# SPACECRAFT WINDOW DESIGN FROM A THERMAL PERSPECTIVE

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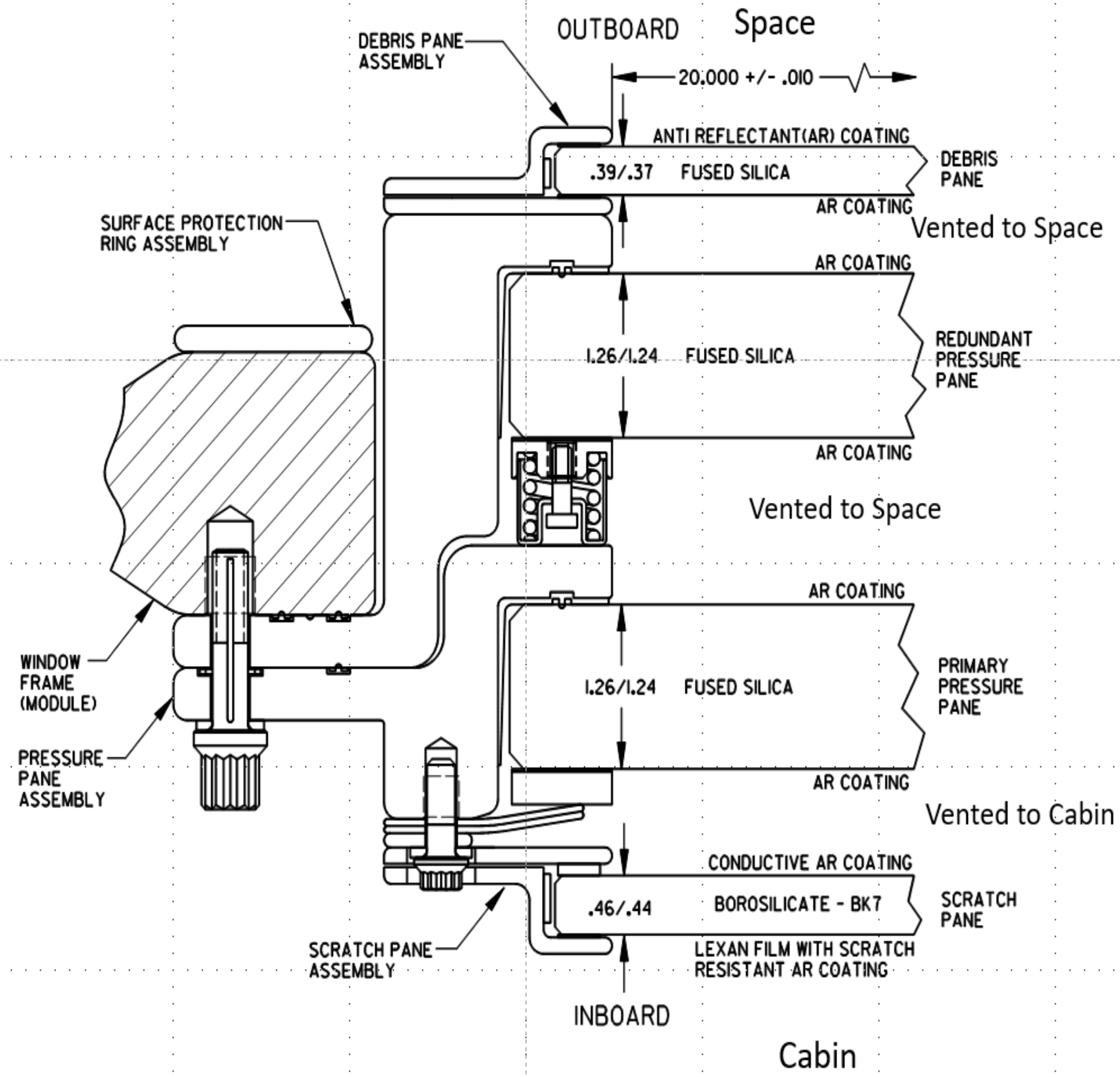
# Introduction

- 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


# Structure

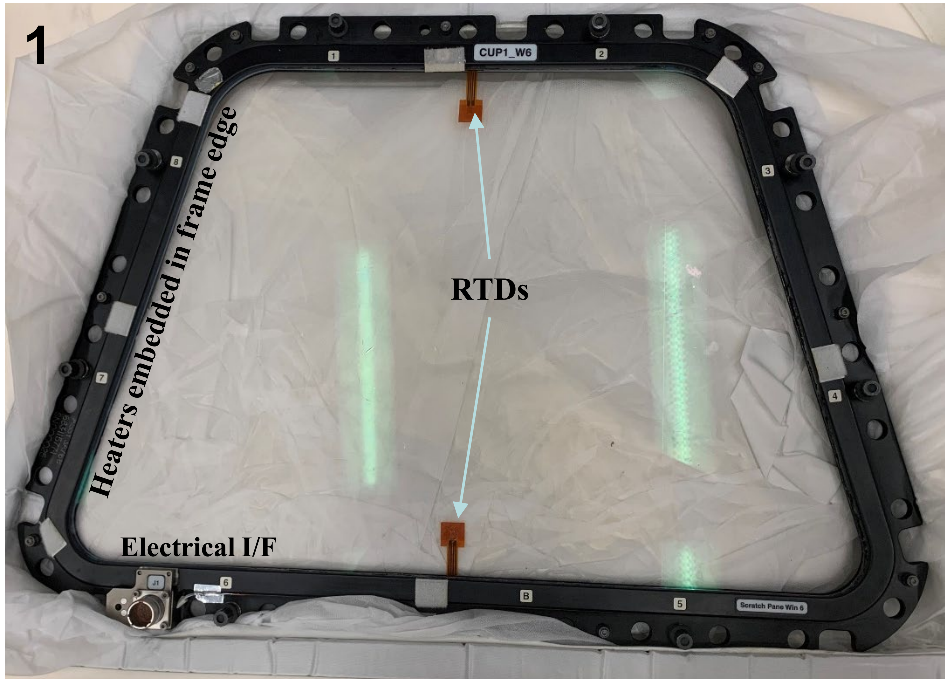
- A window is an assembly
  - Provides through-the-wall viewing
  - Consists of frames, retainers, seals, cushions - aka "Window Stack" {ISS}.
  - Filler between panes (vented? fill gas?)
  - Panes should never be subject to structural s
- Pane Functions and Duties
  - Outer Panes
    - Prevent damage to inner panes
    - Withstand small impacts from debris and mete re-entry
    - ISS outermost "debris pane" is removeable/rep
  - Inner "Pressure" Panes
    - Pressure-vessel boundary, contains atmosphe
    - Shuttle – double paned with dry, inert fill gas fc
    - ISS innermost "scratch pane" is removeable/re condensate)

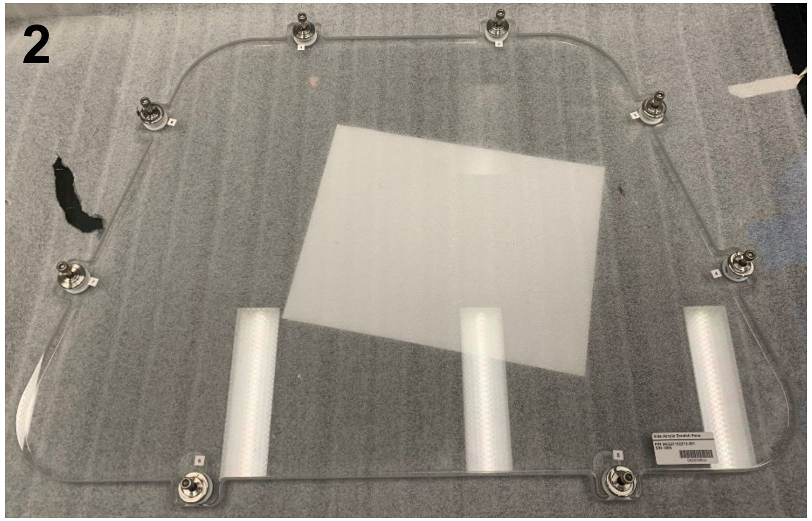
**ISS Cupola Window Cross-section**



# Pane Materials

- 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

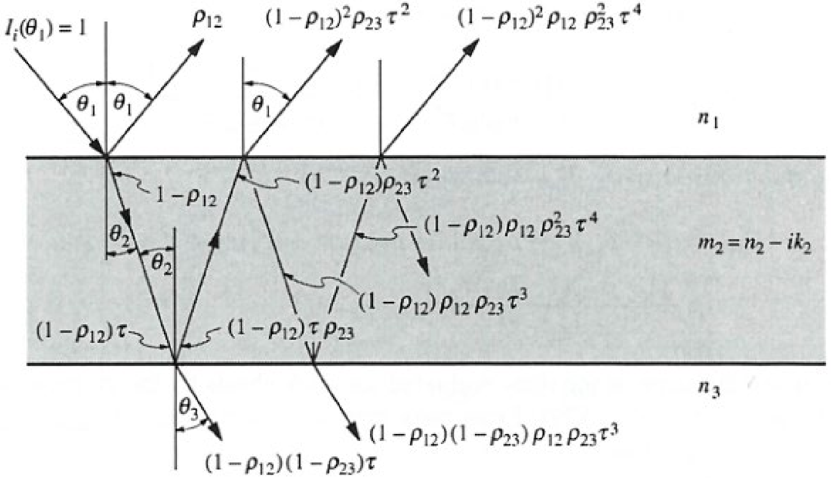
- Part of assembly
  - Holistically consider thermal contraction and response to hot/cold in all materials
  - Touch temperature considerations.
- Transmit thermal radiation in visible and near-infrared ranges by design
  - Into the Spacecraft – from the sun, planetary bodies, or other vehicles.
  - 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/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.

# Thermal Modeling and Testing

- Windows must be included in thermal models to predict temperatures
  - Historically thermal models of transparent materials not accurately corelated (±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. (α+τ+ρ=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.**

# Conclusion

- 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