Thermal Radiative Modeling of Spacecraft Windows in Future Human-Rated Spacecraft

Matthew Adkins, Chris Baker and Terry Hendricks
Space Systems Development
Spacecraft Engineering
Blue Origin LLC
Kent, WA

Presented By
Matthew Adkins
madkins2@blueorigin.com

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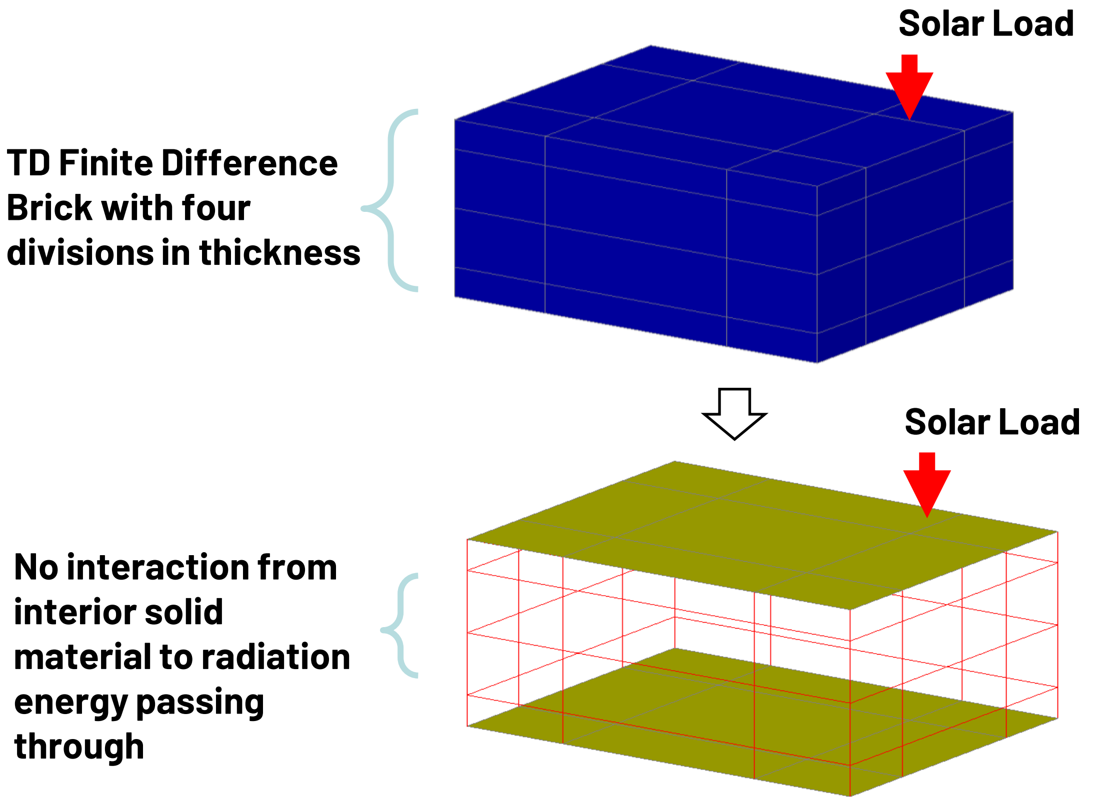
Chris Baker: cbaker3@blueorigin.com
Terry Hendricks: thendricks@blueorigin.com

Introduction

- Blue Origin has the vision for millions of people living and working in space for the betterment of Earth.
- Those folks will want to look outside back at Earth.
- Spacecraft window design for clear viewing and safety will therefore be paramount



- Window thermal analysis is key to this objective and should account for conduction and radiation absorption through the window solid materials.

Tool Process Summary

1. Optical property definition

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2. Single pane analysis by ray trace method

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3. System level analysis by net radiation method

⇩

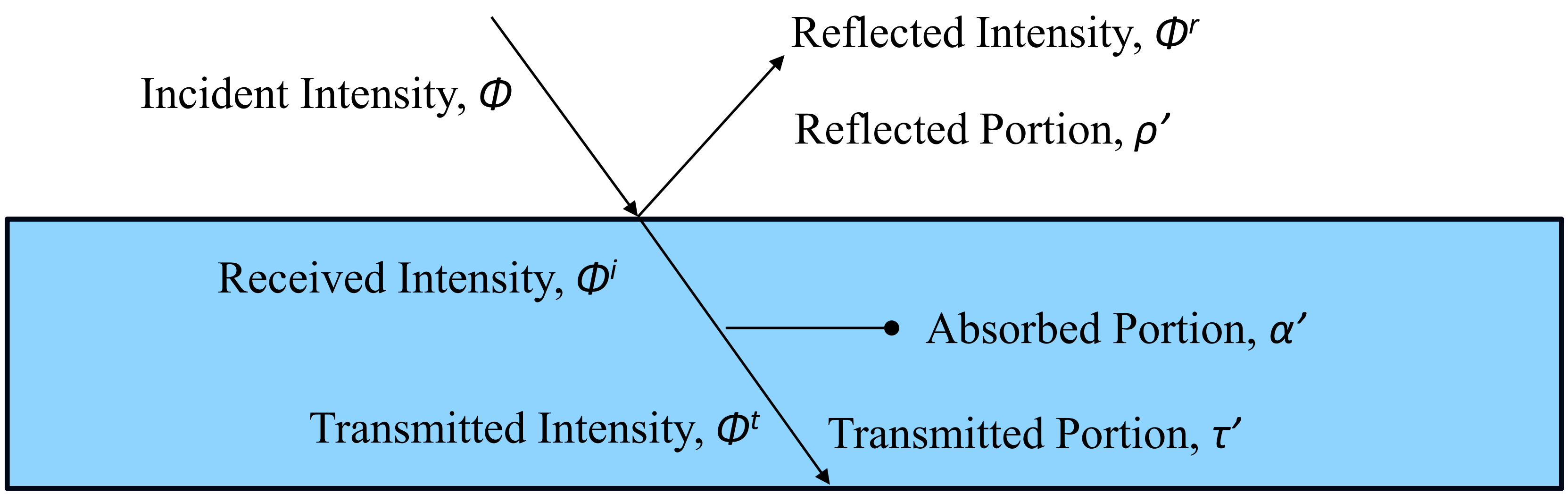
4. Solve for absorption per node within panes

⇩

5. Implement in Thermal Desktop

Optical Property Definition

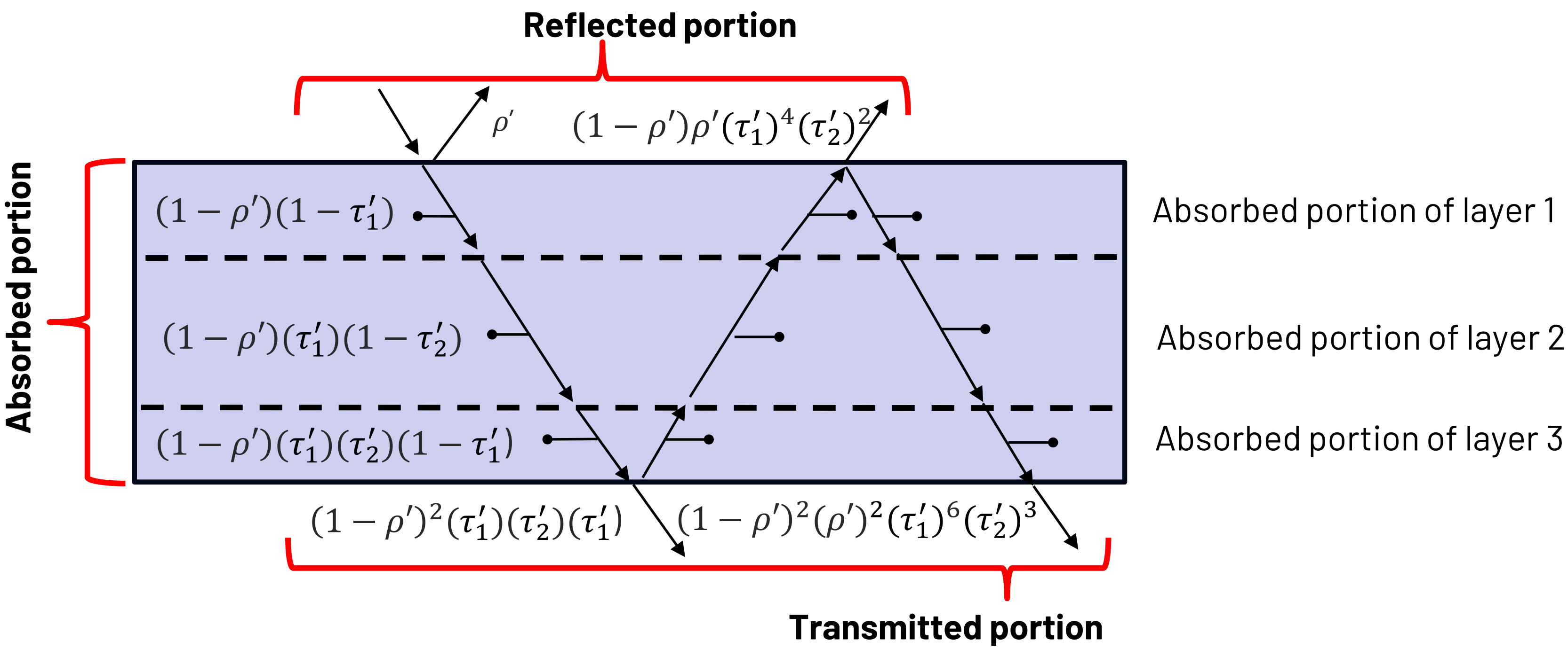
- Adjusted transmissivity, τ', and adjusted reflectivity, ρ', are the building blocks to the tool.
- Properties shown below apply to a single incident ray.
- Properties must be solved for from testing data.



- 1 **Optical Props**
- **Single Pane Analysis**
- **System Analysis**
- **Solve for Absorption**
- **TD Implementation**

- This is conducted for a wavelength spectrum band.
  - Solar spectrum band is the selected range.
  - Could easily be adapted for other wavelength bands.

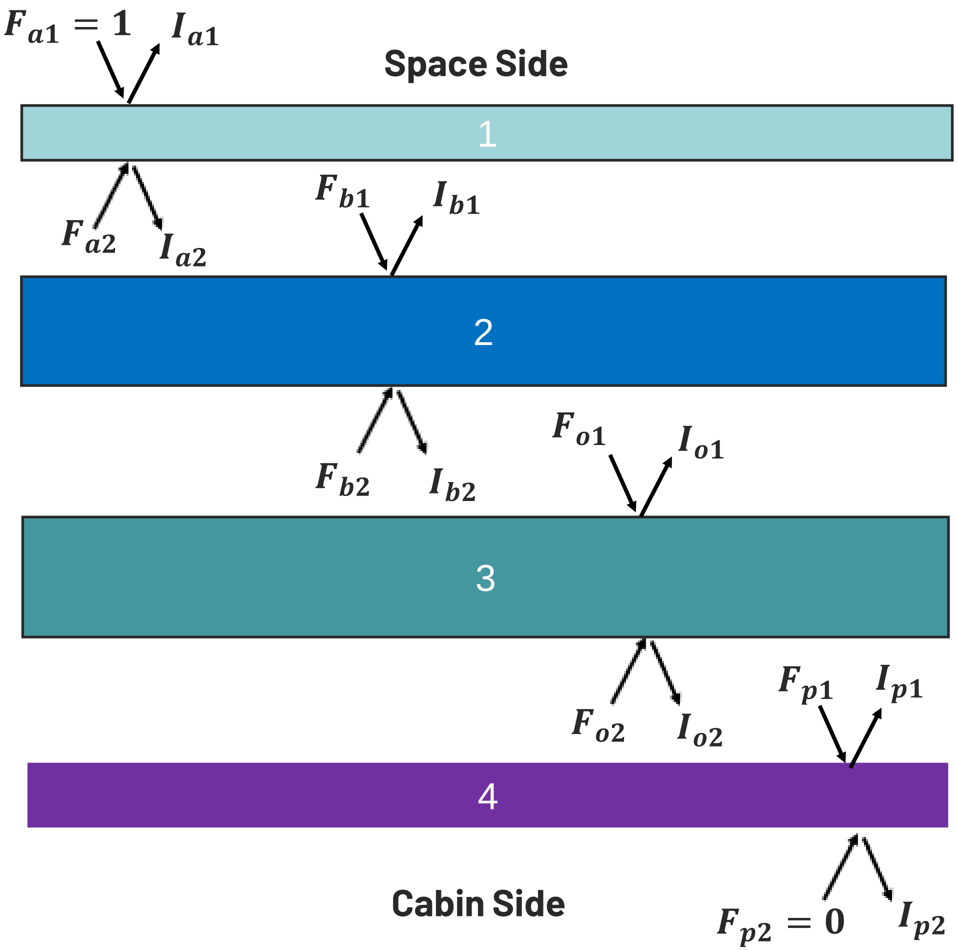
Single Pane Analysis – Ray Trace



- Number of internal divisions must match Thermal Desktop model.
- Two internal reflections is typically adequate for number of terms

System Analysis – Net Radiation

- Net radiation method mathematically ties all the panes together.
  - Equate F terms to I terms by inspection and using ray trace to fill.
  - F_{a1} is the incident sunlight.
  - Solve equations symbolically using MATLAB or preferred software.

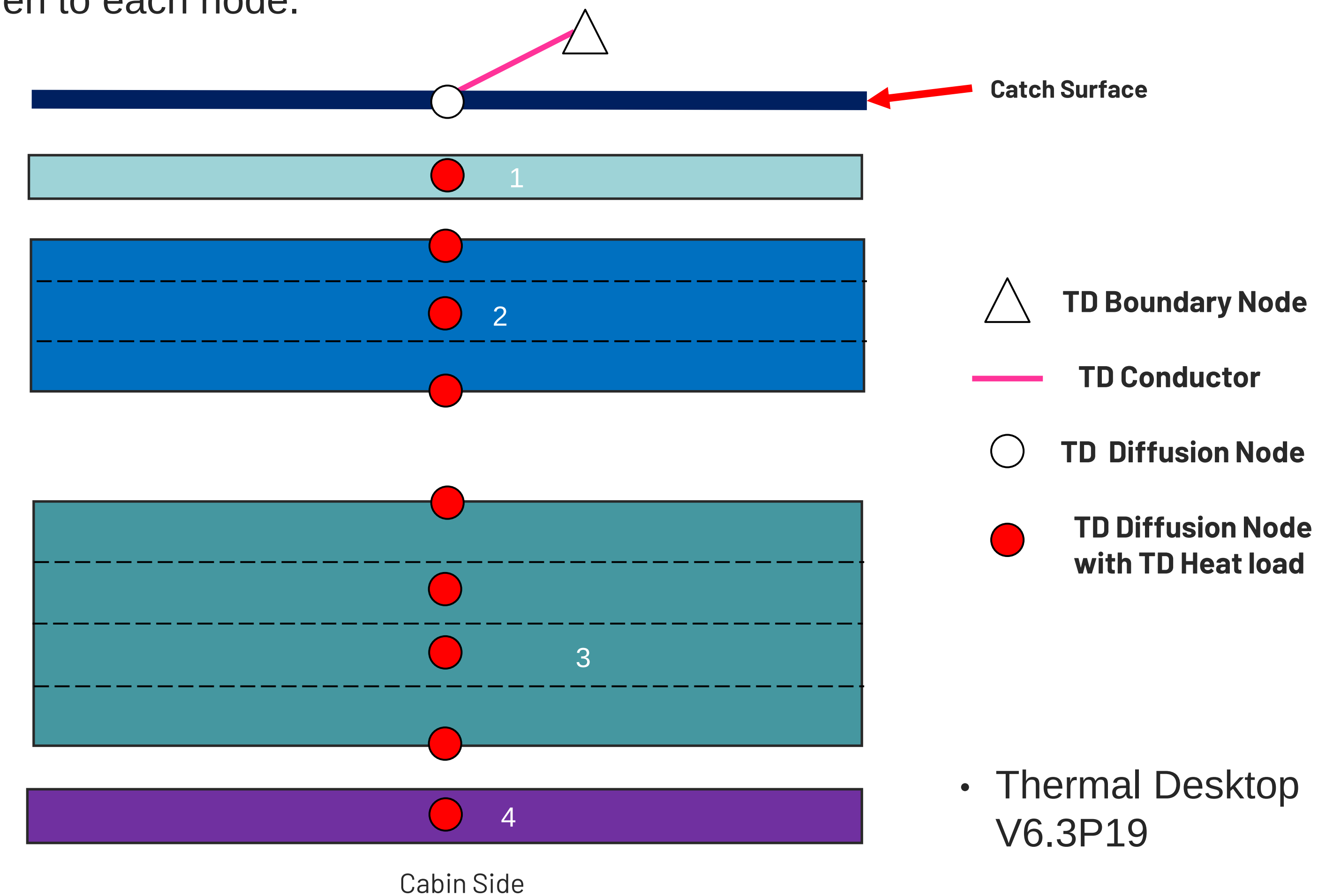


- Optical Props
- Single Pane Analysis
- 3 System Analysis
- 4 Solve for Absorption
- TD Implementation

- Net radiation ties ray trace results into the system level relations.

Thermal Desktop Implementation

- Each pane in the window is modeled as a FD brick in TD.
- Additionally, a thin shell surface dubbed "catch" surface is placed just above pane 1.
  - Calculates incoming radiation.
- Heat loads are given to each node.



- Thermal Desktop V6.3P19

- Optical Props
- Single Pane Analysis
- System Analysis
- Solve for Absorption
- 5 TD Implementation

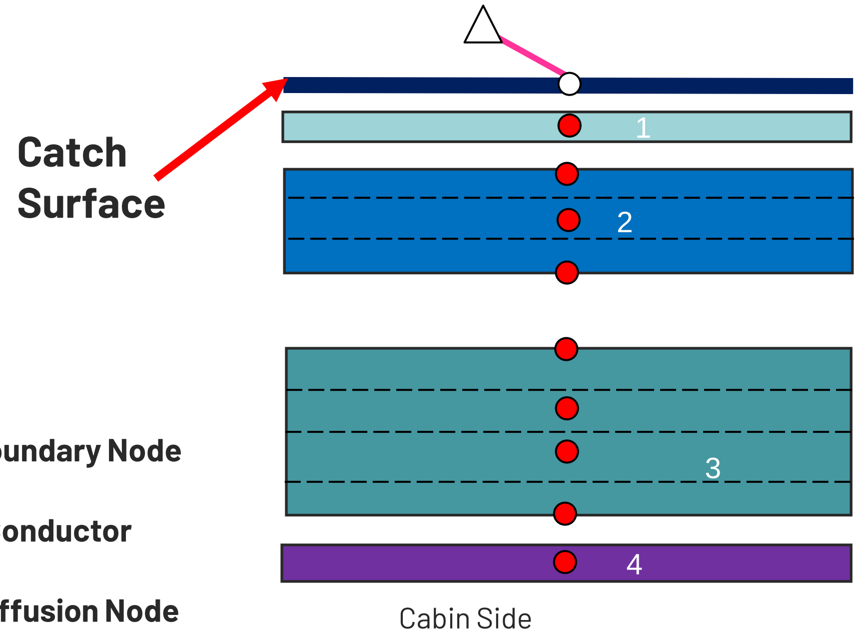
Thermal Desktop Implementation Cont.

- Heat loads are driven by a combination of the previous steps.
- TD model must match internal divisions from ray trace step.
- It is Imperative to tailor each heat load correctly.

$$Q_{per\ node} = Q_{Catch\ Surface} A_{net\ radiation}\ \beta\gamma$$

$$\beta_{ray\ trace\ ratio} = \frac{E_{layer}}{E_{total}}$$

$$\gamma_{area\ fraction} = \frac{A_{area\ per\ node}}{A_{top\ surface}}$$



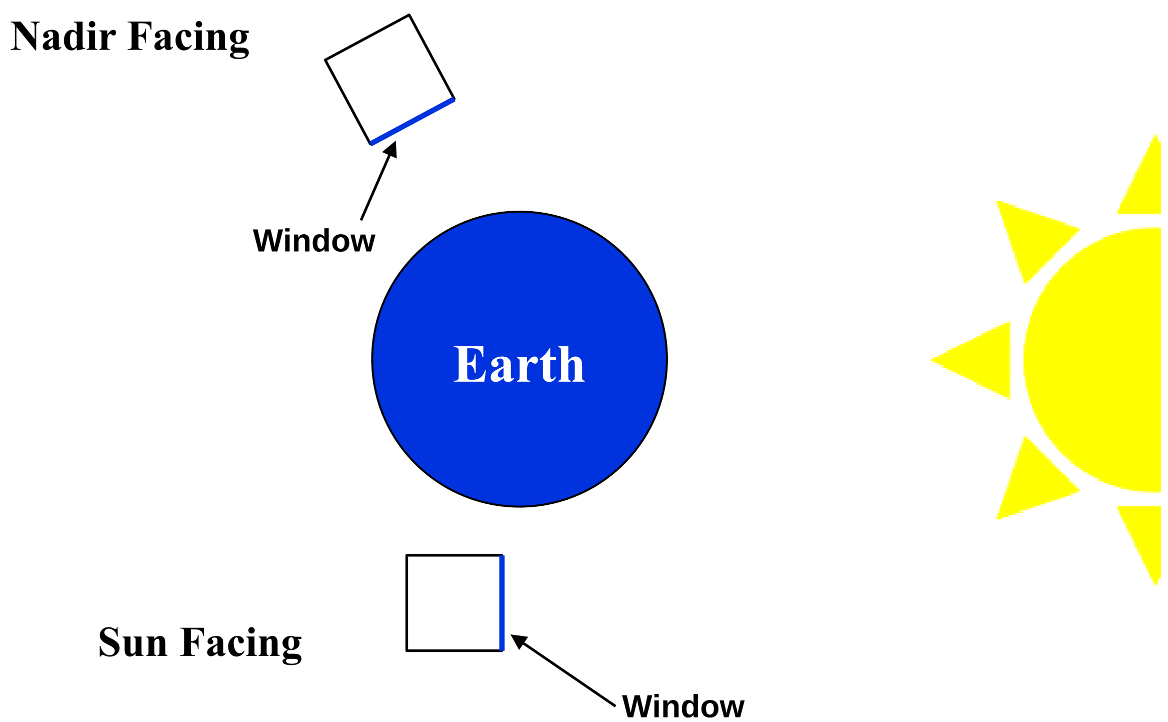
- TD Boundary Node
- TD Conductor
- TD Diffusion Node
- TD Diffusion Node with TD Heat load

- Optical Props
- Single Pane Analysis
- System Analysis
- Solve for Absorption
- 5 TD Implementation

- Must use "catch" surface to tie heat loads to TD radiation calculations.

Analysis Cases

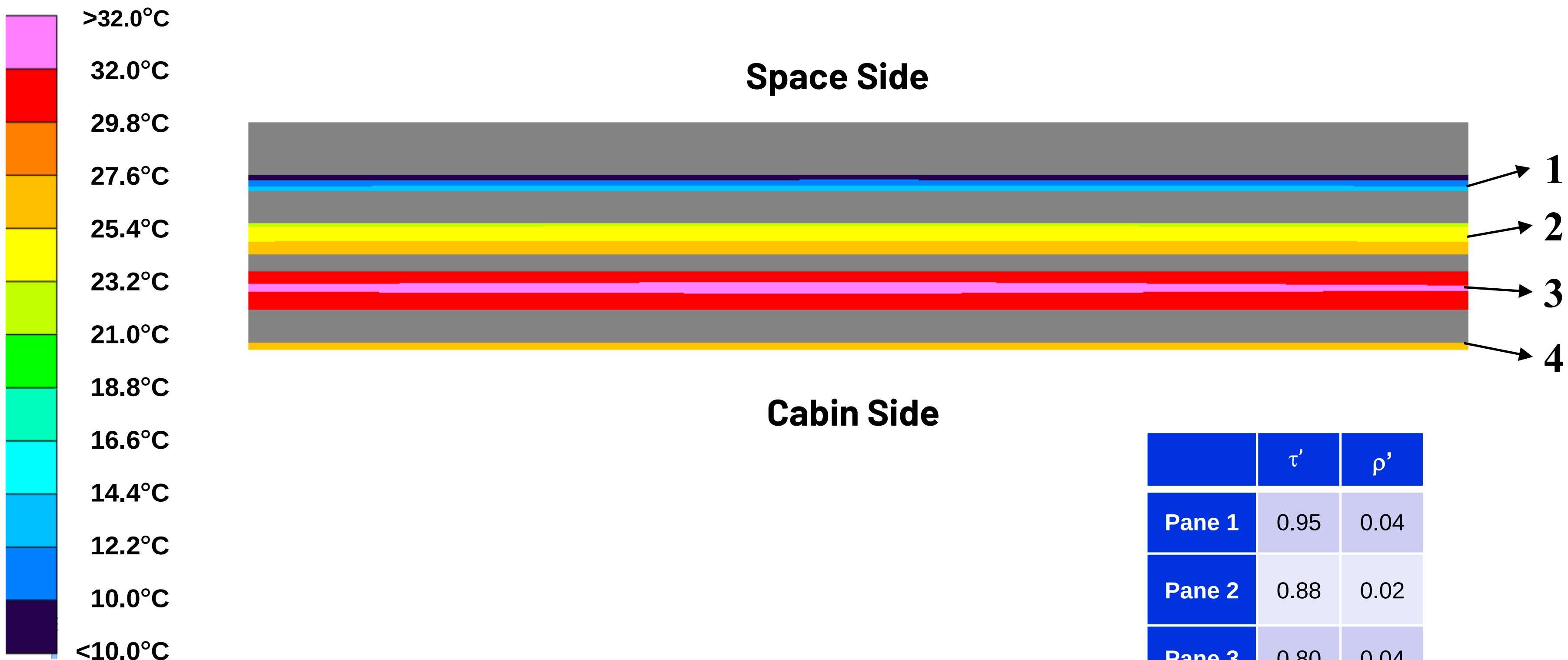
Orbit orientation for windows facing nadir and sun



- Two orientations were run for the analysis cases.
  - Each used orbital inputs similar to the ISS orbit.
  - Beta Angle: 75°

Results, Nadir Facing Window

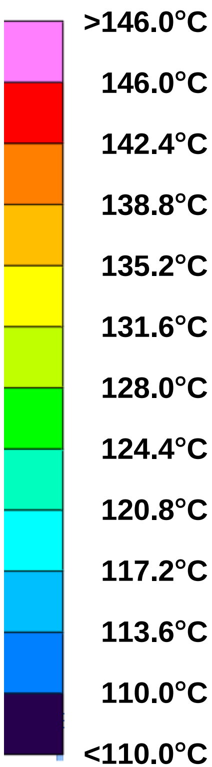
- Pane 2 and Pane 3 account for 86% of the absorbed solar energy on window.
- Inner layers of Pane 3 account for 55% of all absorbed solar energy in the window.
- Highlights the level fidelity achievable with this tool

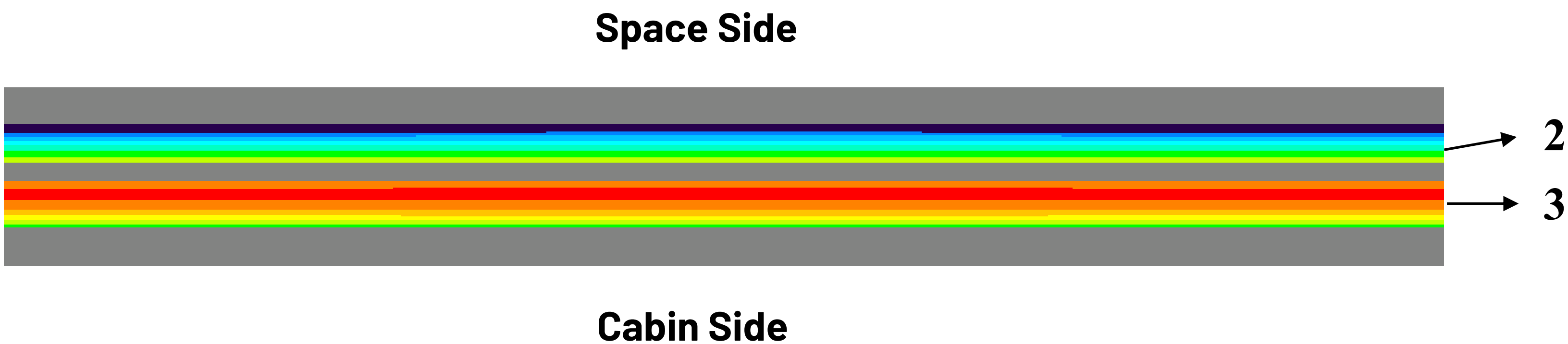


	τ'	ρ'
Pane 1	0.95	0.04
Pane 2	0.88	0.02
Pane 3	0.80	0.04
Pane 4	0.90	0.02

Results, Sun-Facing Window

- Shows a much higher temperature delta across the two panes.
- Higher temperature gradient within Pane 3.
- Shows importance of having high transparency on all windowpanes.





	τ’	ρ’
Pane 1	0.95	0.04
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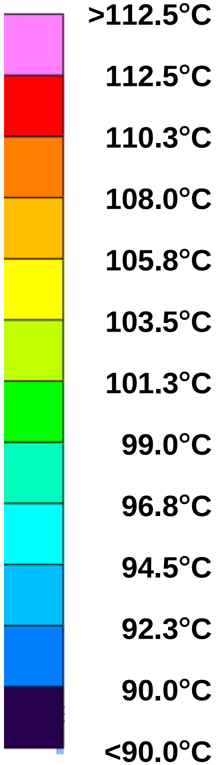
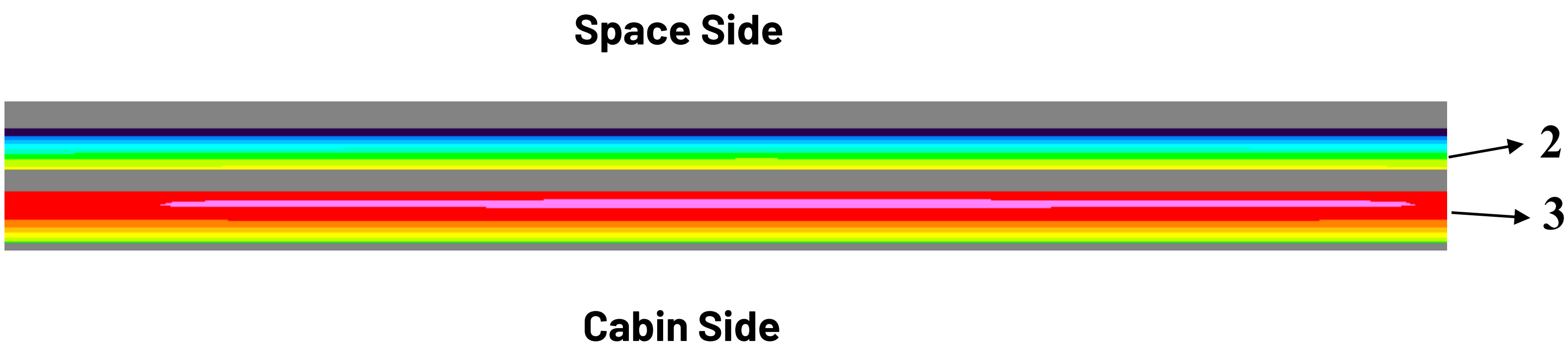
Results, Adjusted τ'

- Increasing τ' by 0.08 to .88 for pane 3 decreases all temperatures significantly
  - Max temperature decreased by 33° C
  - Internal hot spot still identified that would otherwise be unseen without tool
  - Emphasizes and quantifies the critical importance of temperature sensitivities to τ' and ultimate spacecraft window material selection





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Conclusion

- We developed a high-fidelity window radiative analysis tool to support rapid window thermal analysis.
- It provides a deep insight into the wavelength-dependent radiation and material interaction through the thickness of material.
  - Using native TD tools would not provide this capability.
  - Teases out temperature gradients that would otherwise be unseen.
  - Can be applied across various wavelength ranges to understand window design impacts across full wavelength spectrum
- Delivers results to drive window design changes.
- Results will help develop and refine CONOPS of vehicles.
- Thermal testing must still be done to validate assumptions and analytic results.

Acknowledgements

- Thank you to Drew Smallwood at Blue Origin for his vast experience on spacecraft windows and guidance he provided.

Questions?