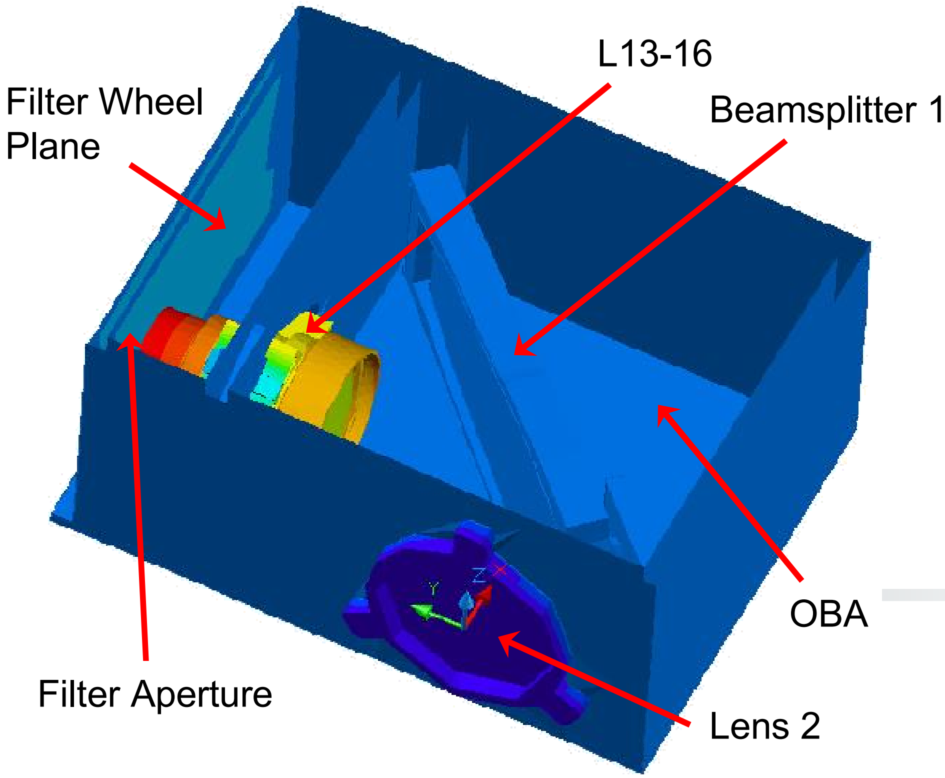
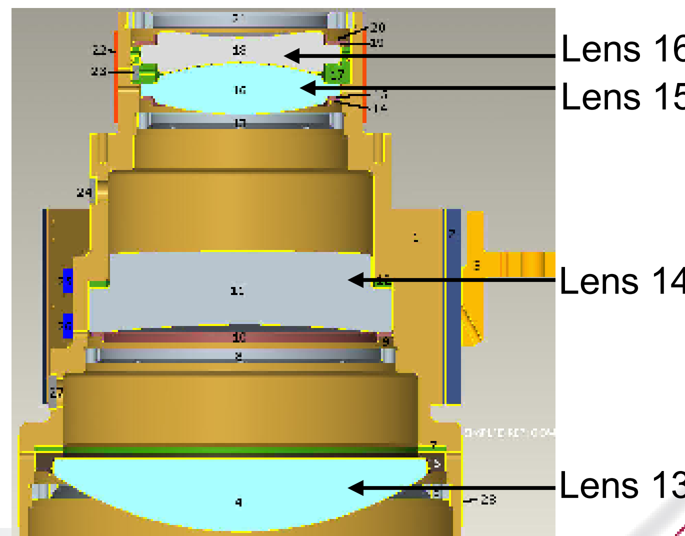
S1 Channel Overview

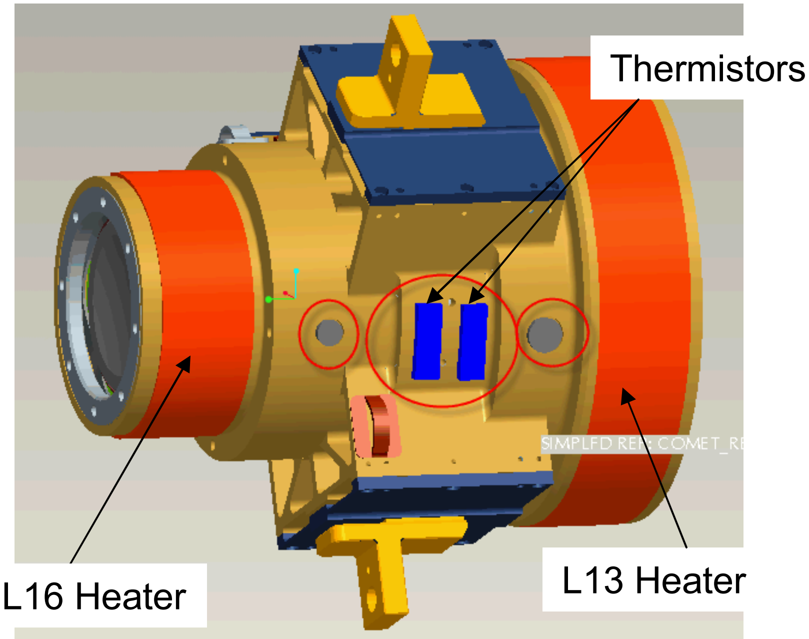
- A highly simplified representation of the Optical Bench Assembly (OBA) was constructed to represent the S1 channel, the detail of the L13-16 assembly remained intact
  - *The OBA is covered with a top that is not shown in this figure*
  - *Optical filters behind L13-16 are represented as a disk that has a different emissivity than the Filter Wheel plane*





Lens 13-16 Thermal Control

- The temperature of L13-16 is controlled by two heaters, one on the L13 side of the housing and one on the L16 side of the housing
- Although the surface area of the L13 heater is larger than the L16 heater, equal amounts of power must be supplied to each heater resulting in a much higher power density near L16
- The lens assembly heater setpoint temperature was controlled to three different values during the test to characterize the on-orbit focus control algorithm



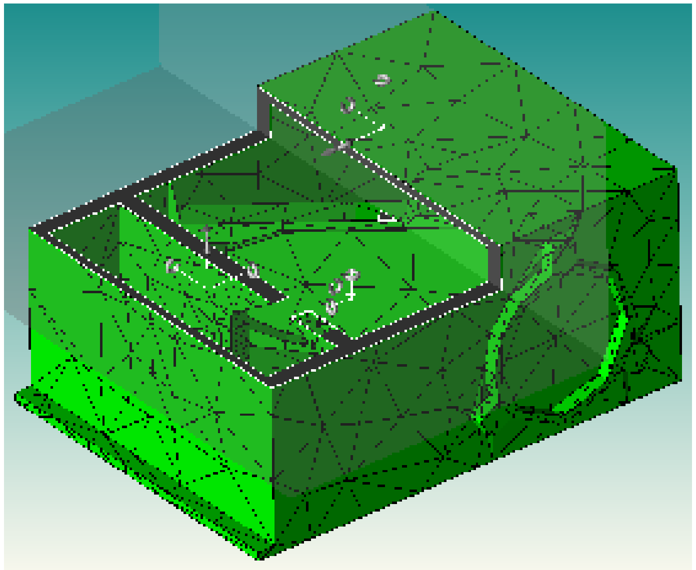
Thermal Analysis Approach

- A finite element thermal model was built in Thermal Desktop through the Comet interface
- The thermal model simulates the conditions experienced during TVAC testing and includes the following details:
  - *Thermal and optical properties of all materials*
  - *Heater Power*
  - *Boundary Temperatures*
  - *Conductances between various components that make up the thermal model*
- The thermal model was built in the Comet workspace by tagging the appropriate parts in the CAD model and setting up abstract domains within Comet
  - *Abstract domains require significant initial setup time, however each time the CAD geometry is updated, the thermal model can be automatically re-created with the use of abstract domains*
  - *Abstract domains allow for easy parametric studies while keeping consistent structural, thermal and optical models at each design stage*

Thermal Finite Element Mesh

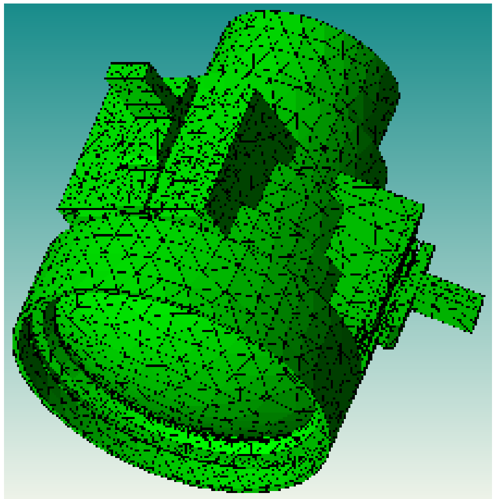
- A finite element mesh comprised of tet-4 solid elements was developed for the thermal analysis via an iterative design process
- Meshing parameters were refined to minimize mesh element aspect ratios (maximize computation accuracy) while also minimizing overall mesh size to hold run time for the radiation calculations within reason for our PC-based computing platform
- The various components of the model were meshed in separate meshing tasks and were conductively coupled in the thermal model by the use of Thermal Desktop contactors
  - *Lens and housing components were the most critical and were refined to a resolution appropriate for thermal analyses*
  - *The S1 enclosure contains only boundary surfaces and was therefore composed of a much coarser mesh*
- Total number of nodes = 7,024

Thermal Finite Element Mesh

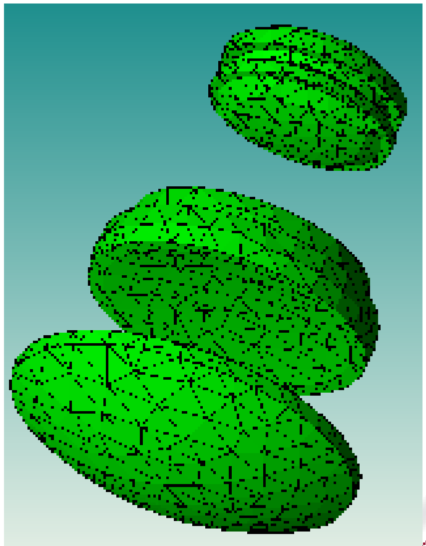


S1 channel enclosure mesh

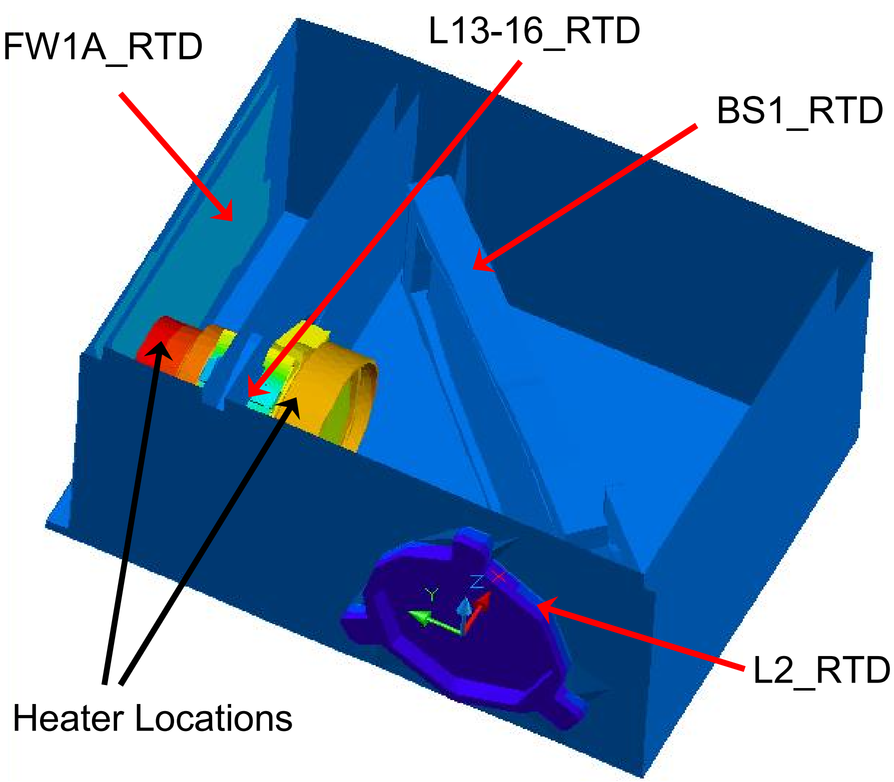
L13-16 Subassembly mesh



Lens 13-16 mesh



TVAC Monitoring Points



- TVAC test data from four temperature monitoring points (RTDs) were used to establish thermal boundary conditions
  - *L2_RTD was used for Lens 2 temperature*
  - *FW1A_RTD was used for filter wheel plane and filter aperture temperature.*
  - *BS1_RTD was used for Beamsplitter 1 and overall OBA temperature.*
  - *The top OBA surface (not shown) was set to a temperature 1 °C warmer than the overall OBA temperature.*
- Heater power levels reported for the strip heaters applied to the lens housing around Lens 13 and Lens 16 were also input as boundary conditions

Thermal Model Inputs

- Boundary temperatures and steady state heater powers for the three thermal soak conditions are summarized on the next slide
- During the test, heater power was adjusted to hold the L13-16 thermistor at a desired setpoint temperature
- For the thermal analysis, the amount of heater power applied during the test was added to the steady state thermal model
  - *The temperature at the location of the L13-16 thermistor was computed and its difference from the actual setpoint temperature was reported*

Thermal Model Inputs

	Applied Heater Power (W)		
Heater Location	**Hot Case**	**Nominal Case**	**Cold Case**
Housing Near Lens 13	0.24	0.74	1.46
Housing Near Lens 16	0.24	0.74	1.46

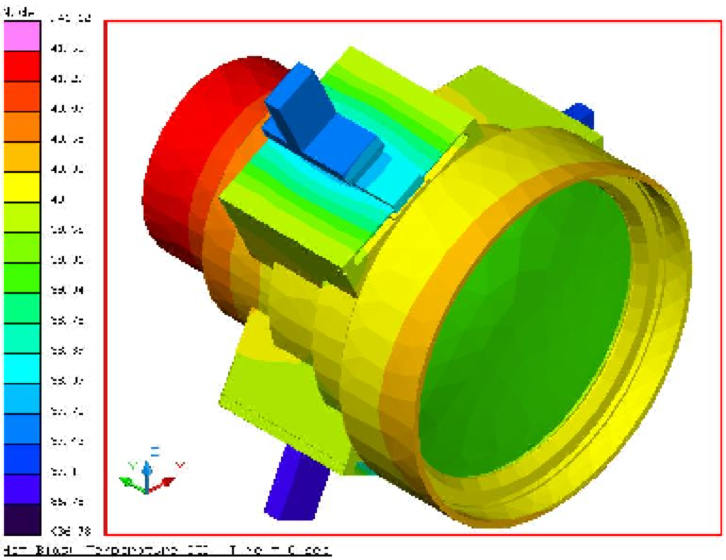
	Boundary Temperatures (°C)		
Boundary Surface	**Hot Case**	**Nominal Case**	**Cold Case**
Beam Splitter 1	36.7	29.6	17.5
OBA	36.7	29.6	17.5
OBA Top	37.7	30.6	18.5
Lens 2	36.9	26.7	13.5
Filter Wheel	39.1	32.2	20.9
Filter Wheel View	39.1	32.2	20.9

Temperature Results

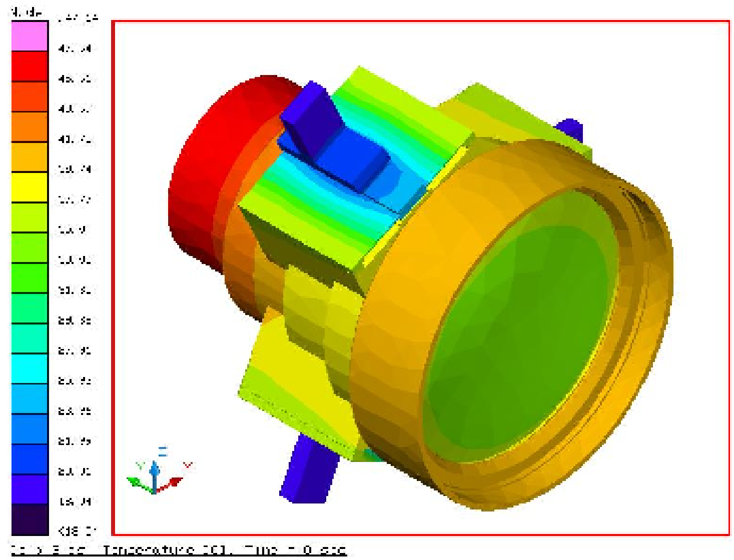
- All data except for first row are computed by STOP analysis
- The difference between computed and measured L13-16 set point temperatures is within 2°C for all cases
- Differences between computed and measured setpoint temperature increase with heater power levels and the degree of departure from the nominal 41°C bias temperature design point for L13-16
- Discrepancies may be due to the fidelity of the CAD geometry surrounding L13-16, limited knowledge of boundary condition temperatures and the accuracy of material thermal properties

Component	Hot Case	Nominal Case	Cold Case
Actual Lens 13-16 Setpoint	39.3	38.3	36.6
Lens 13-16 Setpoint from Model	40.1	40.04	38.98
Difference in Setpoint	0.8	1.74	2.38
Lens 13 Max	39.27	38.28	36.06
Lens 13 Min	39.16	38.03	35.62
Lens 13 Avg	39.21	38.14	35.81
Lens 13 DeltaT	0.11	0.25	0.44
Lens 14 Max	40.06	39.99	38.94
Lens 14 Min	39.95	39.71	38.39
Lens 14 Avg	40	39.83	38.61
Lens 14 DeltaT	0.11	0.28	0.55
Lens 15 Max	41.22	43.31	45.35
Lens 15 Min	41.21	43.29	45.3
Lens 15 Avg	41.22	43.3	45.33
Lens 15 DeltaT	0.01	0.02	0.05
Lens 16 Max	41.3	43.47	45.63
Lens 16 Min	41.24	43.18	45.04
Lens 16 Avg	41.28	43.36	45.41
Lens 16 DeltaT	0.06	0.29	0.59

L13-16 Housing Temperatures



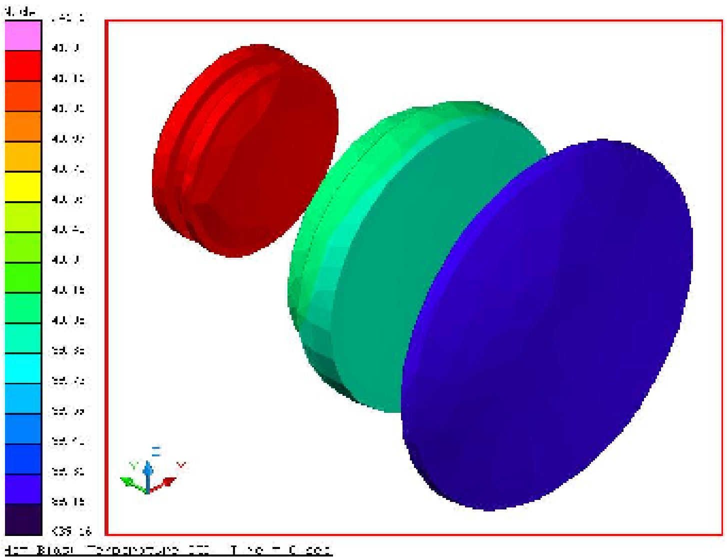
Hot
Max. 41.6°C
Min. 36.8°C

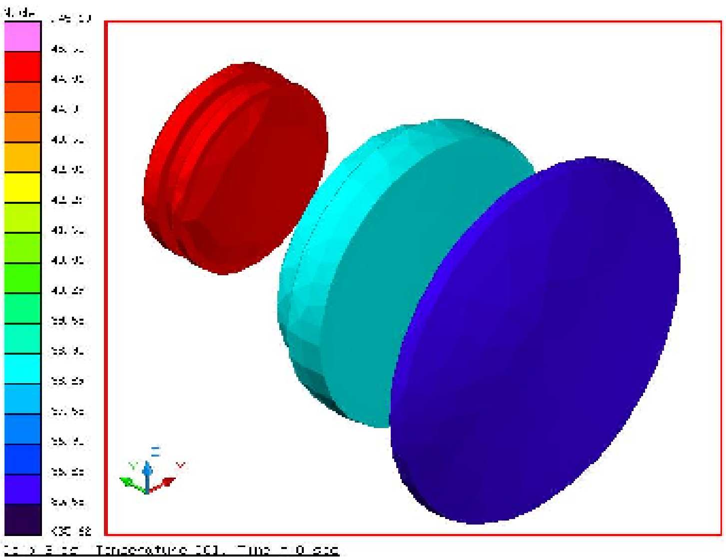


Cold
Max. 47.6°C
Min. 18.0°C

- Temperature distributions computed on the thermal mesh for the L13-16 subassembly are shown above for the hot and cold soak cases
  - *Lens 16 was hotter for the case with cold boundary conditions due to an increase in heater power*
  - *Baseline design assumed L13-16 soaked at 41.0 °C*
  - *Similar analysis for nominal soak condition gave a maximum temperature of 44.5 °C and a minimum temperature of 29.9 °C*

L13-16 Lens Axial Gradients



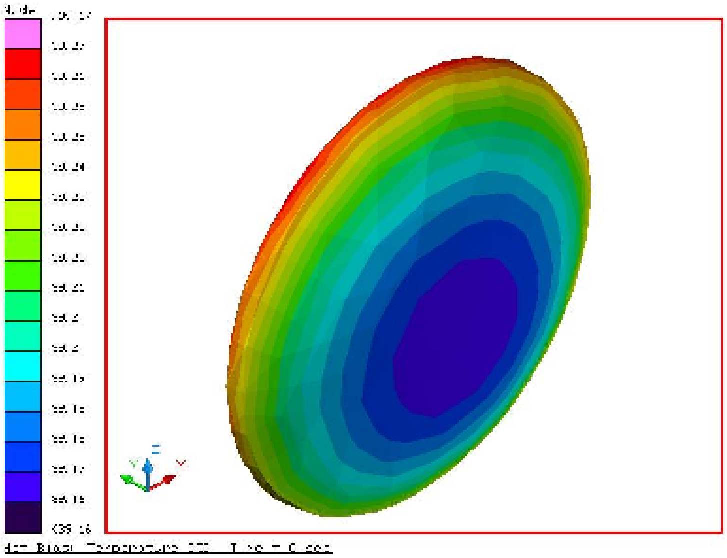


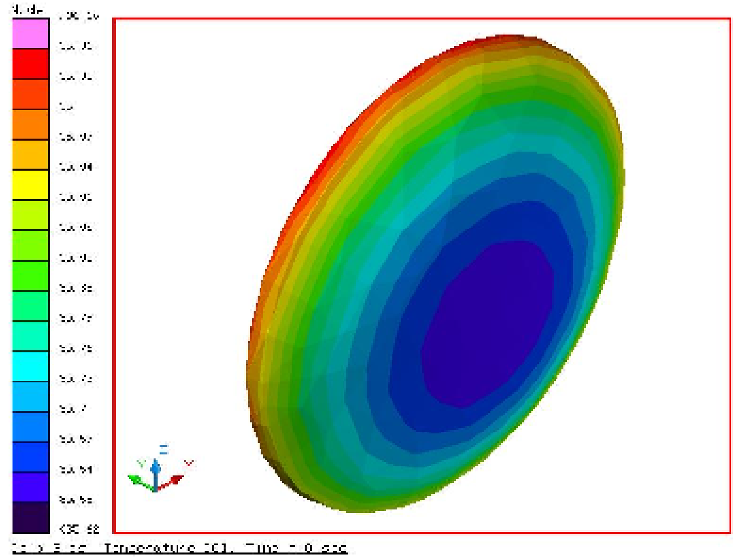
Hot
Max. 41.3°C
Min. 39.2°C

Cold
Max. 45.6°C
Min. 35.6°C

- Temperatures computed for the lenses in the L13-16 subassembly are shown above for the hot and cold soak cases
  - *A significant axial thermal gradient is set up in L13-16 by applying equal heater power to the two ends of the L13-16 subassembly*
  - *The size of the axial gradient increases with an increase in applied heater power*
  - *Baseline design assumed all lenses in L13-16 soaked at 41.0 °C*
  - *Similar analysis for nominal soak condition gave a maximum temperature of 43.5 °C and a minimum temperature of 38.0 °C*

Lens 13 Radial Gradients



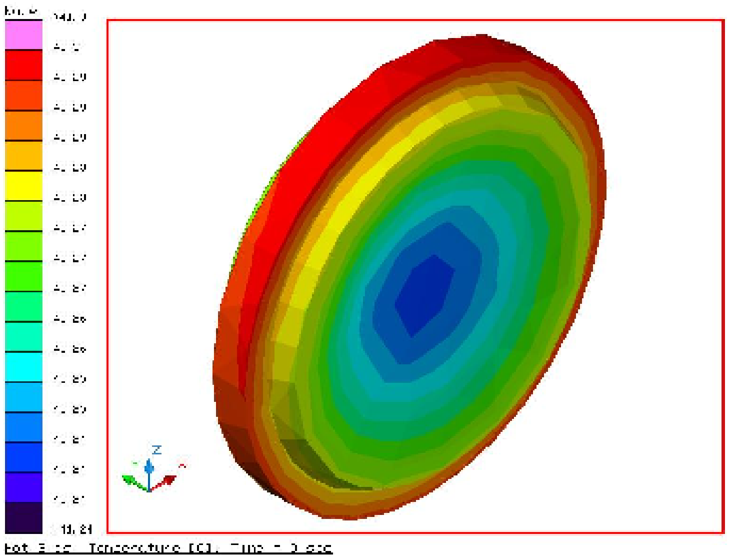


Hot
Max. 39.3°C
Min. 39.1°C
ΔT 0.11°C

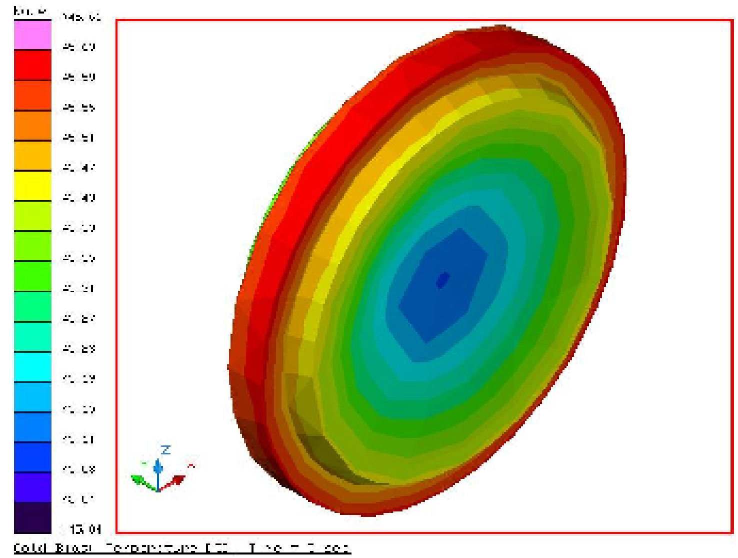
Cold
Max. 36.1°C
Min. 35.6°C
ΔT 0.44°C

- Temperatures computed for Lens 13 are shown above for the hot and cold soak cases
  - *A radial thermal gradient is set up in L13-16 when heater power is applied to the surrounding L13-16 lens barrel*
  - *Baseline design assumed all lenses in L13-16 soaked at 41.0 °C, so overall L13 temperature is biased below the design setpoint for all soak conditions*
  - *The size of the radial gradient increases with an increase in applied heater power*
  - *Similar conditions apply for Lens 14*
  - *Similar analysis for nominal soak condition gave a maximum temperature of 38.3 °C, a minimum temperature of 38.0 °C, and a radial gradient of 0.25 °C*

Lens16 Radial Gradients



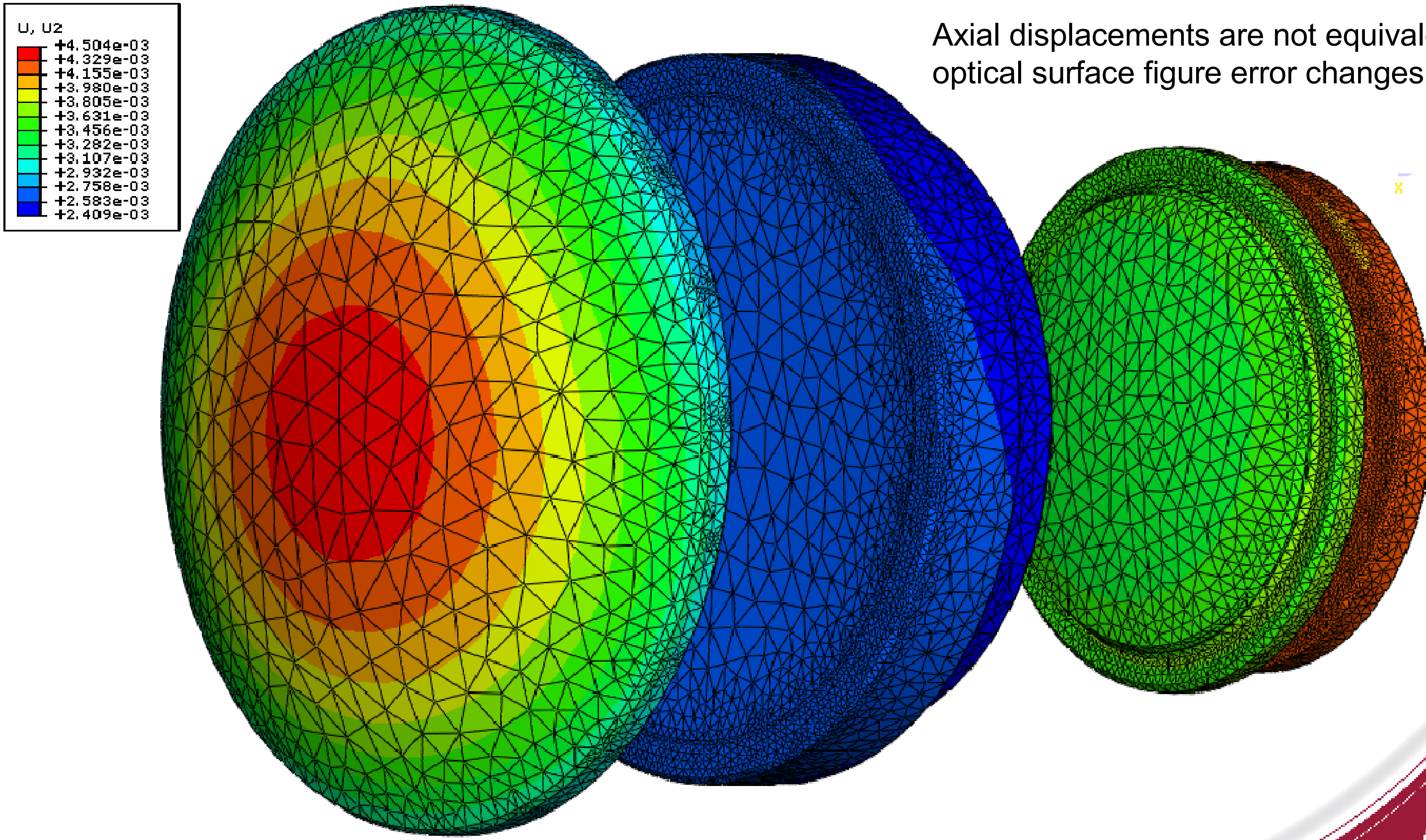
Hot
Max. 41.3°C
Min. 41.2°C
ΔT 0.06°C



Cold
Max. 45.6°C
Min. 45.0°C
ΔT 0.59°C

- Temperatures computed for Lens 16 are shown above for the hot and cold soak cases
  - *A radial thermal gradient is set up in L13-16 when heater power is applied to the surrounding L13-16 lens barrel*
  - *Baseline design assumed all lenses in L13-16 soaked at 41.0 °C, so overall L16 temperature is biased <u>above</u> the design setpoint for all soak conditions*
  - *The size of the radial gradient increases with an increase in applied heater power*
  - *Similar conditions apply for Lens 15*
  - *Similar analysis for nominal soak condition gave a maximum temperature of 43.5 °C, a minimum temperature of 43.2 °C, and a radial gradient of 0.29 °C.*

Example of Structural Results
Cold Case Lens Axial Displacements



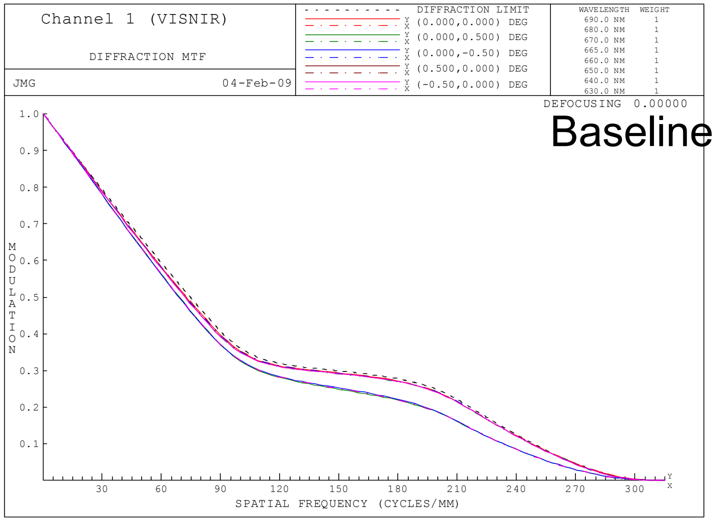
Max. axial displacement = 4.5 microns.

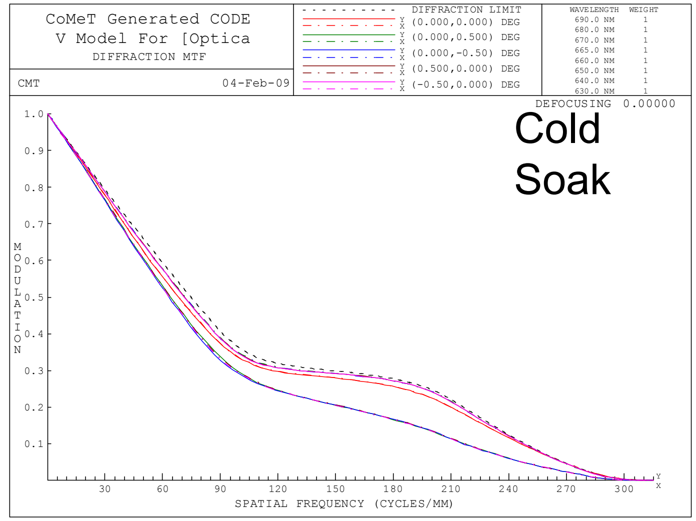
Axial displacements are not equivalent to optical surface figure error changes.

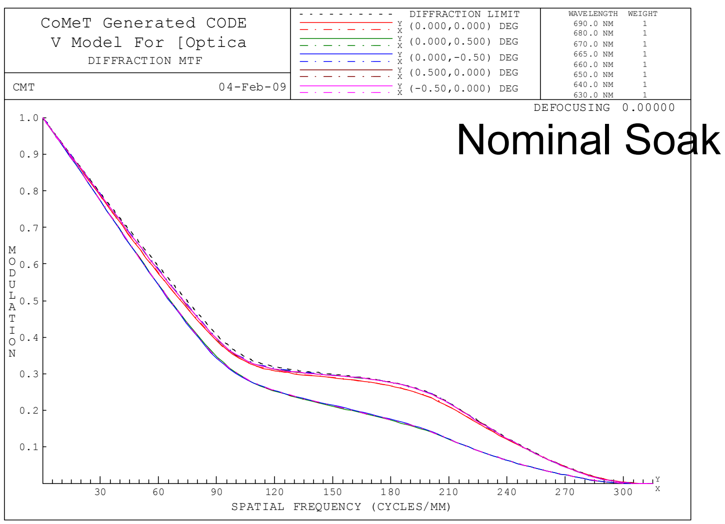
Example of Optical Results

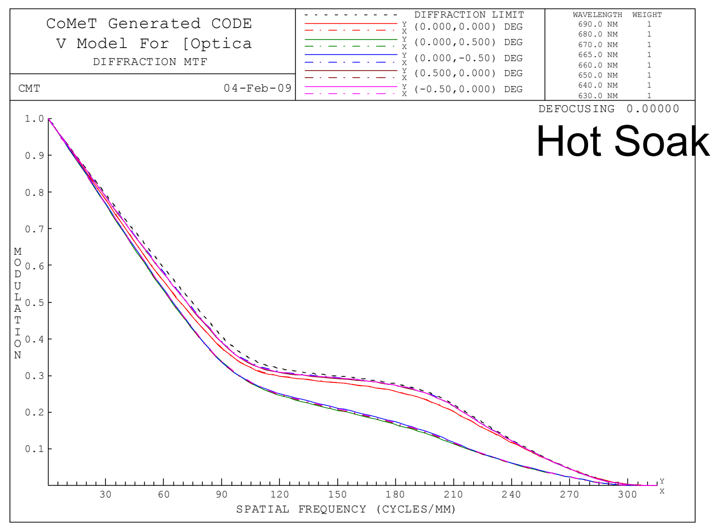
MTF Comparison – Baseline and All Soak Cases

Common focus position, S1 F01 band









STOP analysis shows that L13-16 thermal control system is effective at maintaining focus and image quality over the tested range of thermal soak environmental conditions.

Interpretation of STOP results - 1

- The STOP results confirmed that the instrument contractor's algorithms for setting heater power levels on the L13-16 subassembly in response to changes in thermal boundary conditions imposed on the S1 channel optical system for hot, nominal, and cold soak conditions are effective at maintaining optical focus and image quality over these temperature excursions
- The STOP analysis also confirmed that some simplifying assumptions made by the instrument contractor during the design of the L13-16 focus control algorithm were good ones
  - *Stresses on the lenses from their spring loaded retainers did not result in observable optical performance impacts in our STOP mode*
    - *The instrument contractor ignored these stresses in their baseline structural model, arguing that the lenses would float or slide on the retainers during differential thermal expansion and so not generate additional stresses over those used to preload the lenses against their retainer seats*
  - *The STOP model showed that changes in the average bulk temperatures of the lenses were the dominant thermally induced refractive index effect on optical performance, and that radial gradients in lens refractive index had a secondary to negligible effect*
    - *The instrument contractor included only the bulk temperature changes of the lenses in their optical models*

Interpretation of STOP results - 2

- Our STOP results provide physical insight into how and why the focus control approach for L13-16 actually works
  - *The baseline S1 channel design is configured to have the L13-16 operate at an elevated temperature (41 °C) while the rest of the optics work at nominal room temperature (20 °C)*
  - *The hot soak test condition comes closest to the design setpoint for L13-16; thermal gradients, changes in lens bulk temperature, and heater power levels are smallest for this case*
  - *As the surrounding environment for L13-16 gets colder, the increased heater power needed for the L13 and L16 heaters sets up significant axial thermal gradients in the L13-16 lens components*
  - *Changes in lens bulk temperature from the baseline 41 °C setpoint have the largest impact on optical performance by changing surface curvature and overall refractive index of the lens components*
    - Bulk temperatures of the lenses on the small diameter end of L13-16 (lenses 15 and16) rise above the setpoint temperature, while those on the large diameter end (lenses 13 and 14) fall below the setpoint temperature
    - This causes the refractive index-induced changes in lens power to change in opposite directions at the two ends of the lens assembly, and those changes tend to compensate for one another to leave overall S1 channel focus and image quality relatively unchanged

Conclusions

- An independent STOP analysis was conducted of a flight Electro-Optical sensor using a new Simulation Driven Engineering (SDE) software tool that allows this analysis to be performed in a collaborative fashion across engineering discipline (mechanical, structural, thermal, and optical) boundaries
- This work was accomplished with a relatively modest expenditure of time and resources
- The STOP model developed was of exceptionally high fidelity for the critical lens subassembly (L13-16) of interest, and it provided both confirmation of the instrument contractor’s thermal control approach for L13-16 and physical insight into how and why that approach worked
- STOP model predictions were validated against TVAC measurements of hardware performance to the degree possible

Questions

- Malcolm Panthaki, CTO & Don Tolle, VP Business Development are in attendance today
- Brief flier detailing our entire STOP process is available – see me, or Comet team for a copy
- CONTACT DATA
  - *www.cometsolutions.com*
  - *248-471-7017*