THERMAL RADIATIVE MODELING OF SPACECRAFT WINDOWS IN FUTURE HUMAN-RATED SPACECRAFT

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ABSTRACT

Windows for spaceflight pose a unique thermal analysis challenge due to their transparency. In formulating the analysis in Thermal Desktop, we found additional use of external and native Thermal Desktop tools were required to model solar energy absorption throughout the bulk of an optically thick, multi-layer window. This paper discusses the development and application of these tools. Using a ray tracing method, a set of self-consistent, energy-conserving radiative heat transfer equations between adjacent window layers were developed to calculate the absorbed energy from albedo and direct solar flux. The equations were expanded for multiple panes such that the absorbed energy through the thickness of the window assembly can be calculated in a MATLAB script. MATLAB script outputs are implemented in conjunction with Thermal Desktop symbols and heat loads to complete the tool. Blue Origin developed this tool to support rapid, high-fidelity thermal analysis and design of windows in the space environment.

NOMENCLATURE, ACRONYMS, ABBREVIATIONS

α Absorptivity (averaged over wavelength band)

β Fraction of Energy

ε Emissivity (IR Spectrum) (averaged over wavelength band)

γ Fraction of area

ρ Reflectivity (averaged over wavelength band)

ρ' Adjusted Reflectivity (averaged over wavelength band)

τ Transmissivity (averaged over wavelength band)

τ' Adjusted Transmissivity (averaged over wavelength band)

μ Attenuation Coefficient [1/m]

ϕ Incident Radiative Intensity (W/m^2) (averaged over wavelength band)

$\boldsymbol{\phi}^{\text{i}}$ Received Radiative Intensity (W/m²) (averaged over wavelength band)

$\boldsymbol{\phi}^{\text{r}}$ Reflected Radiative Intensity (W/m²) (averaged over wavelength band)

$\boldsymbol{\phi}^{\text{t}}$ Transmitted Radiative Intensity (W/m²) (averaged over wavelength band)

A_{pane} Fraction of absorbed energy

A_{area} Surface Area

CONOPS - Concept of operations

E   Energy Absorbed

FD   Finite Difference

ISS   International Space Station

LEO   Low Earth Orbit

Q   Heat Load (W)

R_{pane} Fraction of reflected energy

T_{pane} Fraction of transmitted energy

TD   Thermal Desktop

INTRODUCTION

The view of Earth through the ISS windows is breathtaking. One challenge in thermal analysis of spacecraft windows is accurately calculating radiative heat transfer among several transparent panes. This paper will focus on the radiative analysis method developed at Blue Origin for a full window thermal analysis and provide an example. Analysis is discussed in three segments: (1) optical properties for transparent materials, (2) ray tracing and net radiation methods from *Thermal Radiation Heat Transfer*[1], and (3) integration of the analysis tools with Thermal Desktop (TD).

The use of external and additional native TD tools arose from needing to account for heat absorption and conduction through a radiative transparent energy-absorbing solid. TD treats a finite-difference (FD) brick as a hollow box with interior and exterior surfaces. The interior and exterior surfaces must have assigned properties and all surfaces must be in the same analysis group. This results in all energy absorption occurring at the surfaces. In Figure 1Figure 1Figure 1, FD brick 1 is discretized into two layers in the thickness. The thermal conduction and energy absorption will be captured accurately in TD because the discretized layers are adjacent to the surfaces. For FD brick 2 in Figure 1Figure 1Figure 1, which has identical properties to brick 1 but is thicker, TD will not accurately capture the energy absorption in the three middle layers

because the radiation interactions occur only at the surfaces. This work describes a technical approach and technique to properly account for these radiative energy absorptions within the TD environment and analysis structure.
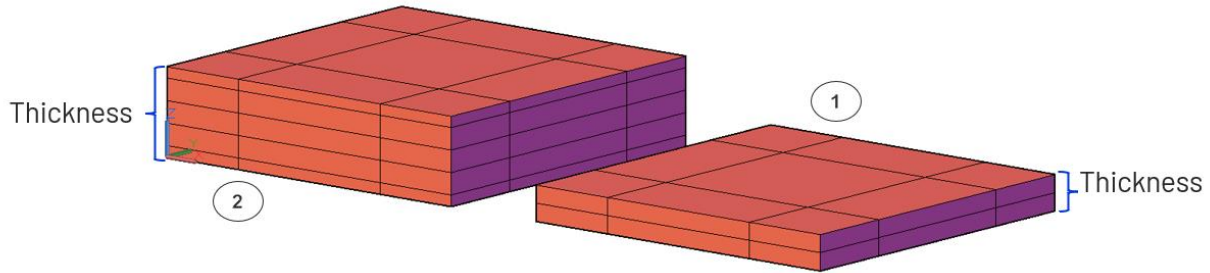

Figure 1. Two TD FD bricks that require different methods of analysis.

OPTICAL PROPERTIES OF TRANSPARENTS SOLIDS

Figure 2 provides a visualization of a single ray's interactions with optical properties inside a transparent solid. Transmissivity adjusted for received intensity, that is not reflected internally, will be referenced as τ' as seen in Figure 2 as well. Using the Beer Lambert law in equation (1)(1)(1), τ'_1 for material thickness l_1 can be used to solve for μ, the attenuation coefficient intrinsic to all materials. Figure 2 also provides context to the received intensity versus the incident intensity regarding τ'. Using μ and equation (1),τ'_1 and τ'_2 equations can be used and manipulated to arrive at τ'_2 in equation (2)(2)(2). τ' is imperative for the use of Howell's ray tracing method discussed in the next section[1]. Reflectivity, ρ', the fraction of reflected incident intensity without internal reflections will be needed.

$$\tau'_1 = \frac{\emptyset^t}{\emptyset^i} = e^{-\mu l_1} \tag{1}$$
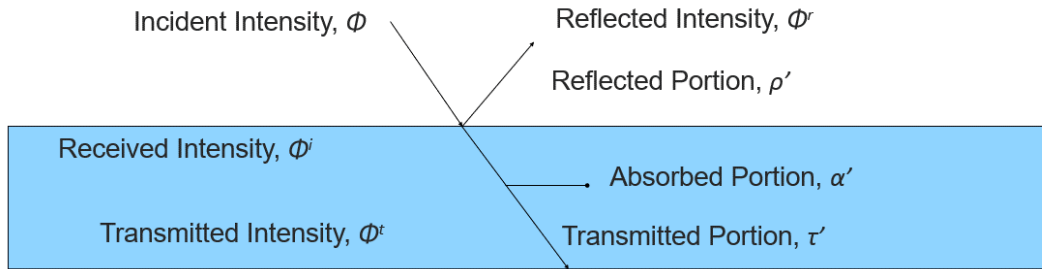
$$\tau'_2 = \tau'^{\frac{l_2}{l_1}}_1 \tag{2}$$

Figure 2. Visual representation of optical properties from a single ray.

Table 1. Optical property variables

τ	Tau is transmittance, classically defined as the amount of transmitted light through a material accounting for internal reflections of a real surface
τ'	Tau prime is the portion of received intensity that is transmitted through the bulk of the material prior to any internal reflections. τ' cannot be measured directly and must be solved from test data
α'	Alpha prime is the portion of received intensity that is absorbed through the bulk of the material prior to any internal reflections
ρ'	Rho is the reflected portion of incident intensity prior to any internal reflections
μ	Attenuation coefficient through bulk material thickness.
ϕ	Incident intensity is the impinging energy load on the surface of the solid prior to reflections
ϕ^i	Received intensity is the energy load that is not reflected off the surface prior and prior to internal reflections
ϕ^t	Transmitted intensity is the intensity that is neither reflected nor absorbed prior to internal reflections

RAY TRACING AND NET RADIATION METHOD

Reference 2 provides two methods, ray trace and net radiation, for analyzing radiation exchange between transparent panes[1]. Each is used in different parts of the analysis.

Figure 3 diagrams the ray trace method which follows one ray as it interacts with the surfaces and bulk of the material. An interaction is when the ray reflects, is absorbed, or transmitted through bulk material or surfaces resulting in additional mathematical terms to each portion of energy. This is conducted with properties averaged across the solar heating wavelength band but

this methodology can be applied to wavelength dependent properties. The resultant portion of absorbed, transmitted, and reflected energy differ from previous mentioned properties as they account for internal reflections of an individual pane. Internal discretization, seen in Figure 3 ray trace, is a critical step to ensuring end-to-end tool fidelity matches analysis needs.

The right-hand side of Figure 3 diagrams the net radiation method for two flat panes. Following Howell, Menguc, and Siegel[1] steps, equations $(3)\cancel{(3)}\cancel{(3)}$, $(4)\cancel{(4)}\cancel{(4)}$, $(5)\cancel{(5)}\cancel{(5)}$, and $(6)\cancel{(6)}\cancel{(6)}$ are the mathematical relations between panes using portions of transmitted and reflected energy from the ray trace. Equations $(7)\cancel{(7)}\cancel{(7)}$, $(8)\cancel{(8)}\cancel{(8)}$, and $(9)\cancel{(9)}\cancel{(9)}$ are simplifying relations. Using the equations $(3)\cancel{(3)}\cancel{(3)}$ through $(9)\cancel{(9)}\cancel{(9)}$, they are rearranged to arrive at $(10)\cancel{(10)}\cancel{(10)}$ through $(13)\cancel{(13)}\cancel{(13)}$ which are solved to arrive at portions of reflected, transmitted and absorbed energy for a window.
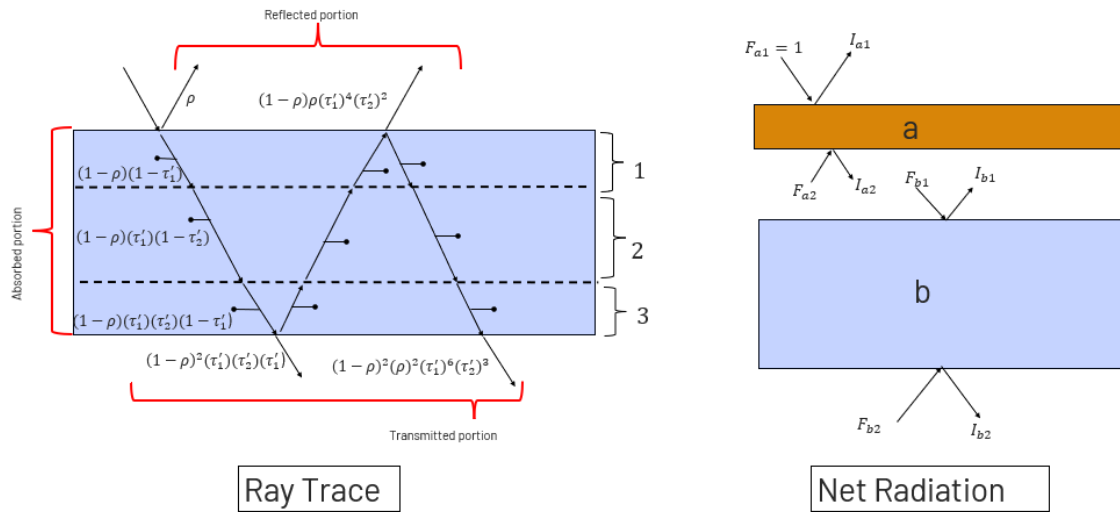

Figure 3. Diagrams of ray trace and net radiation analysis methods

$$I_{a1} = R_a + F_{a2}T_a \tag{3}$$

$$I_{a2} = F_{a2}R_a + T_a \tag{4}$$

$$I_{b1} = F_{b1}R_b \tag{5}$$

$$I_{b2} = F_{b1}T_b \tag{6}$$

$$F_{a2} = I_{b1} \tag{7}$$

$$F_{b1} = I_{a2} \tag{8}$$

$$F_{b2} = 0 \tag{9}$$

$$I_{a1} = R_a + \frac{R_b T_a^2}{1 - R_a R_b} \tag{10}$$

$$I_{b2} = \frac{T_a T_b}{1 - R_a R_b} \tag{11}$$

$$A_a^{(a+b)} = A_a + G_{a2} A_a \tag{12}$$

$$A_b^{(a+b)} = G_{b1} A_b \tag{13}$$

APPLICATION

A combination of ray tracing and net radiation methods is leveraged to provide a high-fidelity model of both transmission through the assembly and heat absorbed throughout the thickness of each pane. Figure 4 shows the block diagram of the windowpane stack up and Table 1 shows the associated material thermal properties required in the analysis.

The ray trace analysis, done in a MATLAB script, tabulates each pane's portion of radiative energy reflected, transmitted, and absorbed. The ray trace process previously described will calculate each discretized layer absorption. Next, adapt the net radiation method from two panes to 4 panes to develop the system level interactions. Expanding the net radiation diagram to 4 panes, seen in Figure 5, drives the mathematical relations for the window seen in equations (14)(14)(14) through (21)(21)(18). After solving for *I* terms (perhaps with the symbolic solver in MATLAB), the results can be implemented into TD to complete the tool set up.
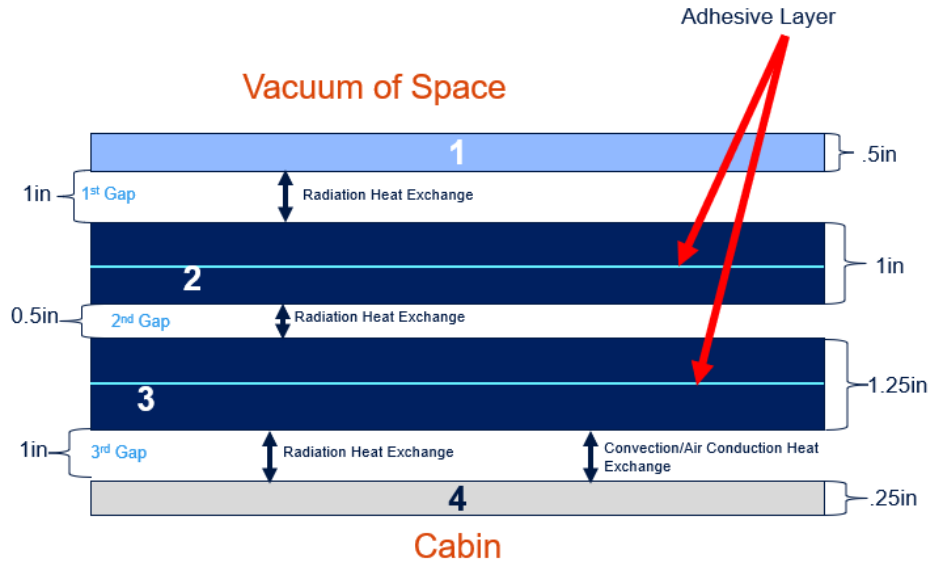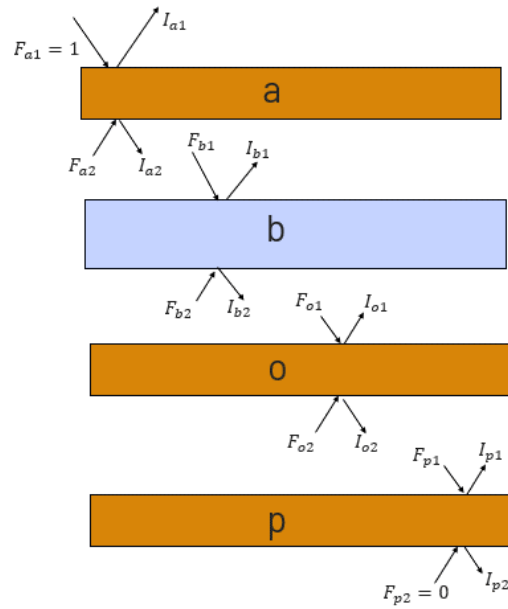
Figure 4. Diagram of example window assembly

Figure 5. Net radiation diagram for window system

$$I_{a1} = R_a + F_{a2}T_a \tag{14}$$

$$I_{a2} = F_{a2}R_a + F_{a1}T_a \tag{15}$$

$$I_{b1} = F_{b1}R_b + F_{b2}T_b \tag{16}$$

$$I_{b2} = F_{b2}R_b + F_{b1}T_b \tag{17}$$

$$I_{o1} = F_{o1}R_o + F_{o2}T_o \tag{18}$$

$$I_{o2} = F_{o2}R_o + F_{o1}T_o \tag{19}$$

$$I_{p1} = F_{p1}R_p \tag{20}$$

$$I_{p2} = F_{p1}T_p \tag{21}$$

Table 2. Thermal Properties

	Thermal Conductivity (W/m/C)	Specific Heat (J/kg/C)	Density (kg/m^3)	τ'	ρ'	ε (IR spectrum)	n (refractive index)
Pane 1	0.1	1200	1200	0.95	0.04	0.96	1.49
Pane 2	0.2	1200	1200	0.88	0.02	0.96	1.49
Pane 3	0.2	1200	1200	0.80	0.04	0.96	1.49
Pane 4	0.4	1200	1200	0.90	0.02	0.96	1.49

THERMAL DESKTOP IMPLEMENTATION

Step one in TD implementation of this analytic technique is to calculate the total amount of sunlight striking the window assembly. This is done with a "catch" surface, which is a 1 node perfectly absorbing thin shell object just outside the window exterior (shown in navy blue in Figure 5). The "catch" surface only participates in TD solar spectrum radiation heat transfer and is transparent for far infrared radiation heat exchange ($\lambda \geq 2.6$ μm). For this paper, we assume the solar heating spectrum to include 0.25 μm to 2.6 μm. The nodal heat load (SUBMODEL.Q syntax) then represents the solar energy striking the window. The "catch" surface needs a conductor to a boundary node so steady-state solutions will converge. The subsequent TD FD brick windowpanes only participate in the far IR spectrum. Solar spectrum heating is achieved through individual TD heat loads on TD brick nodes. Each TD pane must have the same discretization as used in the ray tracing MATLAB script to effectively capture internal material heating.

Implementing the absorbed heat per node is done through symbol expressions. Equation (22)(22)(22),(23)(23)(23) and (24)(24)(24) shows a generic heat load expression using ray trace and net radiation results that can apply to each TD heat load. Figure 6 depicts the window thermal model with applied heat loads.

$$\beta_{ray\ trace\ layer} = \frac{E_{ray\ trace\ absorbed\ per\ layer}}{E_{ray\ trace\ total\ absorbed}} \tag{22}$$

$$\gamma_{area\ fraction} = \frac{A_{area\ per\ node}}{A_{area\ of\ TD\ brick\ space\ facing\ surface}} \tag{23}$$

$$Q_{per\ node} = Q_{Catch\ Surface} A_{net\ radiaiton\ per\ pane} \beta_{ray\ trace\ layer} \gamma_{area\ fraction} \tag{24}$$

This analysis uses ISS altitude, 420 km, and inclination angle, 51.6°, for orbital input. The corresponding planet shine (287 W/m^2), solar (1422 W/m^2) and albedo (0.4) values are taken from *Spacecraft Thermal Control Handbook*[2].Window optical radiative properties and window thermal properties are taken from Table 2. The cabin side of pane 4 was given convection with a constant 4.25 W/m^2 °C heat transfer coefficient as an approximation resulting from internal cabin flow. The gap between pane 3 and pane 4 has a TD contactor thermal conductance through air for heat transfer in that pressurized section.

The example analysis uses a beta angle of 75° for two orbital configurations. The first orients the spacecraft windows nadir to replicate a nominal window environment. The next always has the windows oriented normal to the sun to represent a worst-case hot environment.
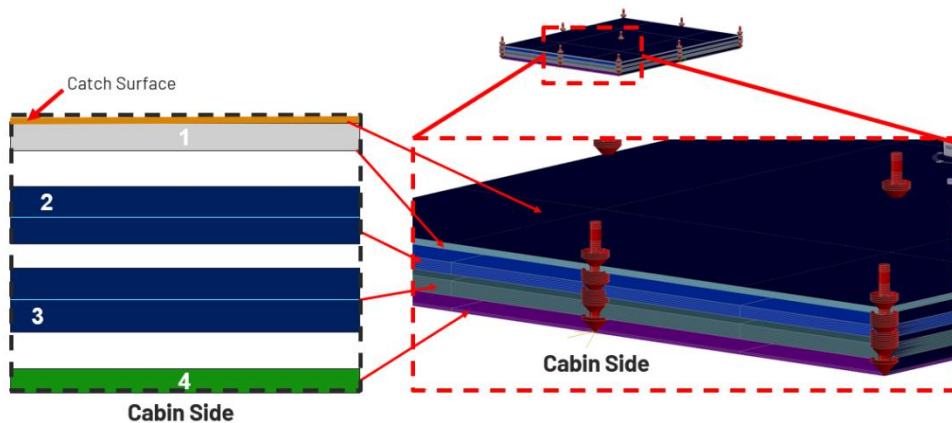
Figure 6. Diagram of the tool implementation into TD.

RESULTS

Figure 7 shows the temperature map of the window assembly during normal spacecraft operations. Figure 8 and Figure 9 show the temperature map of the two innermost panes. The window assembly is subject to the greenhouse effect where peak temperatures are found in the inner two panes. The two inner panes (panes 2 and 3 in Figure 6) account for 86% of absorbed energy. Additionally, the inner layers of pane 3 account for 55% of all absorbed solar energy in the window with the peak temperature within these layers. A combination of thermal resistance and solar absorptance through the thickness of the material results in this greenhouse effect. Figure 8 and Figure 9 highlight the gradient in pane 3 where the interior material is hotter than the exterior surfaces. These figures show high window temperatures are possible from greenhouse effects and require judicious selection of window material and optical radiative properties in the design process. Without this tool, the internal temperature gradients would otherwise be unaccounted for in the design process. The worst-case hot environment demonstrates the importance of highly transparent optical properties in the visible spectrum if sunlight will be directly incident on the window. Ultimately, these results can be used during window design and influence vehicle CONOPS to protect the window. The tool discussed throughout this paper made it possible to highlight and quantify this greenhouse phenomena through the bulk of the material and can be integrated into the vehicle CONOPS design and specifications development.
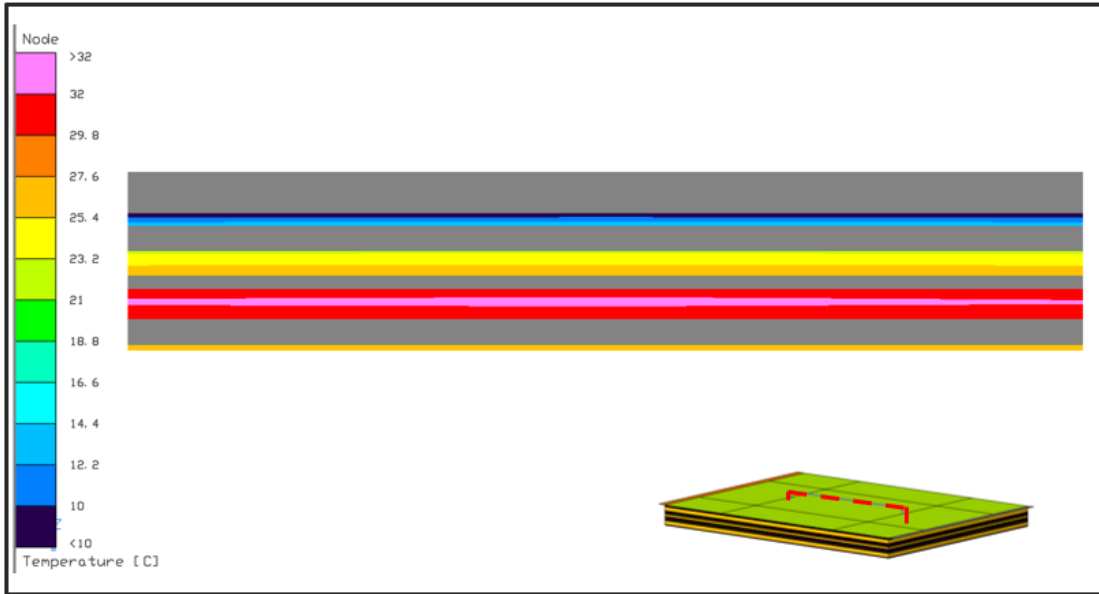
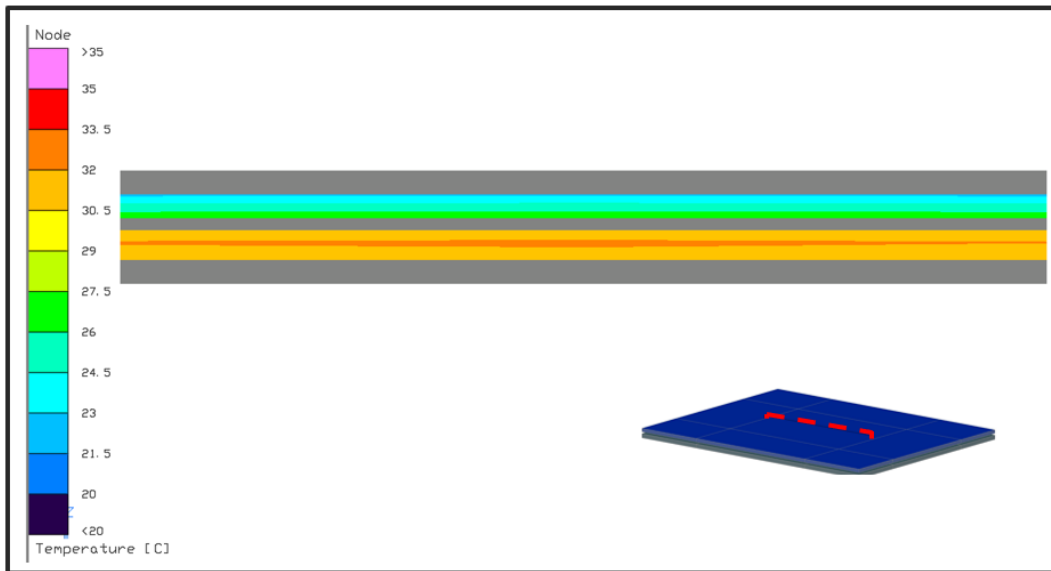**Figure 7. Normal Operations gradients within the window system.**

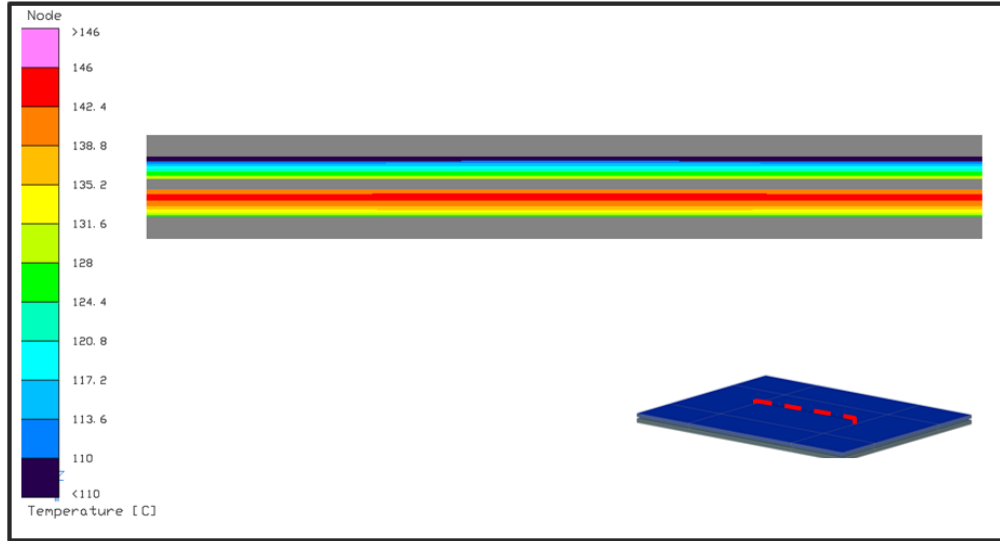**Figure 8. Normal operations steady state gradient on the two inner most panes.**

Figure 9. Worst-case hot environment temperature predictions for the two inner panes.

CONCLUSIONS

This paper presented a method to predict temperatures in a window assembly using Thermal Desktop. The method is able to capture internal heat absorption in the bulk of the windowpanes, whereas a direct application of Thermal Desktop's transmissive material modeling only generates heat at the outer surface of the panes. The methodology can be extended for different numbers of panes using different materials and properties. This tool teases out unexpected gradients through the interior of the material that are otherwise unaccounted for in a direct application of Thermal Desktop's transmissive material modeling. Without this tool, design changes would be implemented without full consideration of the window thermal environment. This tool's impact is not limited to window design changes and optimization but will also provide key inputs to CONOPS design and specifications to protect the window from maximum and minimum temperature exceedances.

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REFERENCES

1.) Howell, J., Menguc, M., & Siegel, R. (2018). *Thermal Radiation Heat Transfer.* dddd: CRC Press.

2.) Gilmore, D. (2002). *Spacecraft Thermal Control Handbook.* El Segundo: The Aerospace Press.