



SPACECRAFT WINDOW DESIGN FROM A THERMAL PERSPECTIVE

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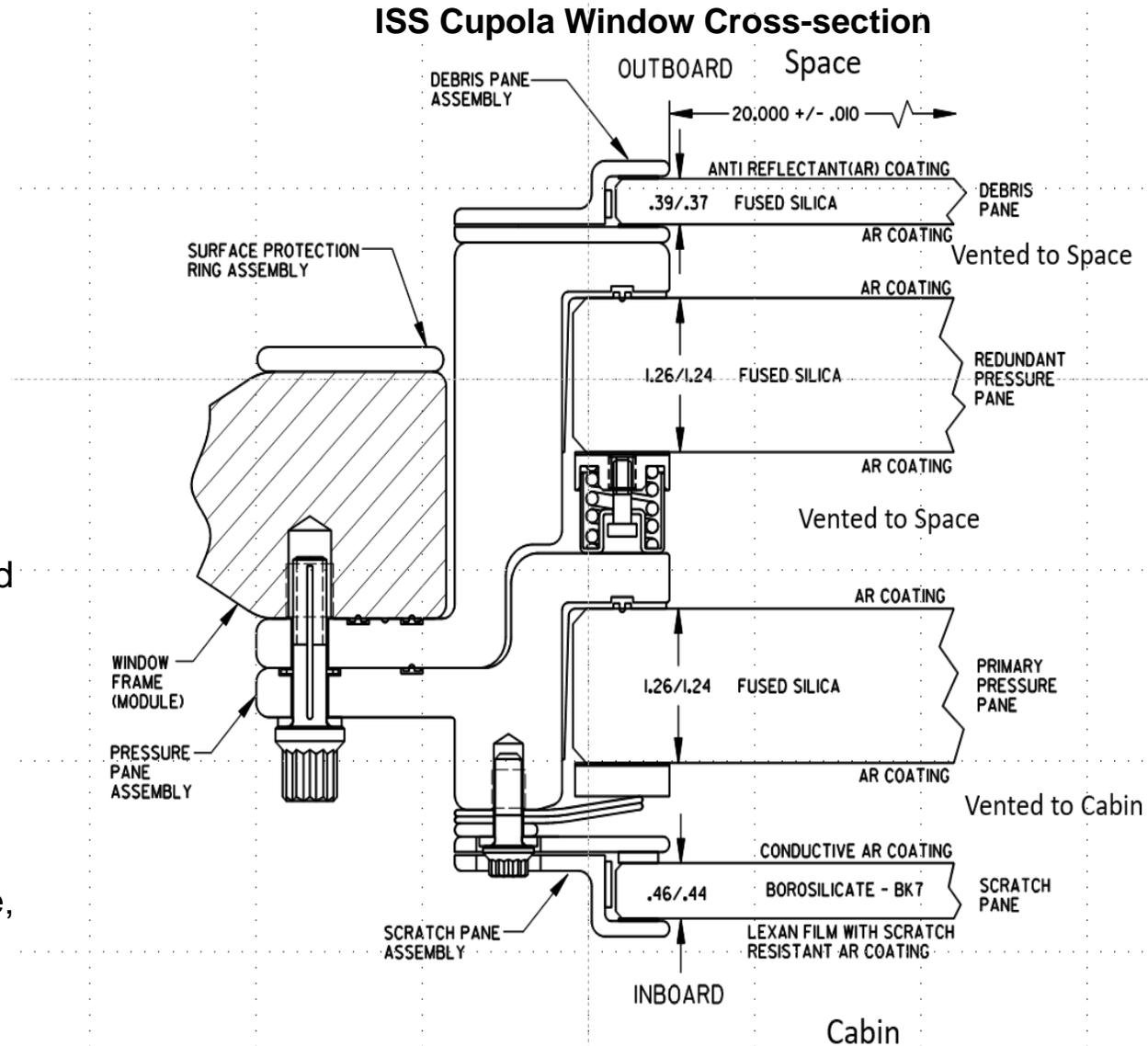
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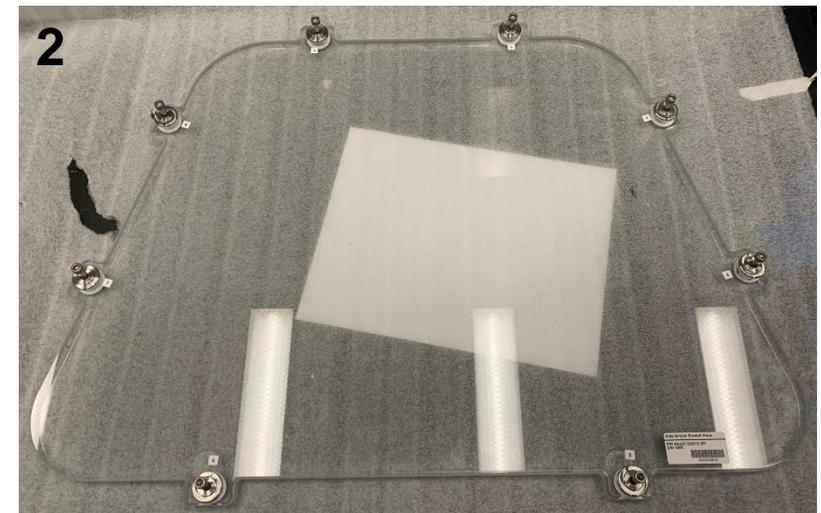
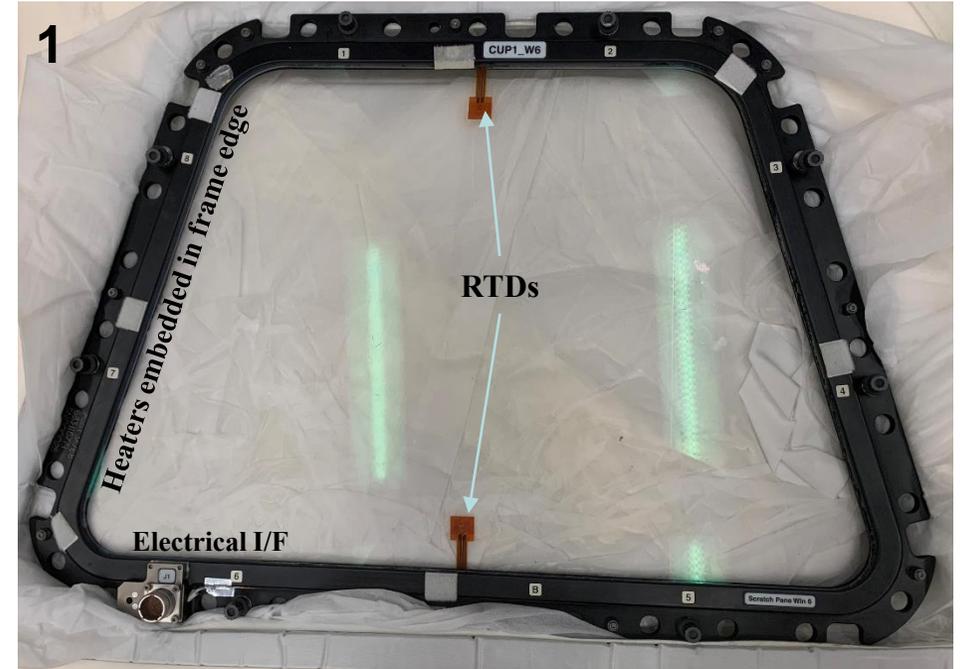
- Windows have been integral to every crewed NASA spacecraft
 - ISS Cupola
 - Pics to the right
 - Largest windows flown to date!
 - Navigation and photography for Shuttle, Apollo, Orion
- Thermal Considerations
 - Integration with Structure and Materials
 - Panes transmit thermal radiation in/out
 - Thermal protection system
 - Condensation control
 - Modeling and testing are necessary but tricky given nature of materials



- A window is an assembly
 - Provides through-the-wall viewing
 - Consists of frames, retainers, seals, cushions, vents, bolts, and several panes - aka “Window Stack” {ISS}.
 - Filler between panes (vented? fill gas?)
 - Panes should never be subject to structural stress.
- Pane Functions and Duties
 - Outer Panes
 - Prevent damage to inner panes
 - Withstand small impacts from debris and meteoroids and extreme aero-heating during atmospheric re-entry
 - ISS outermost “debris pane” is removeable/replaceable
 - Inner “Pressure” Panes
 - Pressure-vessel boundary, contains atmosphere
 - Shuttle – double paned with dry, inert fill gas for redundancy, structure
 - ISS innermost “scratch pane” is removeable/replaceable, protects pressure pane, heater (to control condensate)



- **Pics of ISS Scratch Panes to right**
 - FLOWN! old glass style with scratches, RTD's, heaters, electrical I/F, InSn coating {green}
 - New acrylic pane
- **Pane Core Material**
 - **Brittle Materials – Glass Ceramics – Silica, Aluminosilicate, Borosilicate**
 - NASA Usage – Shuttle windshields, Orion's outermost panes, all panes in Apollo, ISS cupola
 - Good: Best optics, compatibility, and thermal protection
 - Bad: Brittle – no non-destructible means of determining actual strength, no radiation shielding, heavy compared to ductile materials
 - **Ductile Materials – Plastics - Acrylics and Polycarbonates**
 - NASA Usage – Orion's innermost panes, Shuttle payload bay windows
 - Good: Cheaper to manufacture, better structural properties and lighter than glass; optics are decent
 - Bad: no established industry material property data, can be sensitive to environmental factors (radiation, atomic oxygen, UV) causing degradation such as yellowing, sometimes flammable, and has the potential for creep.
- **Pane Coatings**
 - Thin barrier on pane core material surface, improves windowpane performance in
 - Optics, Durability, Crew Safety, Pane Compatibility
 - Examples:
 - Light-filtering (Anti-Reflective, Polarizing, UV reducing), Anti-scratch, and even Heating
 - How coatings are applied:
 - Plastic: vapor deposition, chemical coating, or other surface treatment processes
 - Glass: a very thin sheet of plastic vacuum sealed onto the pane material
 - Not the end-all be-all though – must consider the system as a whole
 - Compatibility issues, manufacturers' secrets, UV degradation, complicate analysis and testing
 - Orbiter had a red reflector (RR) coating found to detrimentally affect the strength of the glass, causing a late design change that placed it on the internal side of the cabin





Thermal Functions and Issues



- Part of assembly
 - Holistically consider thermal contraction and response to hot/cold in all materials
 - Touch temperature considerations.
- Transmit thermal radiation in visible and near-infrared ranges by design
 - Into the Spacecraft – from the sun, planetary bodies, or other vehicles.
 - From the Spacecraft – heat leak to space during cold operations, can cause condensation
 - Condensation forms on a surface if its temperature is lower than the dewpoint of the air around it.
 - Air revitalization, heating, and cooling systems and local heaters are main responsive controls.
 - Some solutions to problems caused by the above
 - Pane coatings, soft goods like curtains, shades, exterior window covers
 - Design-wise, ensure ARS can handle peak moisture generating activities (namely exercise), heaters can keep surface warm enough; that sufficient airflow in cabin/near surface – mockups and CFD also help characterize how air flows around the surface.
- Thermal Protection System for entry vehicles
 - Consider material response, ablation
 - Traditionally glass is used for the outermost pane for this
 - Some ductile materials might be able to withstand the extreme aeroheating – shuttle Columbia's acrylic "B" Hatch Window survived the event.

- Windows must be included in thermal models to predict temperatures

- Historically thermal models of transparent materials not accurately correlated ($\pm 10\%$ accuracy); correlation is elusive.
- Increased modeling complexity due to transparency, thickness, and coatings
- Recommendations
 - Need high fidelity, transparent solids (not surfaces)
 - Be careful about light leakage around materials that touch but are not “sealed” per se.
 - Use slab methods: refractive index, thickness, and extinction coefficient of the pane material allow for computing absorptivity, transmissivity, and reflectivity. ($\alpha + \tau + \rho = 1$):

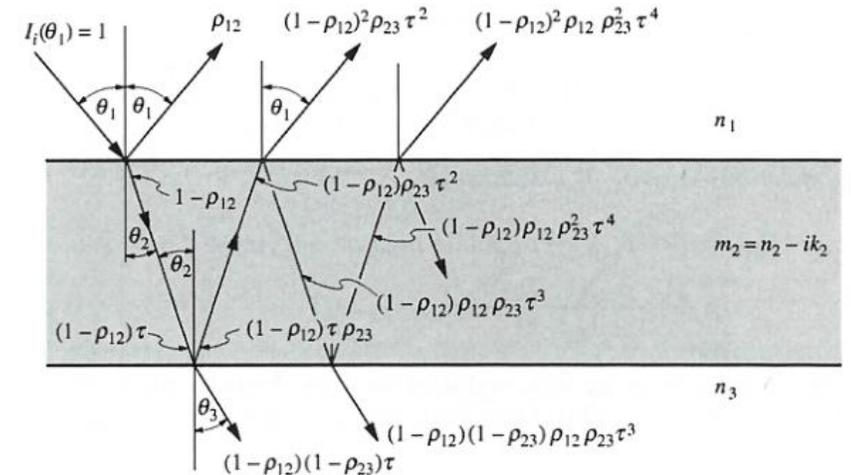
$$R_{Slab} = \rho \left[1 + \frac{(1 - \rho)^2 \tau^2}{1 - \rho^2 \tau^2} \right], T_{Slab} = \frac{(1 - \rho)^2 \tau}{1 - \rho^2 \tau^2}, A_{Slab} = \frac{(1 - \rho)(1 - \tau)}{1 - \rho \tau}; \tau = \exp\left(\frac{-\kappa_2 d}{\cos \theta_2}\right) = \exp\left(\frac{-4\pi k_2 d}{\lambda \cos \theta_2}\right)$$

- Typical thermal properties

- Thermal conductivity is mid for glass and low for plastic.
- Heat capacity tends to be high for glass but low for plastics.
- Caveat: consult the material’s manufacturer, especially for ductile materials.

- Testing more complex than typical spacecraft structure

- Uniqueness of each assembly
- Panes – trust your manufacturer but verify
- Physically measuring pane material temperature is difficult
 - Thermocouples/RTD’s – due to typically low thermal conductivity
 - Thermography
 - Difficult due to reflective/transmissive nature of material
 - Can erroneously measure either environment or backing material
 - A strategically placed piece of black electrical tape may help



Reflectivity and transmissivity of a thick, semi-transparent sheet. From Modest’s Radiative Heat Transfer.

- **Windows are important assemblies**
 - Frames / retainers, seals, cushions, vents, bolts, several panes with coatings
 - Panes transmit thermal radiation in visible and near-infrared ranges by design
- **Pane materials come with structural & thermal design challenges**
 - Issues include:

Compatibility and environmental factors, optics, mass, stress and fragility, heat leak & condensation generation, properly modeling heat transfer and optics, availability of thermal properties, accurately measuring temperatures.
 - There are ways to overcome some challenges
 - Size, testing, coatings, several panes/filler materials, imbedded heaters, coverings, shades, etc.
 - Lots of room for improvement in the future!



Sources



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Shuttle Windshield Cross-Section

