Development, Validation, and Practical Application of a Fast-Solving General-Purpose Thermal Analysis Tool – ONYX

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Introduction

- Modern computer-aided engineering (CAE) thermal analysis tools has produced software that is capable of extensive multidisciplinary simulations
- Drawbacks despite the sophistication of these tools:
  1. Costly, which tends to limit license availability
  2. Many first-order engineering thermal analysis problems do not warrant application of an extensive modern CAE toolset
- General purpose solver needs:
  1. Solve conjugate fluid and solid element heating in three dimensional (3D) domains
  2. Model natural convection and surface-to-surface radiation thermal couplings
  3. Solve steady-state and long-duration transient simulations
  4. Rapid model construction (minutes)
  5. Rapid model solution (minutes)
  6. Integrated post-processing

Rationale for ONYX

- CAE simulation tools tend to be bound by two ranges:
  1. Fully coupled conjugate computational fluid dynamics and heat transfer (CFD-CHT)
  2. One-dimensional (1D) macro solvers
- Both have tradeoffs and limitations:
  - Fully coupled conjugate CFD and CHT solutions
    - High fidelity
    - Solutions that can taking hours to days
    - Limited parametric simulations related to throughput
  - 1D macro solvers
    - Fast solving
    - Limited ability to model more complex geometry and thermal couplings
    - Limited graphical visualization of the model as built and solution results

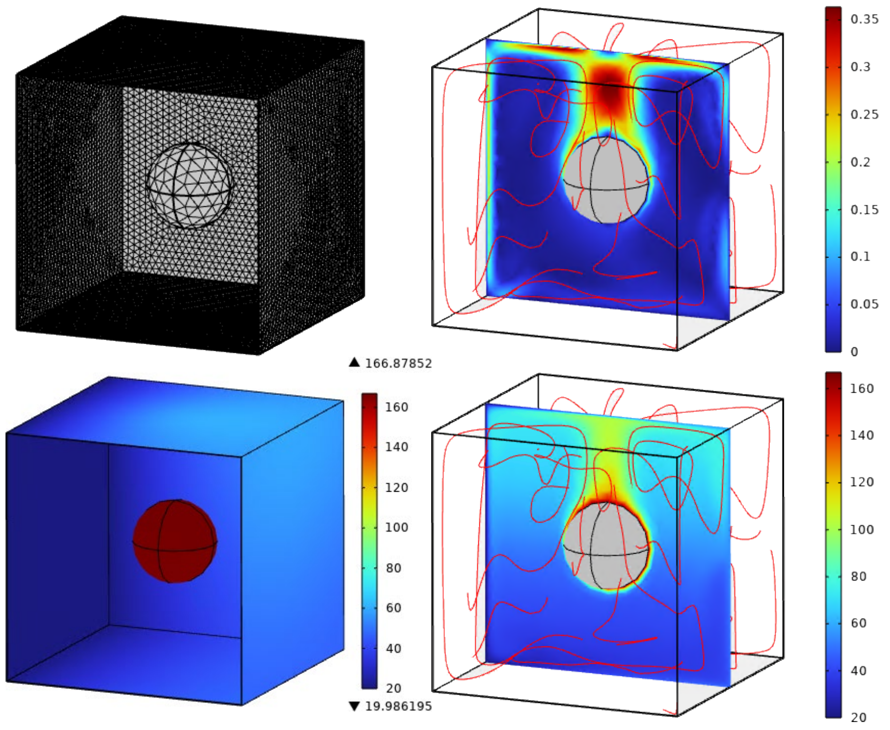
ONYX was developed as a niche software to bridge these two ranges

Rationale for ONYX

- Candidate conjugate heat transfer problem to illustrate the effect
- Arguably a fairly simple model
  - Includes grey-body surface-surface radiation
  - Conduction heating, enclosure walls and solid sphere
  - Natural convection couples the sphere to the left wall temperature boundary
- Coarse mesh in COMSOL
  - Required almost 9 hour to solve
  - Considerable RAM usage
  - Acceptable for single case studies
- Can we get an 80% solution more quickly?

COMSOL model coarse mesh

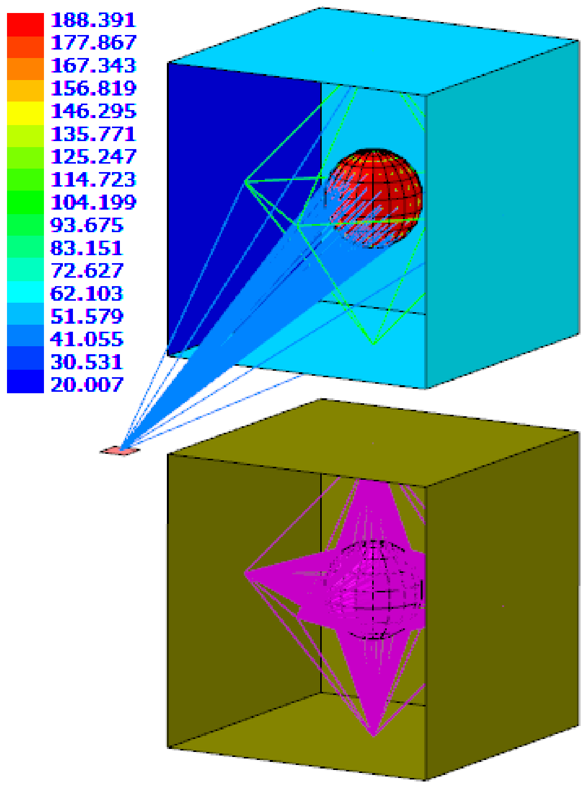
Flow speed (m/s)



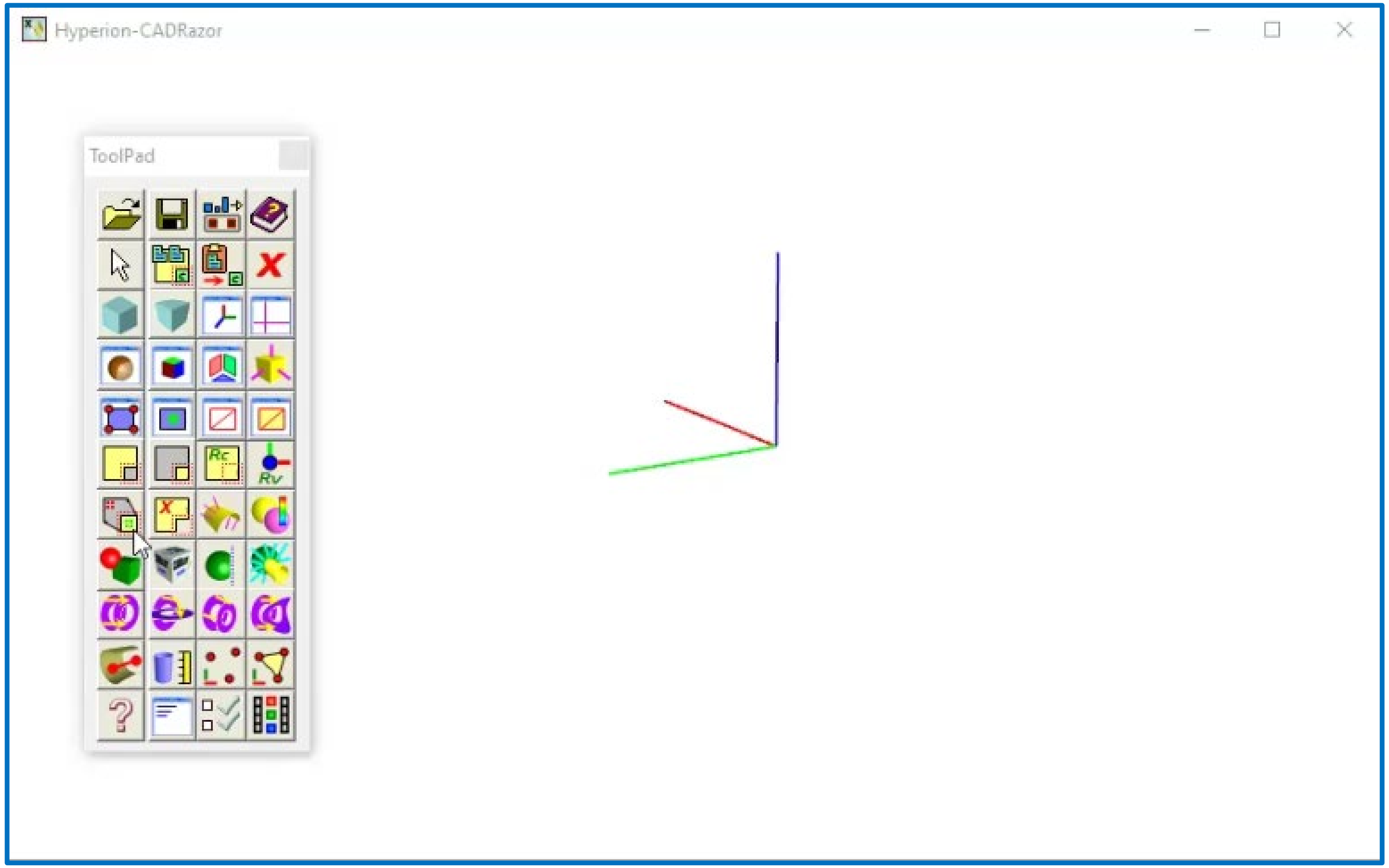
Fluid temperature (°C)

- Sphere heated at 100 W
- Left wall forms boundary at 20 °C

Rationale for ONYX



Final ONYX Model
9 minutes



Illustrates the ONYX process, applies limited shape factor integration and solution residual at termination

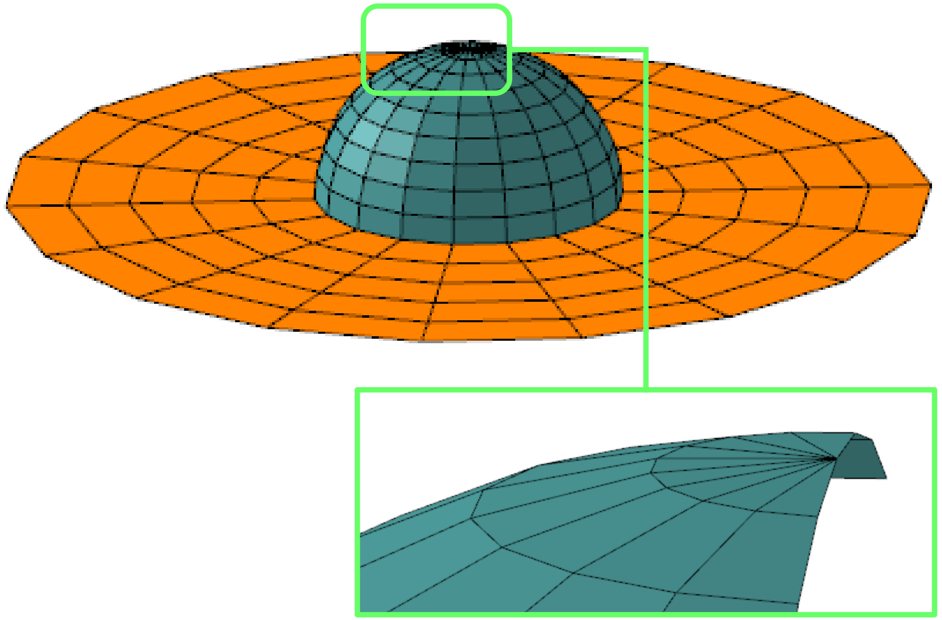
Software Goals for ONYX

- Software goals
  - Simplified 3D model representation
  - Construct detailed models in minutes rather than hours
  - Simplified conductance networks that can be hand calculated and verified
  - Common steady-state and transient solver routines
  - Robust solvers not prone to instability
  - Expandable framework

Approach - Quad

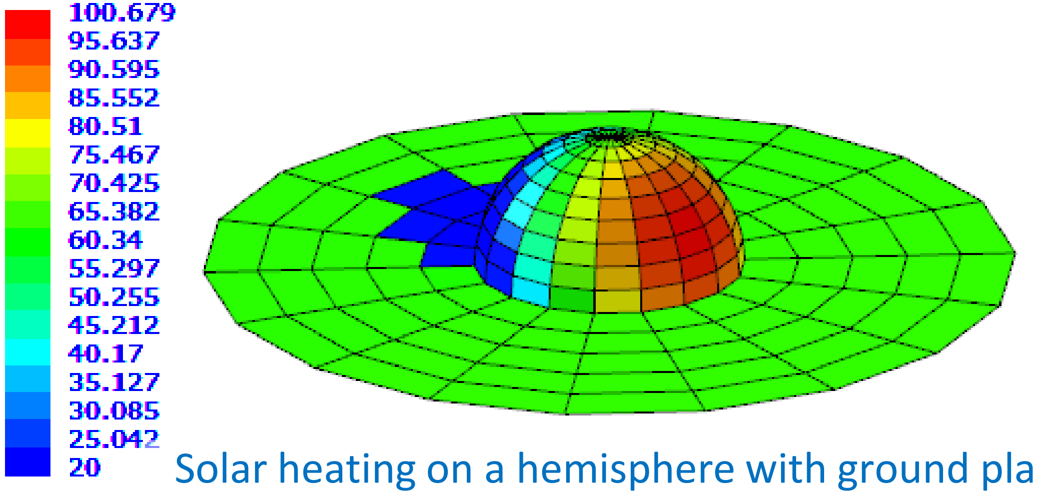
- Equivalence of geometry elements and control volumes
- Leads to sparse geometry modeling
- Eliminated the costly geometry-to-mesh conversion step in the modern CAE toolset
- Harkens back to a lost era
  - Heritage codes applied this method
  - CINDA and SINDA days, TAS, TAK, Pthermal, etc.
- The ONYX framework will be built around a single element type – quadrilateral (quad)
- Questions remain:
  - Can we represent our geometry with sufficient fidelity?
  - Can we accurately depict the physics?
  - Can we accurately model the conductance network?

Distorted quad elements to represent a hemisphere on a plane



Approach - Quad

- Quad elements:
  1. Quad elements represent a geometric four-sided control volume (CV)
  2. Quad elements take little memory to represent, process, and render
  3. Quads can be subdivided into two triangles to compute surface normal and intersection logicals
  4. Quad-quad connections can be processed for the conductance and advection matrices
  5. Quad elements can be readily distorted to form any geometric shape

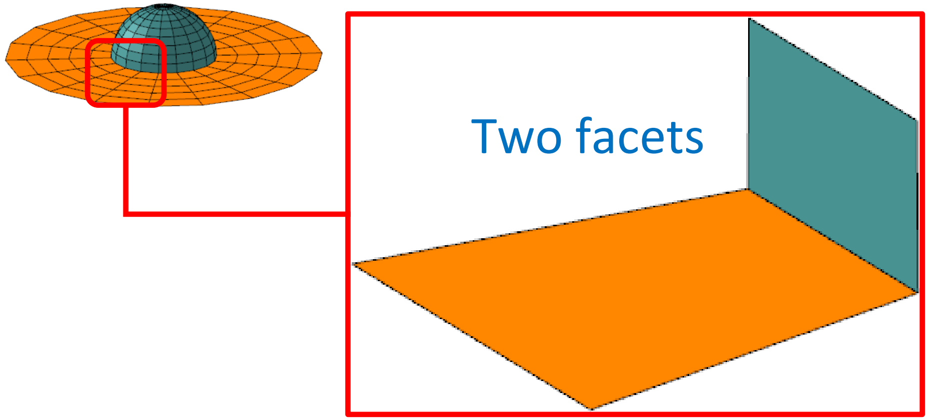


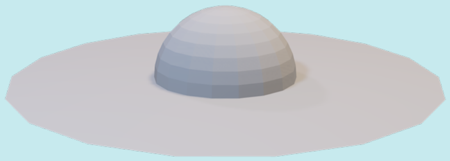
Solar heating on a hemisphere with ground plane

1. Solving vector-based heating
2. Element obscuration for shadowing
3. Conduction through the hemisphere
4. Radiation to the ground plane
5. Convection and radiation to the ambient

ONYX Neutral File – Wavefront

- A neutral file interface is used to prepare geometry models for solution
- ONYX applies a modified Wavefront format
  - Utilizing the standard facet-vertex formation
  - Adds a custom color tag that references the property associated with the quad element
- Wavefront is ideal:
  1. Free formatted ASCII text model construction
  2. Small model files that are human readable and easily modified
  3. Three designators v, f, c to define a model
  4. Color extension that allows the ONYX software to reference a property definition to each quad
  5. Compatible format with CAD tools, pdf, PPT, etc.





Shows hemisphere model dragged into this presentation

Eight vertices

```
v -8.550798E-2   .4849397   .0867286
v -8.682411E-2   .4924039 -2.185569E-8
v -.25   .4330127 -2.185569E-8
v -.2462104   .4264488   .0867286
v -8.682411E-2   .4924039 -2.185569E-8
v -.1215538   .6893654 -2.185569E-8
v -.35   .6062178 -2.185569E-8
v -.25   .4330127 -2.185569E-8
```

Two facets

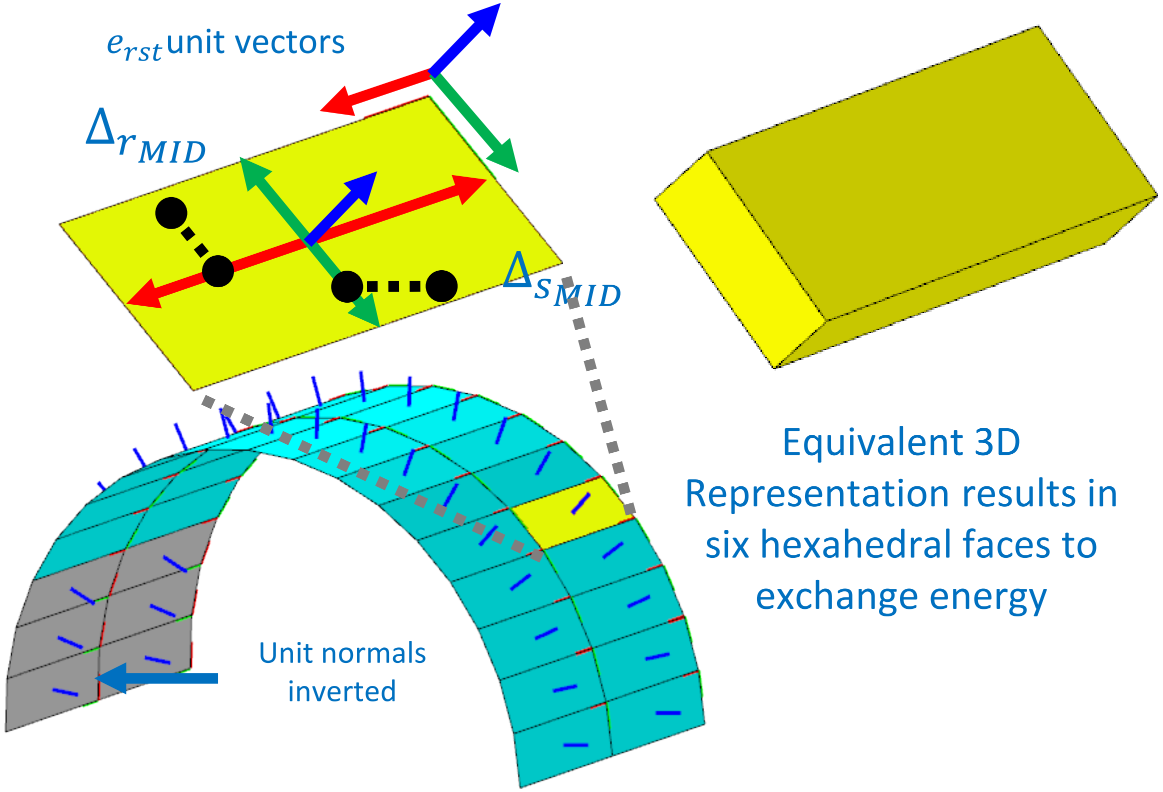
```
f  1  2  3  4
f  5  6  7  8
```

Facet color

```
c  8421440
c  33023
```

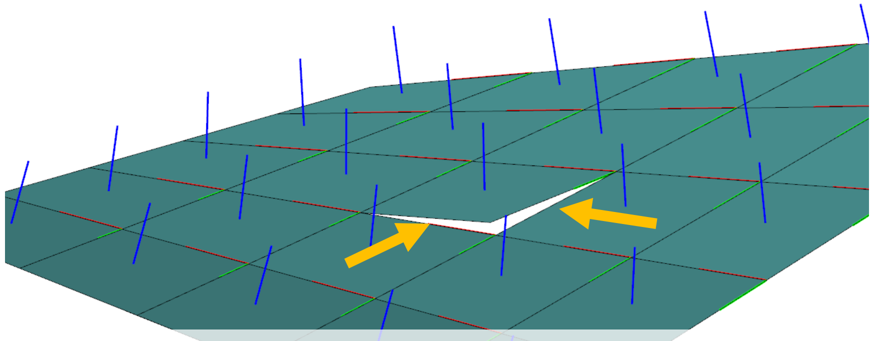
2D Quad to 3D Control Volume

- Any thermal solver must represent three-dimensional (3D) elements to have any practical consideration
- ONYX quad elements extended to 3D by assigning a thickness in the color-referenced property
  - Unit directions $\boldsymbol{e_r}\ \boldsymbol{e_s}\ \boldsymbol{e_t}$
  - Element size $\Delta_{rst} = \begin{bmatrix} \Delta_r \\ \Delta_s \\ \Delta_t \end{bmatrix}$
- Creates virtual hexahedral control volume but is very efficient

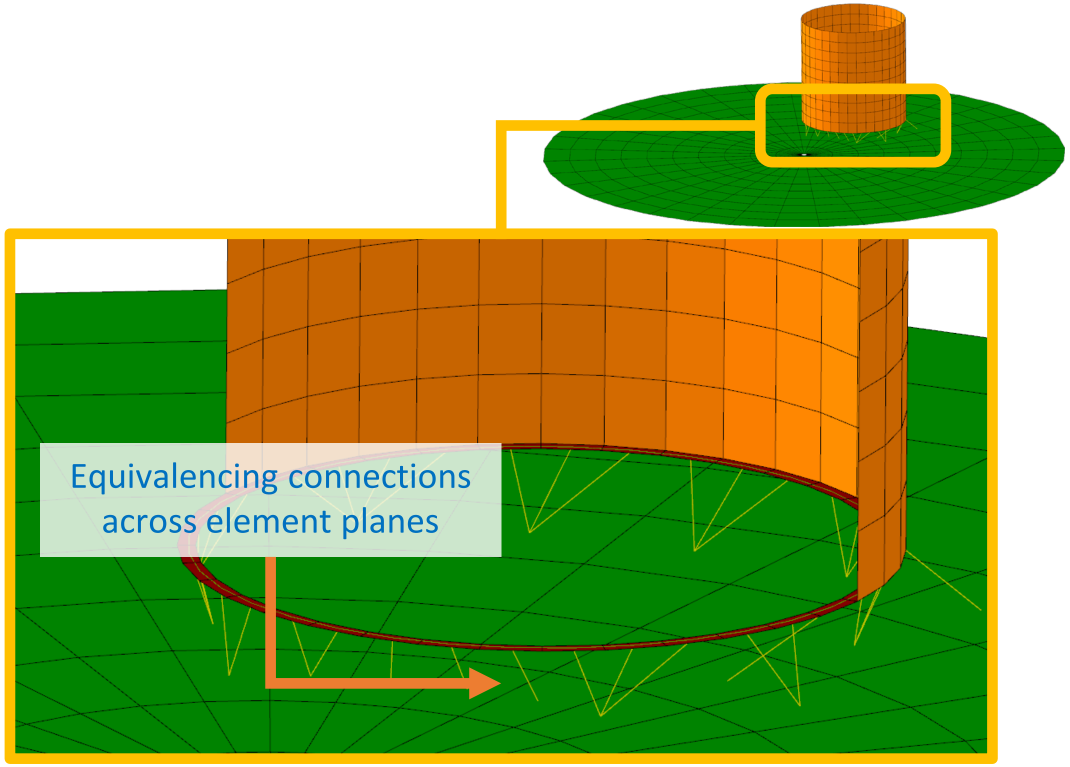


Equivalencing

- ONYX equivalencing method
  1. In-plane equivalencing
  2. Plane-normal equivalencing
- Colinear quad edge lines defines the equivalencing in the $\boldsymbol{e_r}$ and $\boldsymbol{e_s}$ planes
- Plane-normal equivalencing is determined with projected mesh couplings. This involves projecting normals to the nearest intersecting surface.



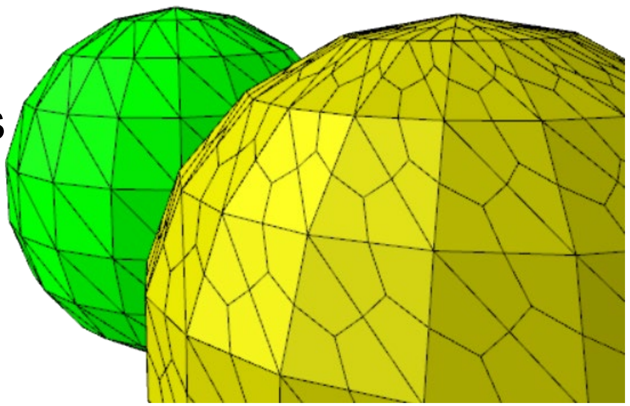
Intentional crack is placed on element which breaks the connection on these edges.
Element will only connect thermally on two edges

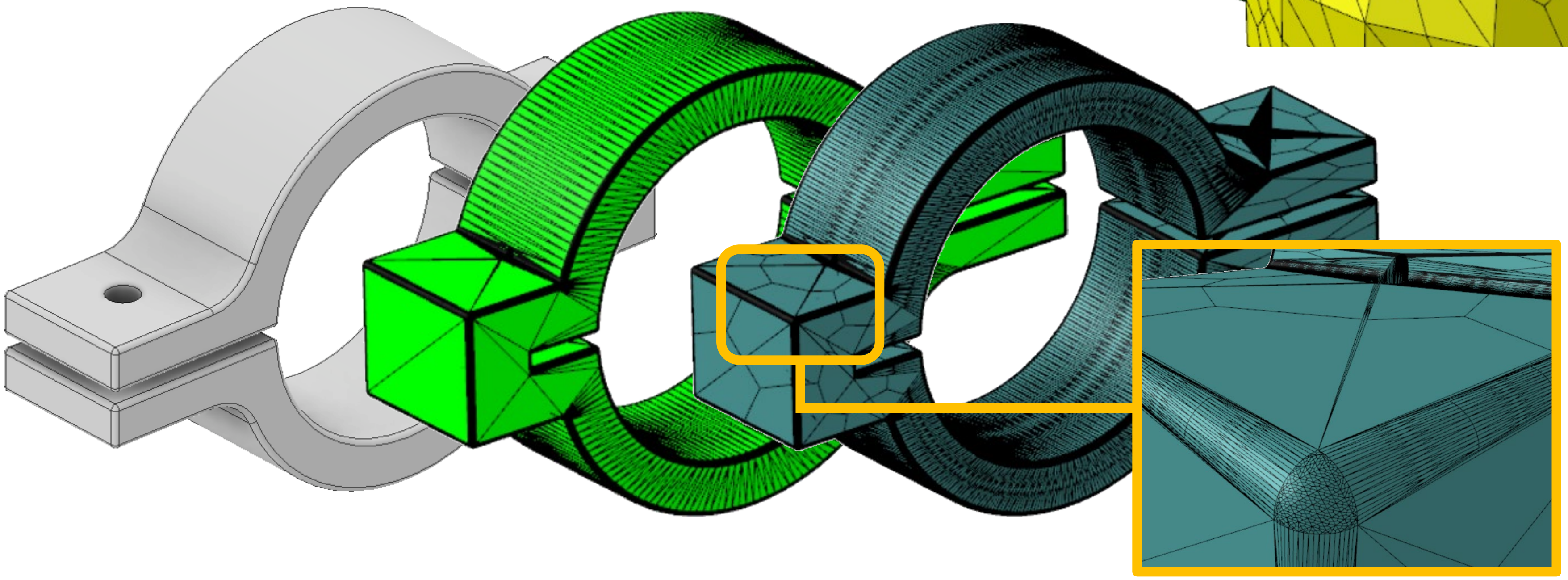


Shows projected mesh equivalencing that connects dissimilar mesh elements.
These connections emanate from centroid of defined elements, pointing in the direction of the unit normal.

Rapid CAD Conversion

- Easy conversion of CAD export meshes
  - STL triangles and be trisected to create three quad elements
  - Trisecting from placed centroid equivalencing of elements
  - Rapid conversion of Inventor geometry





Inventor IPT ➡ CAD Tri STL ➡ STL to quad ➡ ONYX

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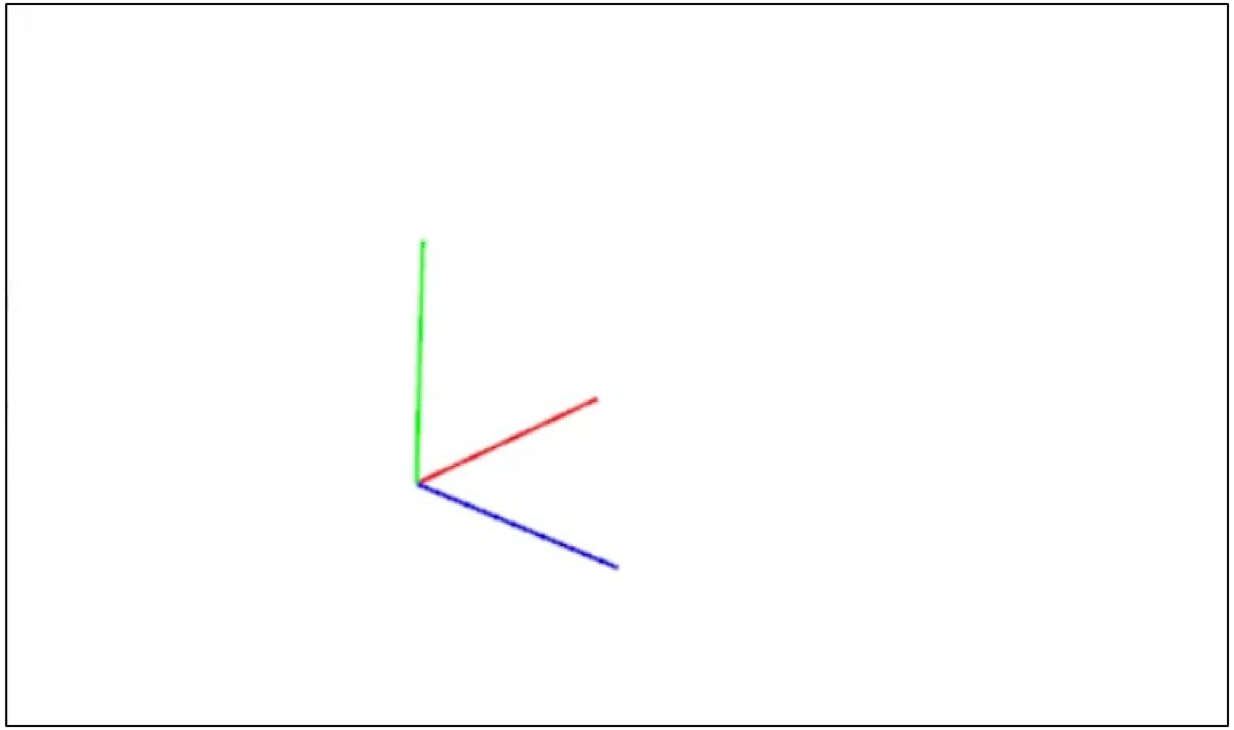
Mesh Refinement

- Mesh refinement
  - Variable *n-secting* of quad elements along $\boldsymbol{e_r}$ $\boldsymbol{e_s}$ lines
  - Also ensure equivalencing
  - Rapid refinement for mesh consistency testing
- Vaporware under development
  - Combine two tri to make one quad
  - Automatic coupling of different n-sected meshes



Conservation Equation

- Energy conservation in an control volume
- Vectorized ODE with conductance matrices and source vectors
- Vector-matrix form is useful to implement solution methods
  - Promote code reuse
  - More advanced solution algorithms
- Solve this equation for all control volume temperatures $\boldsymbol{T}$

$$\boldsymbol{C}\,\frac{d\boldsymbol{T}}{dt} = \boldsymbol{G}(\boldsymbol{T})\,\boldsymbol{T} + \boldsymbol{H}\,\boldsymbol{T} + \boldsymbol{S}$$

Capacitance term

Conductance term

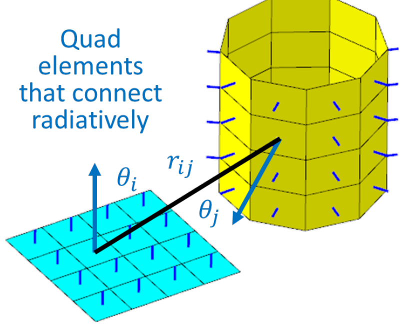
Advection term

Source term

Conductance Matrix

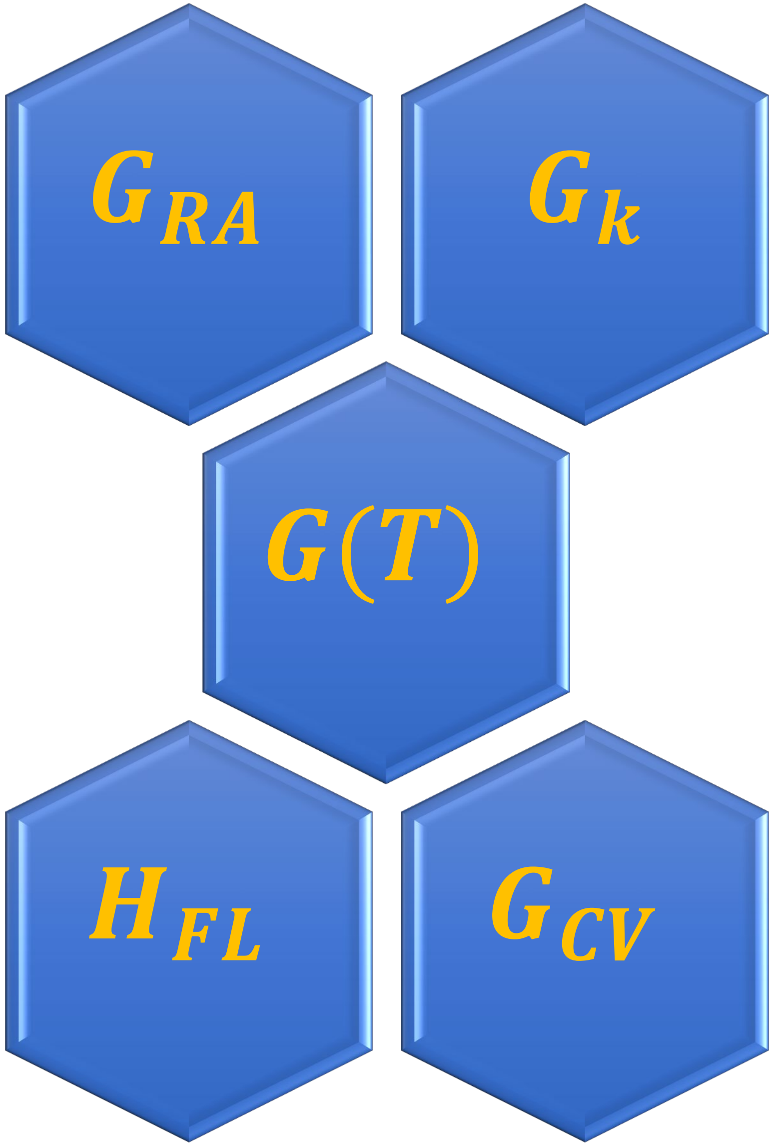
Radiation

- $G_{RA_{i,j}} = \sigma \dfrac{(T_i+T_j)(T_i^2+T_j^2)}{\frac{1}{A_{RA_i}}\left(\frac{1}{\varepsilon_i}-1\right)+\frac{1}{A_{RA_j}}\left(\frac{1}{\varepsilon_j}-1\right)+\frac{1}{A_{RA_i}F_{i,j}}}$
- Includes shape-factor matrix $\boldsymbol{F}$ computed by double integration



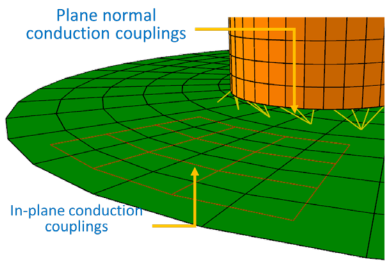
Advection

- $\boldsymbol{H} = -\boldsymbol{C}\,\boldsymbol{u}\cdot\nabla\,\boldsymbol{T}$
- rs-plane flow conductors
- Windward, one-sided



Material conduction

- $\boldsymbol{G_k} = k\,\boldsymbol{V}\,\nabla^2\boldsymbol{T}$
- Connects quads both in-plane and plane-normal
- $G_{k_{e_n}} = \boldsymbol{k}\cdot\boldsymbol{e_n}\dfrac{\boldsymbol{A}\cdot\boldsymbol{e_n}}{{}^1/_2\boldsymbol{\Delta_{rst}}\cdot\boldsymbol{e_n}}$
- Includes anisotropic conductivity $\boldsymbol{k}$

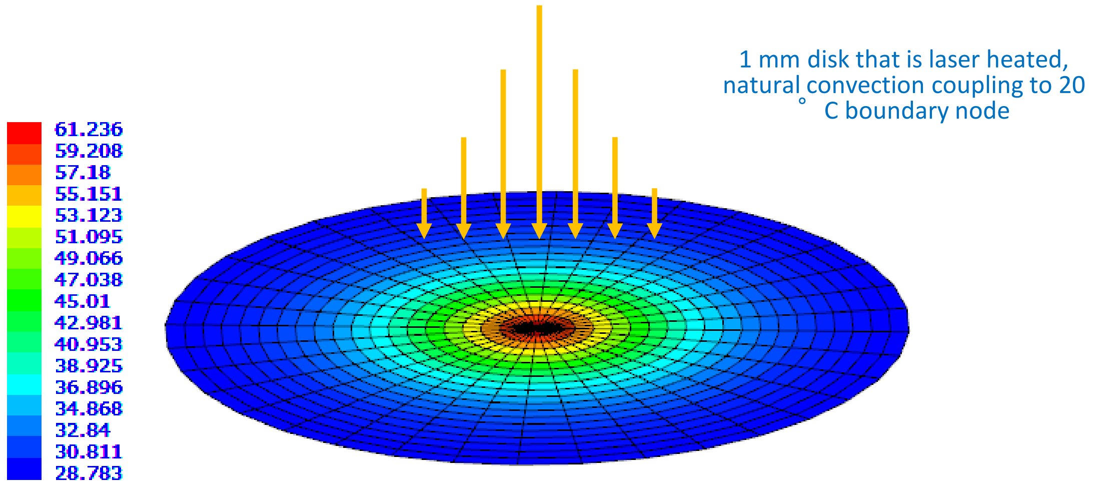


Convection

- $G_{CV} = h_{CV}\,\boldsymbol{A}$
- Connects quads plane-normal $\boldsymbol{e_t}$
- $G_{CV_{e_n}} = h_{CV}\,\boldsymbol{A}\cdot\boldsymbol{e_t}$

Source Heating

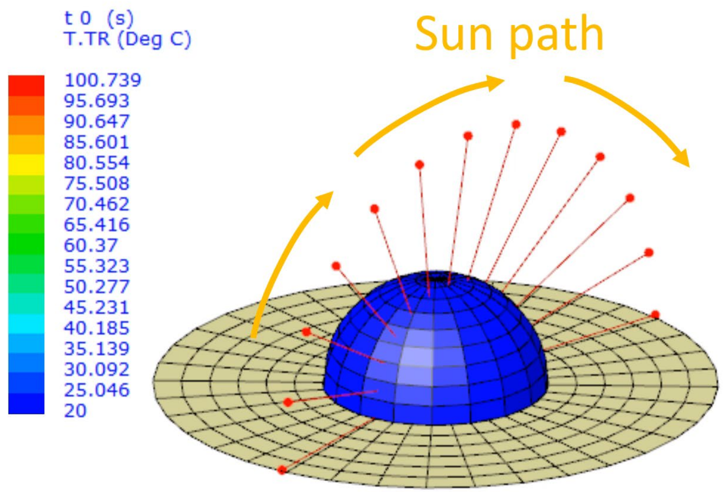
- Source heating
  - Various source heating terms
  - Solar heating
  - Defined heat flux
  - Function-defined heat flux



$$q''(r) = q_{MAX} \cdot e^{\left(-\frac{r^2}{R_{1\sigma}{}^2}\right)}$$

$$Q_{Disk} = \int_0^{R_{Disk}} q_{MAX} \cdot e^{\left(-\frac{r^2}{R_{1\sigma}{}^2}\right)} \cdot 2 \cdot \pi \cdot r \, dr$$

ONYX function-derived heat flux to simulate Gaussian beam heating



Hemisphere model, one solar day-night cycle

Solution Phase

- Implicit time differencing to ensure numerical stability
  - Used for steady-state and transient solutions
  - Applies common solution code
- Introduce an energy residual function $\boldsymbol{\phi}$
- Solved using Generalized Newton's(GN) method with successive over relaxation (SOR) factor
  - GN SOR is easy to develop
  - Reasonably fast solving

$$\boldsymbol{T}^{(k+1)} = \boldsymbol{T}^{(k)} - \omega_{SOR}\left(\frac{\partial\boldsymbol{\phi}\left(\boldsymbol{T}^{(k)}\right)}{\partial\boldsymbol{T}}\right)^{-1}\boldsymbol{\phi}^{(k)}$$

$$\boldsymbol{C}\,\frac{\boldsymbol{T}^{(n+1)} - \boldsymbol{T}^{(n)}}{\Delta t} = \boldsymbol{G}\left(\boldsymbol{T}^{(n+1)}\right)\boldsymbol{T}^{(n+1)} + \boldsymbol{H}\,\boldsymbol{T}^{(n+1)} + \boldsymbol{S}$$

Drop capacitive term for steady-state residual function

$$\boldsymbol{\phi}_{SS}\left(\boldsymbol{T}^{(k)}\right) = \left(\boldsymbol{G}\left(\boldsymbol{T}^{(k)}\right) + \boldsymbol{H}\right)\boldsymbol{T}^{(k)} + \boldsymbol{S}$$

Transient residual formulation

$$\boldsymbol{\phi}_{TR}\left(\boldsymbol{T}^{(n+1,k)}\right) = \boldsymbol{\phi}_{SS}\left(\boldsymbol{T}^{(n+1,k)}\right) - \boldsymbol{C}\,\frac{\boldsymbol{T}^{(n+1,k)} - \boldsymbol{T}^{(n)}}{\Delta t}$$

Special Adaptations

- ONYX framework accommodates add-ons
  - Added physics, transport mechanism, heat flow sources
  - Modifications to the property data structure to include these new additions
- Recent additions include:
  - Advective flows
  - Aeroheating simulation
- Future additions such as solidification, transpiration, orbit heating

Quad is ideal to describe flows with defined advective velocity. The rs plane defines the area of flow passage and the property-defined thickness completes the 3D hexahedral flow passage

$$\boldsymbol{H} = -\boldsymbol{C}\,\boldsymbol{u}\cdot\nabla\,\boldsymbol{T}$$

$$G_{FL_{e_n}} = \boldsymbol{m_t} C_p \cdot \boldsymbol{e_n}$$

Aeroheating is predicted by converting specific boundary quads to adiabatic wall nodes. These nodes have property definitions that carry an imbedded trajectory.

$$T_{AW} = T_{ATM} + r(Re_x, Pr)\,(T_x - T_{ATM})$$

$$h_{CV_{AVG}}(x_o, L_{STA}) = \frac{1}{L_{STA}} \int_{x_o}^{x_o+L_{STA}} h_{CV}(x)\,dx$$

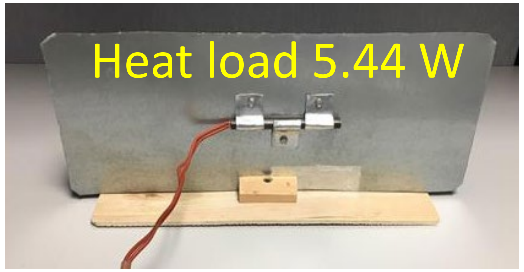
$$G_{CV_{e_n}} = h_{CV}\,\boldsymbol{A}\cdot\boldsymbol{e_t}$$

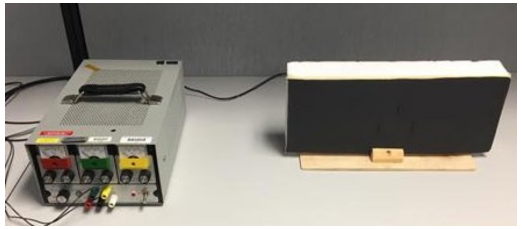
Validation Overview

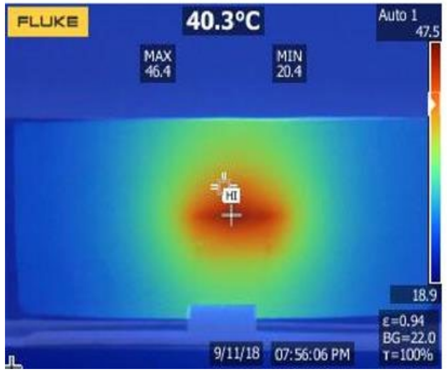
- Validation is an important step to weed out code errors
  - ONYX validation is a continual process
  - Extensive collection validations are built for this testing process
- Code-code comparisons
  - Termed *soft validations*
  - Possibility of simply repeating errors
  - Good for fast sanity checks
- Comparisons to experimental data
  - Believed to be more rigorous
  - But more challenging:
    - Model construction
    - Unknown boundary conditions
- We present a small sample of both types of validations

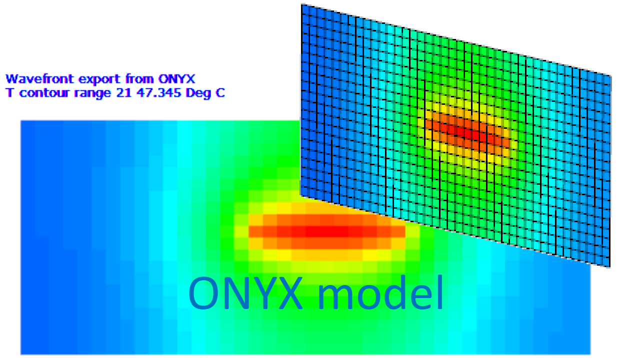
Validations with Experimental Data

- Natural convection and radiation
- Compares maximum temperature to IR thermal image at steady state
- Test data:
  - Derived from https://www.solariathermal.com/ThermalTestCorrelation.html
  - Images used with permission
- ONYX and test data agree to within 1.1 ℃, approximately 4% based on overall temperature difference







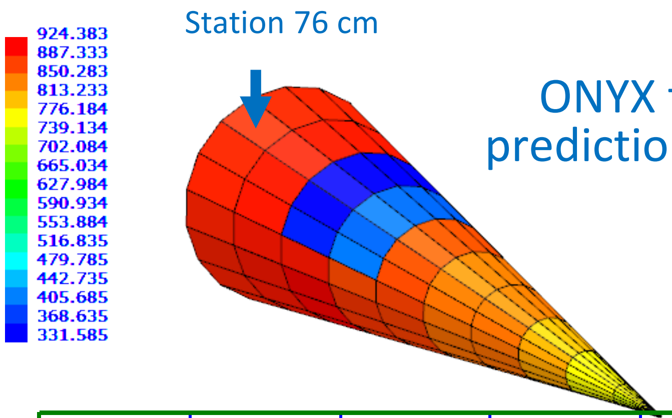


Radiation and convection cooled surface that has backside heater

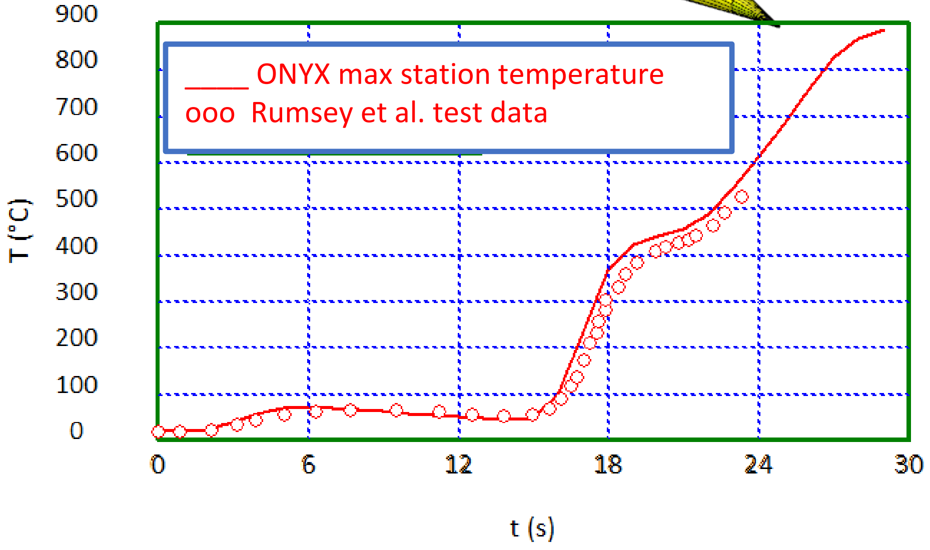
Front side convection and radiation to 21 ℃ ambient temperature

Validations with Experimental Data

- Aeroheating simulation
  - Transient simulation
  - Compares evolving transient wall temperature maximum temperature to IR thermal image at steady state
- Special adaptation
  - Create an adiabatic wall boundary node in the model
  - Node is tied to the transient trajectory
  - Element centroid and size determine position and characteristic length
  - Heat transfer coefficient integrated over this length
  - $h_{CV_{AVG}}(x_o, L_{STA}) = \frac{1}{L_{STA}} \int_{x_o}^{x_o+L_{STA}} h_{CV}(x)\, dx$
- Test case derived from Rumsey et. al
- ONYX and test data agree to within 34 ℃ at t = 24 s, approximately 6% based on overall temperature difference $T_{AW} - T_W$



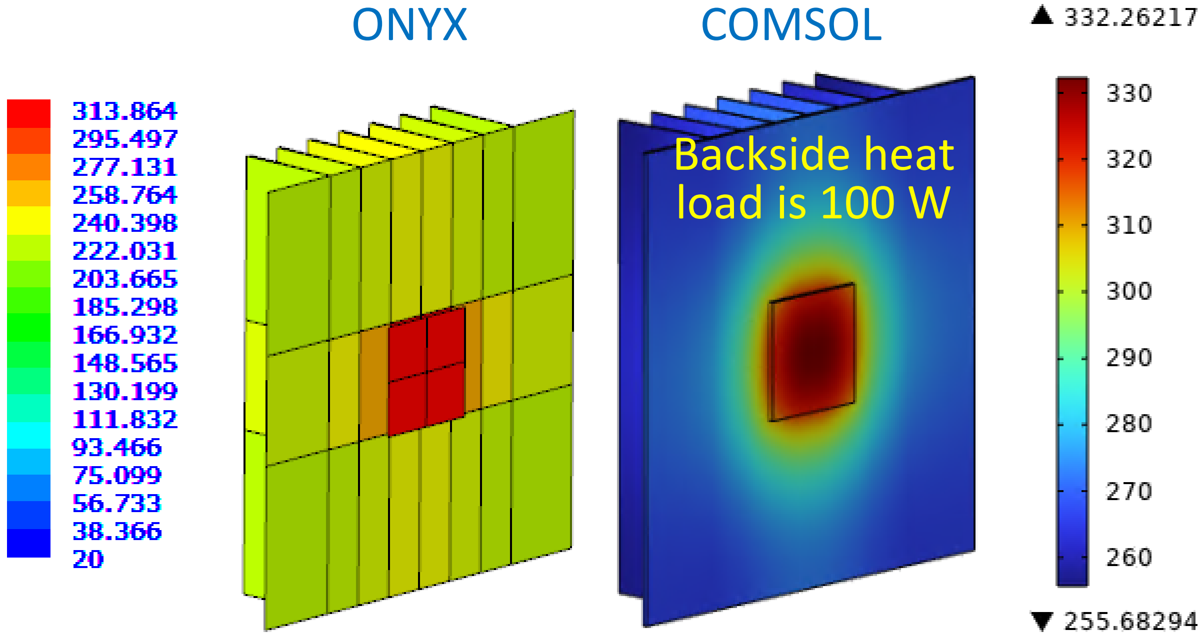
ONYX transient prediction at t = 30 s



Rumsey, Charles B. and Lee, Dorothy B., Langley, October 15, 1956, Measurements Of Aerodynamic Heat Transfer and Boundary - Layer Transition On A 15 Degree Cone In Free Flight At Supersonic Mach Numbers Up To 5.2, Report Number RM L56F26, Aeronautical Laboratory Langley Field, Va., https://ntrs.nasa.gov/api/citations/19930089362/downloads/19930089362.pdf

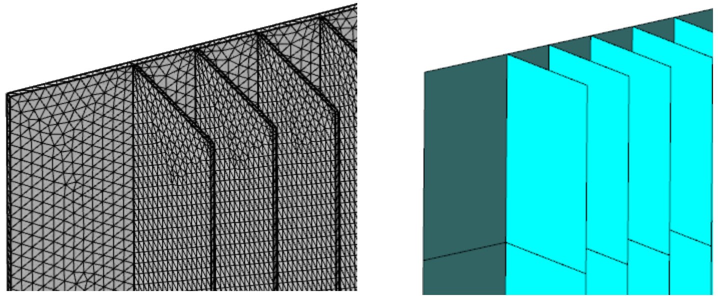
Code-Code Validation – Fin Bank with Heater

- Applies simplified natural convection coupling in both models
- Note the different in mesh refinement to achieve near same results
  - COMSOL 60,000 TET4 elements
  - ONYX 49 quad elements
- ONYX and COMSOL simulation to within 7 ℃, approximately 7% based on overall temperature difference



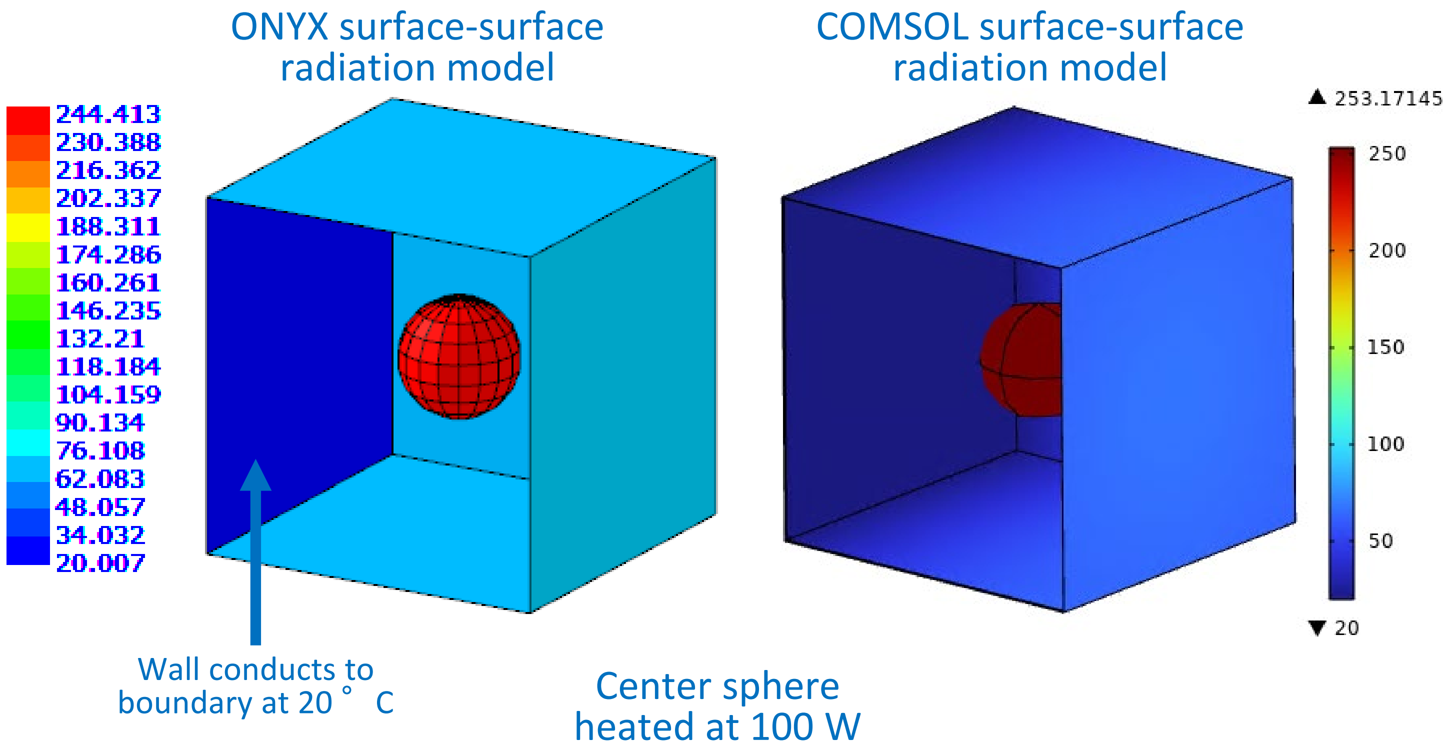
Fins are 0.5 mm thick, cooled by natural convection to ambient 20 °C

Note the mesh difference between the two treatments



Code-Code Validation – Radiation Exchange

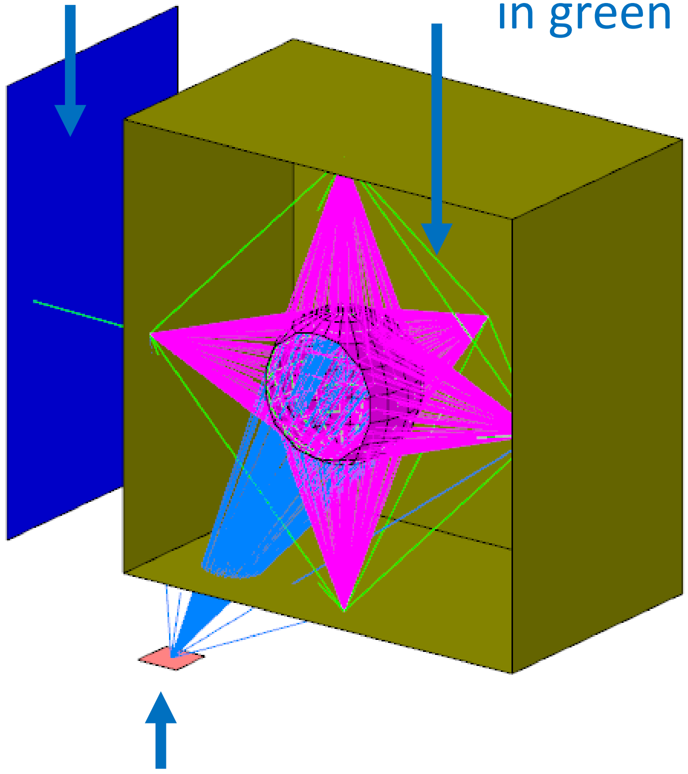
- Heated sphere with grey body radiation to outer enclosure walls
- ONYX and COMSOL simulation to within 9 ℃, approximately 4% based on overall temperature difference



All surfaces have an emissivity of ε=0.9. The walls are 2 mm thick Al 6061. Models are solved to steady state.

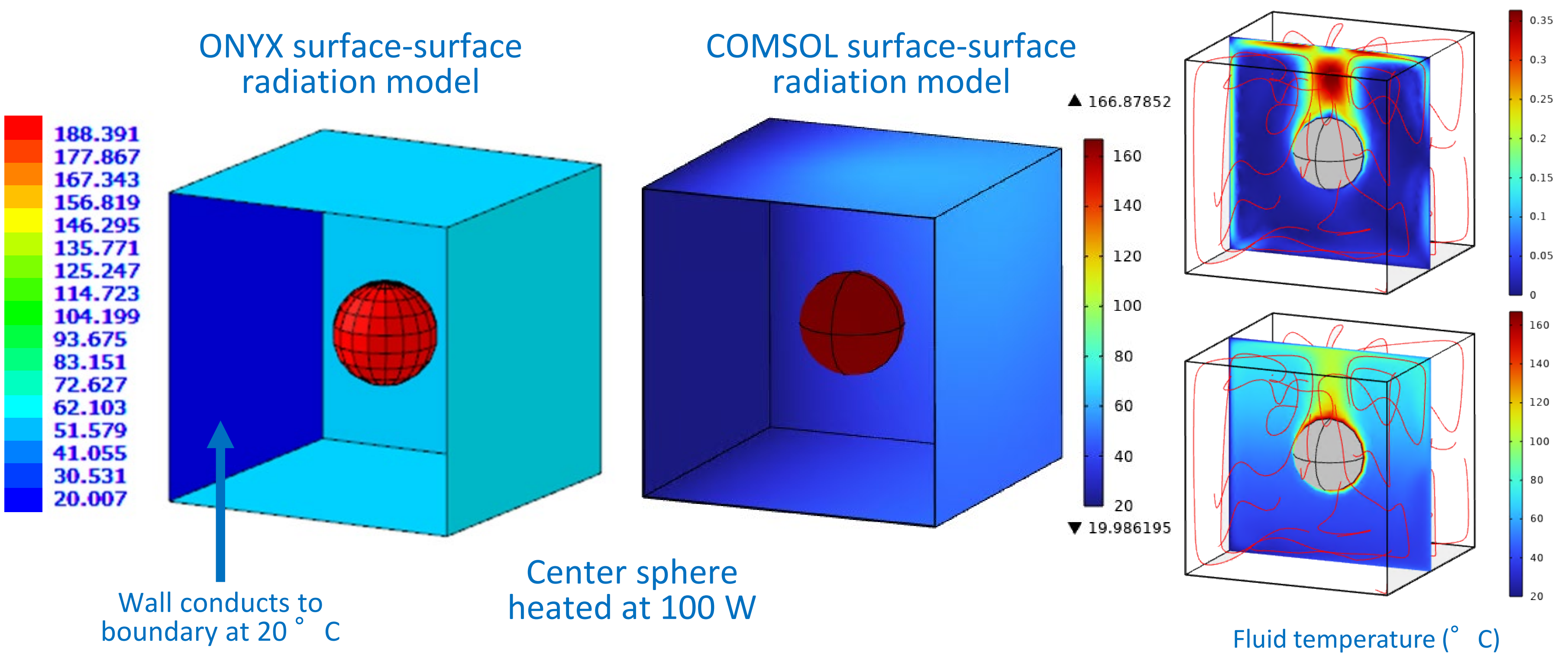
Code-Code Validation – Full Conjugate

- Baseline model with radiation from last slide
- Includes natural convection exchange between the enclosure and sphere
- Approximate the convection exchange using a *transfer node:*
  - Figure shows this node
  - Treated as an arithmetic node without capacitance
  - Both solids connect to this element
- Transfer node makes an efficient thermal connection between the inside walls of the enclosure and the surface of the sphere
- Eliminates the need for full CFD simulation to couple these components



Code-Code Validation – Full Conjugate Treatment

- ONYX and COMSOL simulation to within 22 ℃, approximately 13% based on overall temperature difference
- Some differences however note the overall CPU time
  - ONYX model constructed in minutes, solved in 9 minutes
  - COMSOL model constructed in about 30 minutes, solved in 9 hours



Summary

- ONYX software is a return to the common geometry and control volume modeling
  - Achieves efficient, fast model construction, and solution
  - Fast throughput allows expanded parametric trade space to be explored
- Validation of the ONYX tool with practical engineering problems gives confidence in this solution approach
- Development framework promotes extension of the ONYX toolset
  - Added physics
  - Solve more sophisticated problems
- Reinforces the notion that first-order solutions to many engineering problems are sufficient to support preliminary design and trade-space scoping