

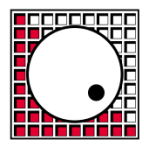
NanoPore Insulation

Accelerated lifetime testing of vacuum insulation panels

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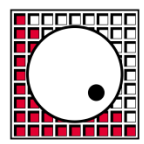
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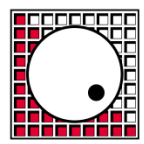
What is NanoPore Insulation LLC?

- NanoPore Insulation LLC is a joint venture of NanoPore Inc. and Sealed Air corporation (a 4 billion+ \$ packaging company with extensive expertise in high-speed vacuum packaging and barrier films)
- NanoPore Insulation LLC has three US-based VIP production lines including a new automated facility and a UK plant producing VIPs to the same specifications.
- NanoPore is the **only** producer of nanoporous carbon-silica vacuum insulation panels (VIP's) and has been producing these for >10 years.
- NanoPore has developed and continues to develop a range of barrier/core materials optimized for various applications
- In '09, we will produce >1M VIPs and >3M in '10.



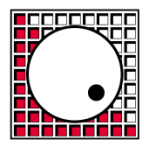
Lifetime of Insulation

- The thermal performance of all thermal insulation degrades over long time periods because of:
 - Water adsorption/absorption
 - Structural degradation from thermal and barometric cycling, water adsorption, etc.
 - Outgassing
 - Temporal decomposition for foams
- How to define lifetime for VIP's? Difficult given the logarithmic change of thermal conductivity with pressure/time
- The lifetime of a VIP is more dependent on both its' use conditions and dimensions than other insulation
- We normally define predicted lifetime as the time required to lose 10% of the thermal resistance under use conditions



Key issues in VIP lifetime

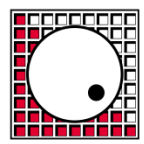
- Operating temperature and humidity
- VIP design
 - Core material
 - Barrier film
 - Getters/desiccants (if any)
 - Thickness (affects the surface area to volume ratio)
 - Seal layer (material type, thickness, width)
- Barrier film specifications are only a starting point since they will degrade over time with:
 - VIP production
 - VIP handling and system integration
 - Barometric pressure cycling
 - Thermal cycling
- Lifetime performance in a “system” can be very different (better or worse) than that for the VIP only.



Effect of flexing

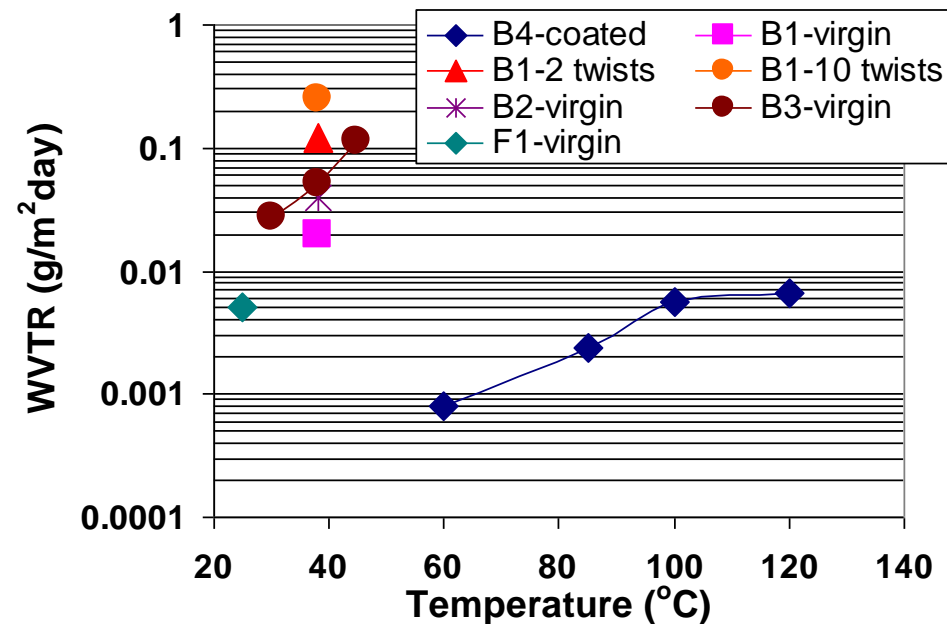
- We know that the WVTR and OTR (hence lifetime) of metalized films changes dramatically (>100x worse) with flexing.
- Impossible to relate laboratory flex testing back to the real world of VIP use in production and application!
- EvOH-only does not degrade but not nearly as good to begin with!
- No data on either mEvOH or mPET with an EvOH seal layer

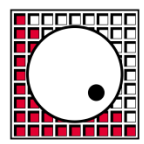
			OTR (cc/m ² d)	
	Virgin	Flex/Lab 1	Flex/NP 2 cycles	Flex/NP 10 cycles
Met #1	<0.01	0.75	1.5	4.3
Met #2	<0.0005	0.15	na	na
EvOH	<0.2	0.06	na	na
			WVTR (g/m ² d)	
	Virgin	Flex/Lab 1	Flex/NP 2 cycles	Flex/NP 10 cycles
Met #1	0.02	0.20	0.12	0.25
Met #2	0.01	0.084	na	na
EvOH	2.12	2.43	na	na



Temperature dependence on barrier film permeation

- There is a strong temperature dependence on gas/vapor permeation rates through VIP barriers. Going from 20 to 80 °C represents a **~20x increase** in aging rate
- Results for:
 - current virgin films
 - current flexed films
 - next generation barriers

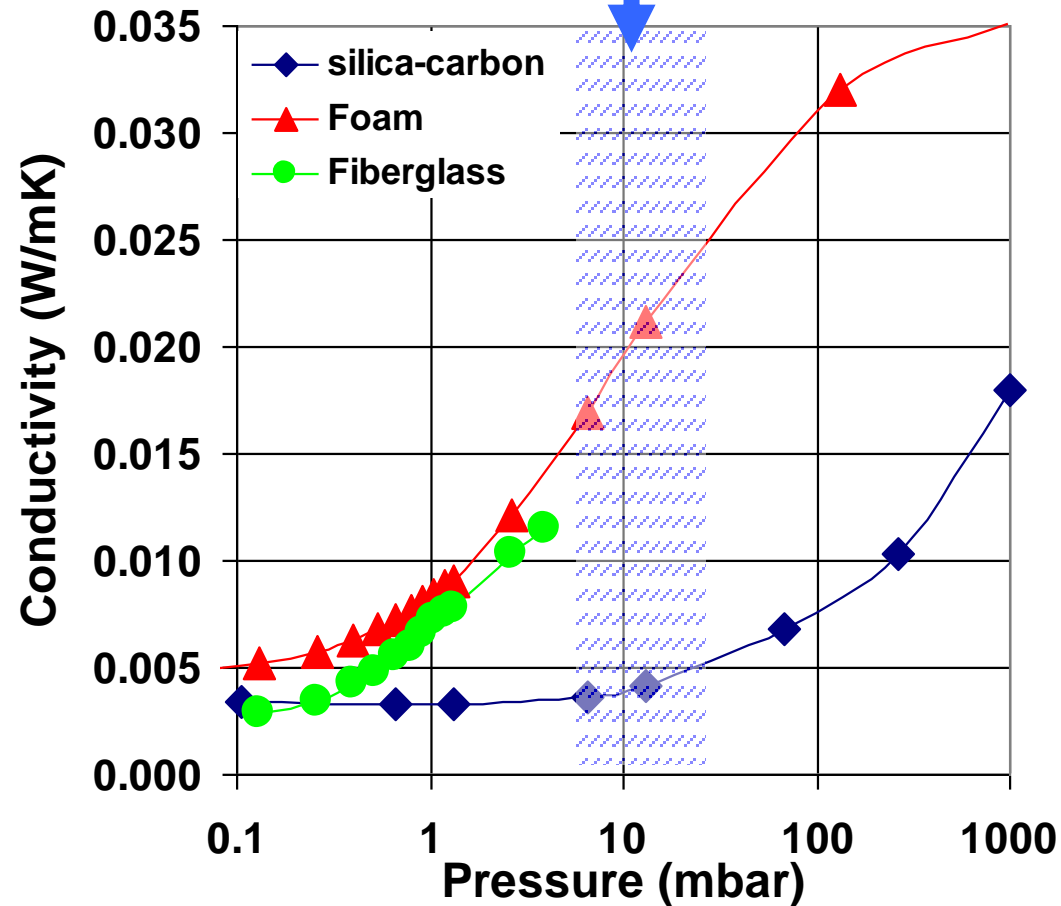


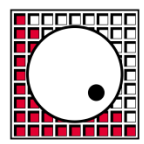


Water Vapor: The problem for non-nanoporous cores!

ambient
humidity

- Typical ambient water vapor pressure is 5-30 mbar
- In buildings, the VIP's coldest side sets the vapor pressure (<ambient)
- For foams and fiberglass, the useful capacity of the desiccant is used up at <5% relative humidity!
- Foams/fiberglass VIPs are just not applicable for building applications, impossible to add enough desiccant!

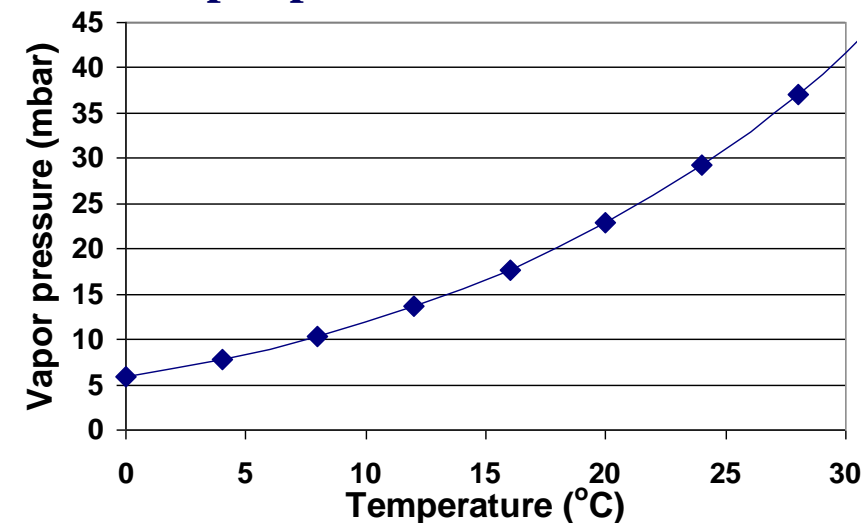




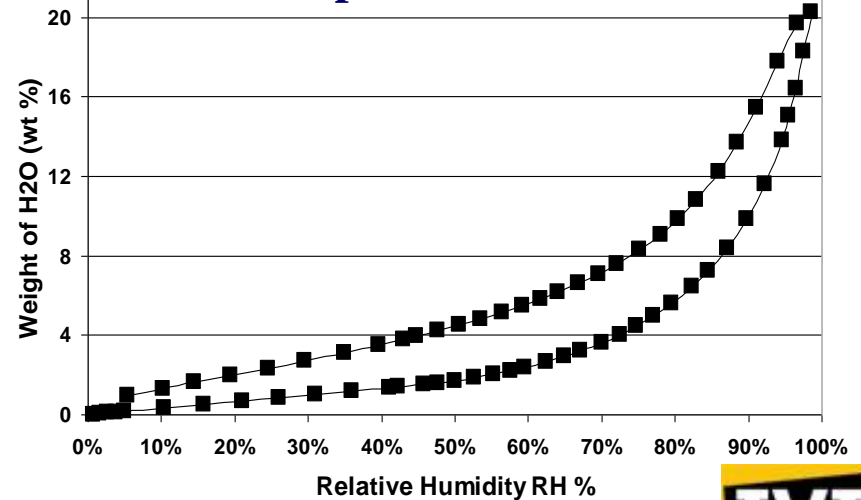
Water Vapor in Construction

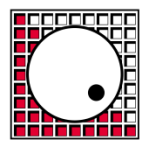
- During summertime, maximum water vapor pressure is the inner wall (22 °C/100% RH) or ~25 mbar independent of the atmospheric temperature/humidity.
- For winter, even at 100% RH, the lower outer wall temp. means that water vapor will actually be leaving the VIP, not entering!
- Because of the high adsorption capacity in the 70-80% RH range, water vapor pressure in the VIP should never exceed 20 mbar in most geographies (except tropical)

Water vapor pressure at 100% RH



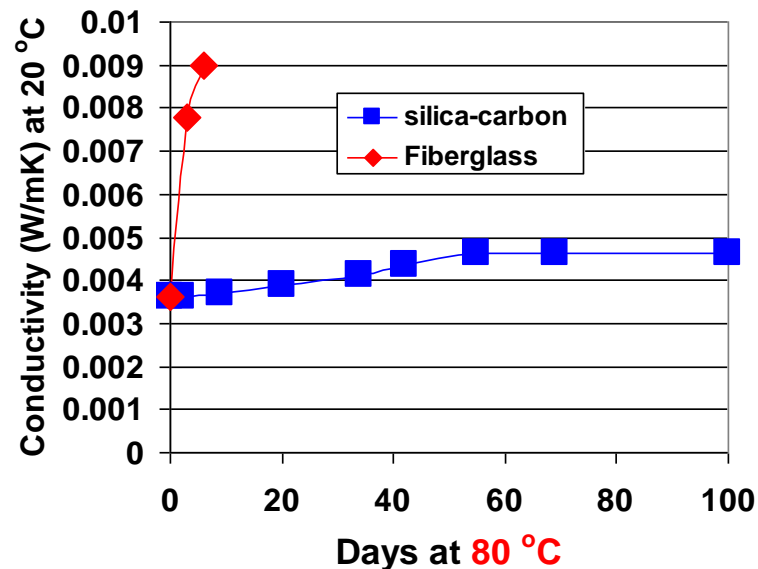
Water adsorption on NanoPore core

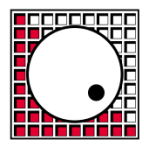




Does the core really matter?

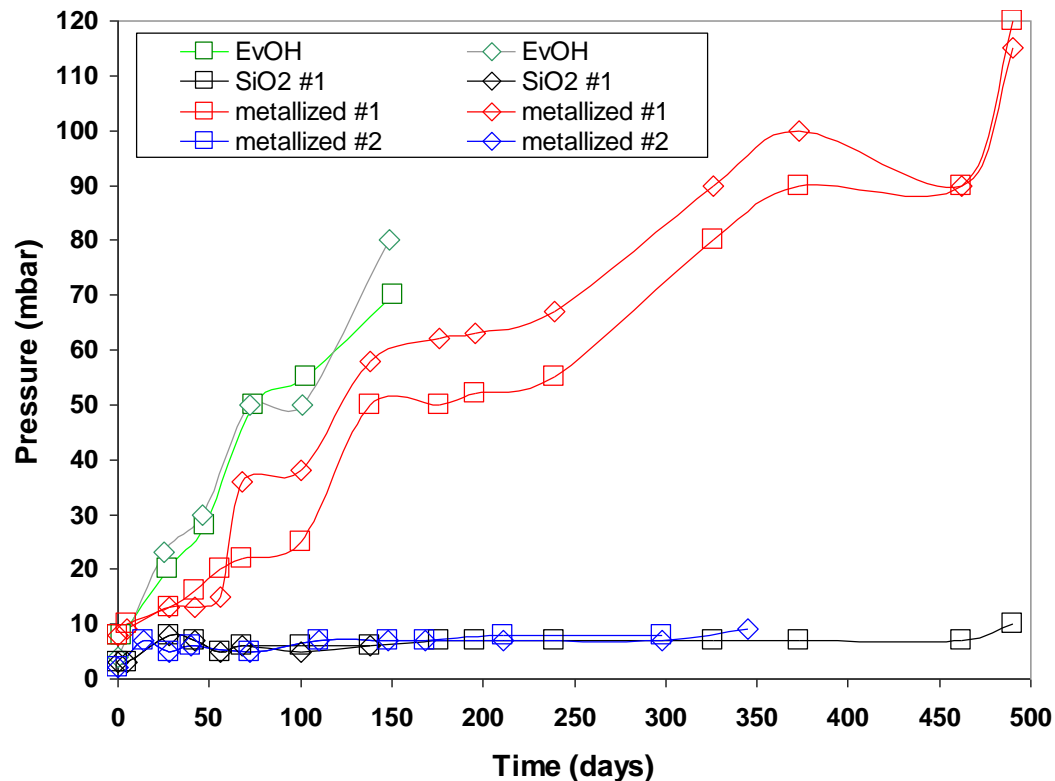
- Compare a silica-carbon VIP with no desiccant to a commercially available (for warm applications) fiberglass VIP with a desiccant
- 25 mm thick panels and both have similar metalized barriers
- Store at 80 °C, cool to ambient and measure the panel pressure. Convert the pressure to the room temperature conductivity
- Fiberglass VIP conductivity doubled in two days!
- Silica VIP reached a pressure plateau and has now been aged for over ~450 days at 80 °C with only 20% loss in thermal performance.

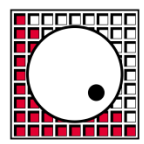




Long time 80 °C accelerated testing

- Compare 25 mm silica-carbon VIP's with no desiccant and different barrier materials
- The two metalized barriers have the same 3xmPET structure!
- Store at 80 °C, cool to ambient and measure the panel pressure.



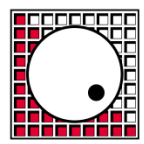


Thermal cycling

- In a 50 year service life, a VIP will go through >18,000 thermal cycles due to diurnal temperature variation!
- Silica CTE is different than plastic barriers and other building materials.

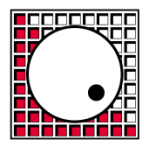
Material	CTE (ppm /°C)
Silica	0.5
PET	73-92
Aluminum	22
Mild steel	12
Wood (perpendicular to grain)	30-50
Wood (parallel to grain)	3-5
Polyurethane	40-160
Masonry brick	6-9
Glass	6-9

- Thermal cycling induces repeated stress on the barrier material as the plastic barrier expands and contracts with ambient temperature variation.
- Stress from barometric cycling is much lower



Thermal cycling (cont)

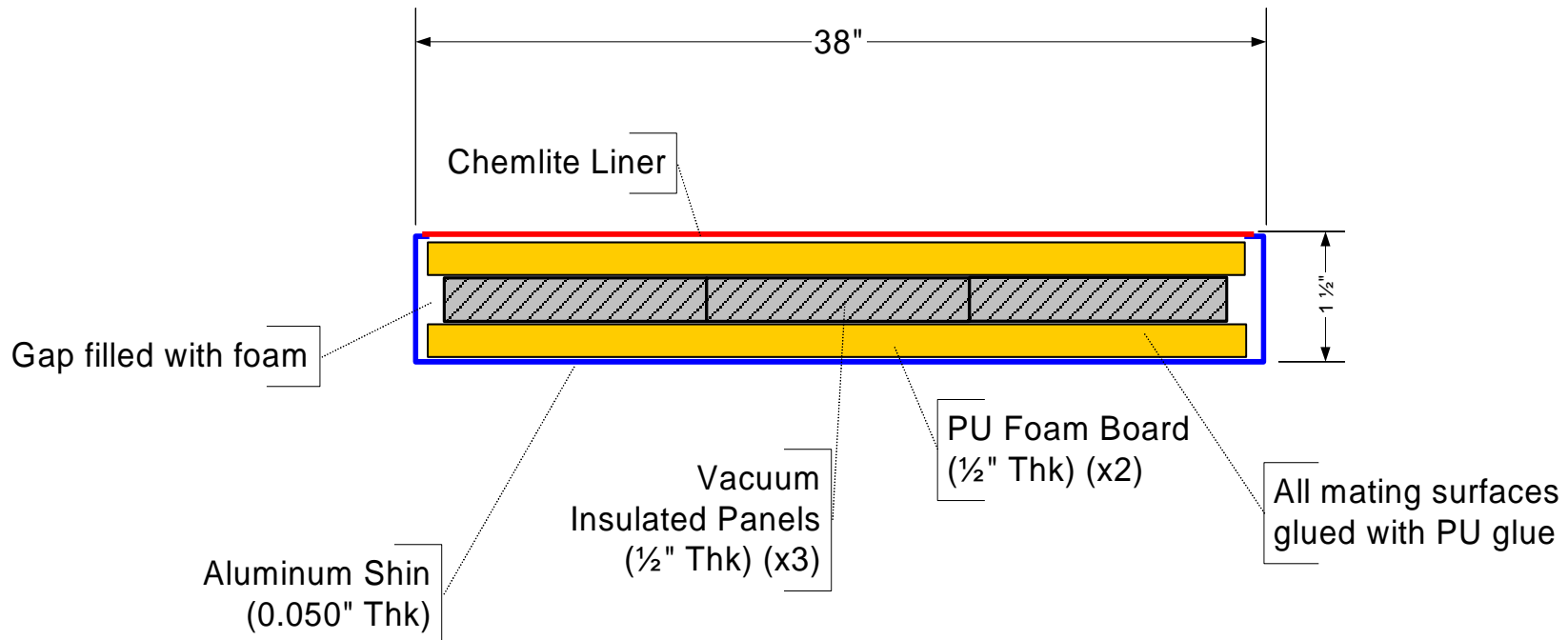
- In buildings, although the interior side of the VIP is essentially isothermal, the outer VIP surface temperature can vary significantly depending upon the climate zone.
- Not normally addressed in VIP lifetime analysis! Not an issue for many VIP applications such as refrigeration (where temperatures are essentially constant with time)
- Effect of thermal cycling is system design dependent.
- Depends on CTE and modulus of adjacent layers.
 - Best case is a VIP only (just CTE mismatch between core & barrier)
 - Worst case is a VIP bonded directly to a metal with a rigid adhesive
- Stress relief at the VIP interface is a major design consideration

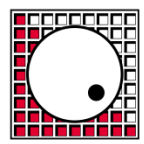


Thermal Cycle Testing

- Multiple silica/carbon VIPs in an Aluminum/PU foam/VIP/PU foam/plastic sandwich

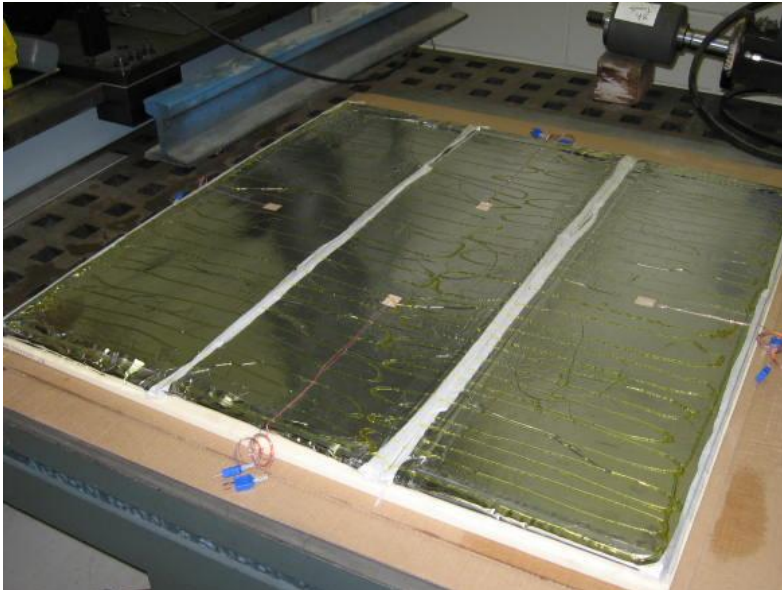
Construction Diagram





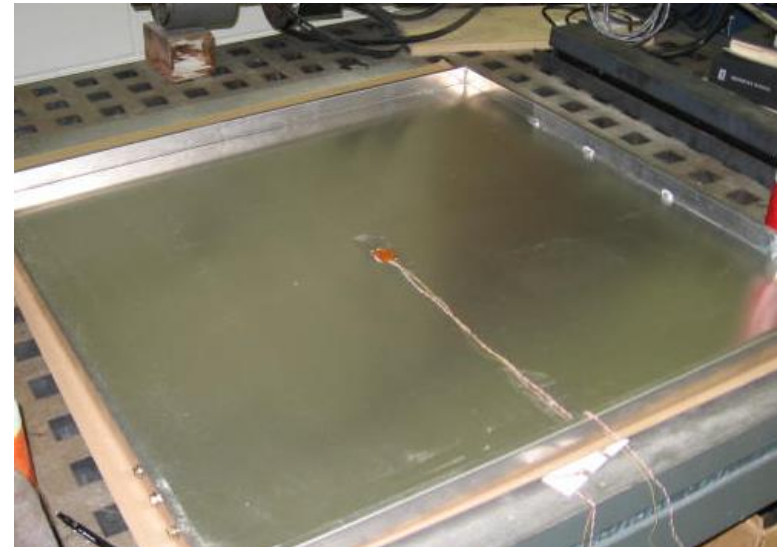
Thermal Cycle Panels

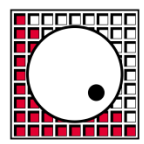
Build-up



- Attached Aluminum and FRP skins during second gluing operation
- Mounted heat flux sensor to inside of skins at center of door
- Filled voids at edges with expandable PU foam.

- Built-up core (PU/VIP/PU) first
- Attached surface mounted, Type-T thermocouples to each side of VIP's (8 total)
- Packing foam attached to side of VIP to prevent wear
- Applied PU glue to all surfaces

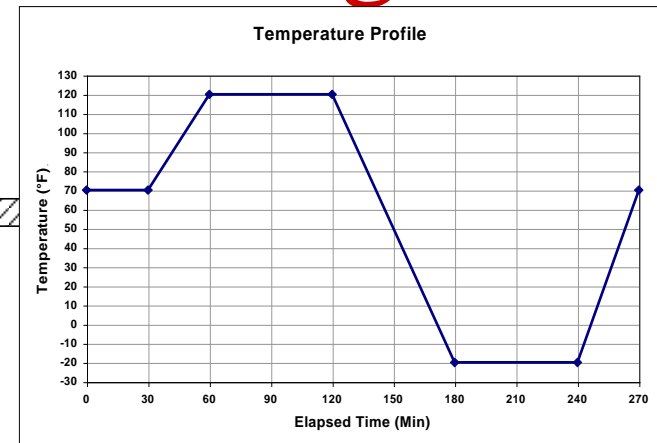
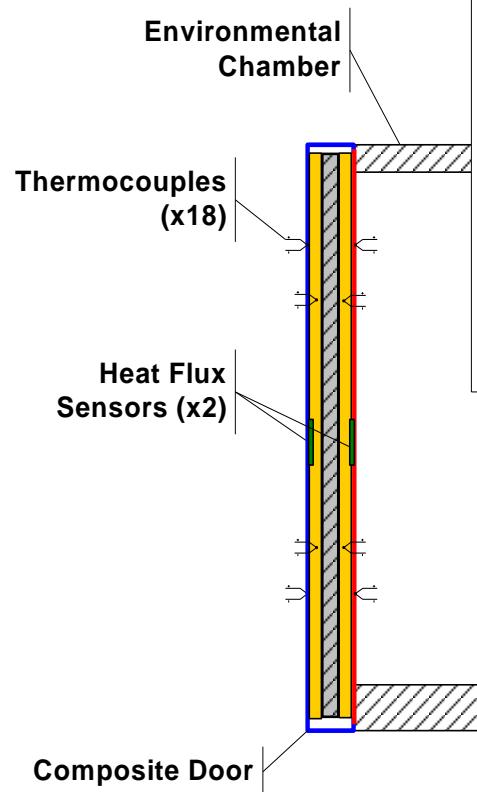


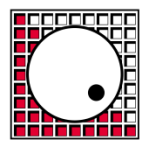


NanoPore Insulation

Test Set-up

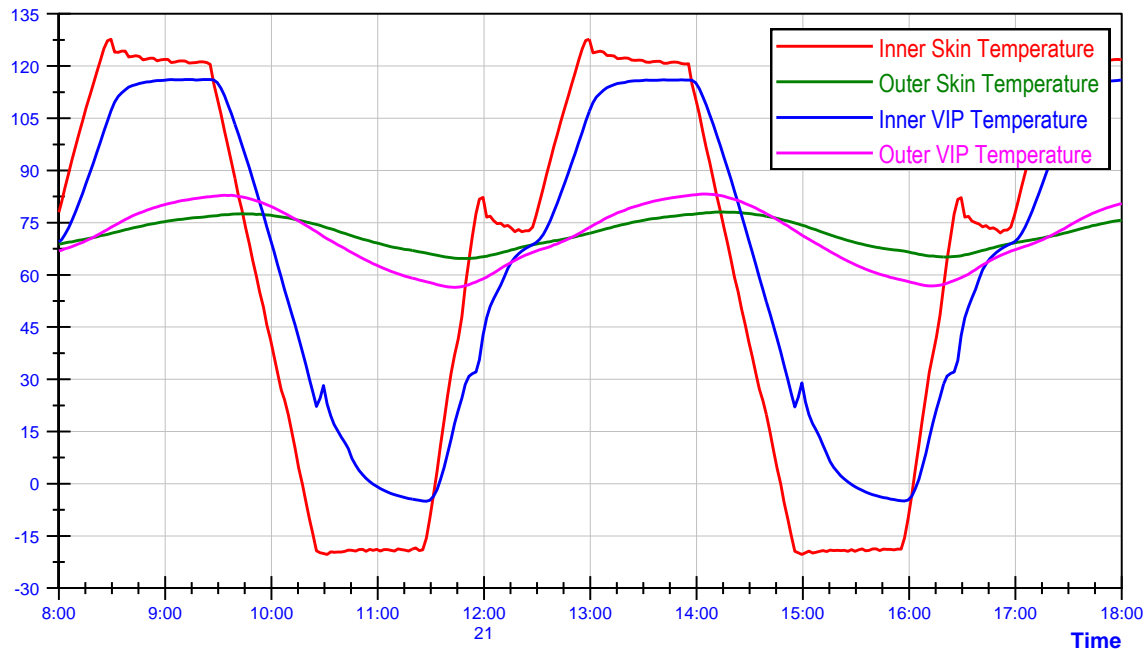
- Composite panel mounted to chamber
- Interior cycled from 50 °C to -30°C (i.e. much larger swing than normal building applications to accelerate aging)
- Exterior ~20 °C
- Measurements
 - 2x Heat flux sensors with integrated TC
 - 8x Surface TC
 - 8x Embedded TC on VIP

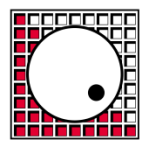




Single cycle

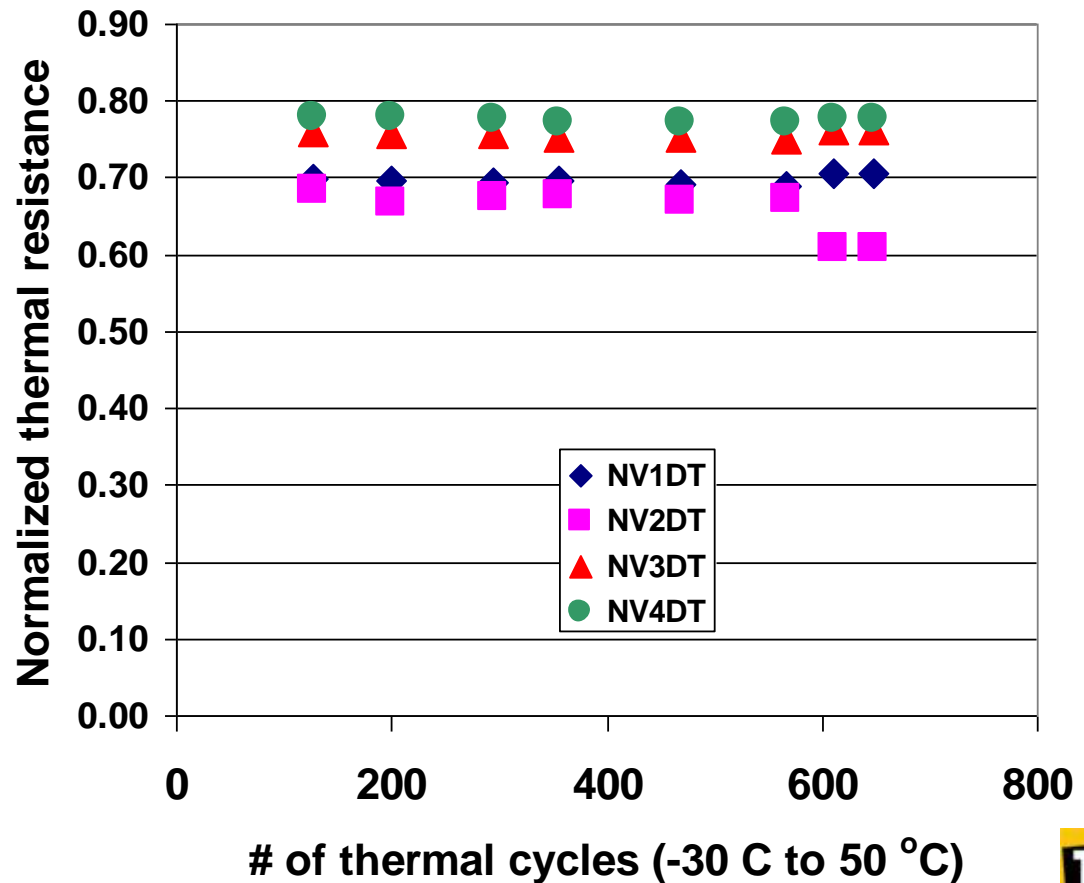
- Because of the low thermal diffusivity of VIP's, a single cycle takes ~6 hours to stabilize at high and low temperatures
- In climates with large diurnal variation (such as New Mexico!), this shows that it is not just thermal conductivity that matters but also thermal diffusivity. With more thermal mass or thicker VIPs, this effect becomes more pronounced!

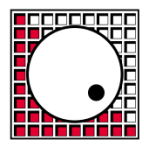




Thermal resistance versus time

- 647 cycles (>160 days), there was minimal thermal resistance change
- After 647 cycles, a temperature controller malfunction caused the chamber to spike to $>100^{\circ}\text{C}$ so the test was stopped and panels were pressure tested





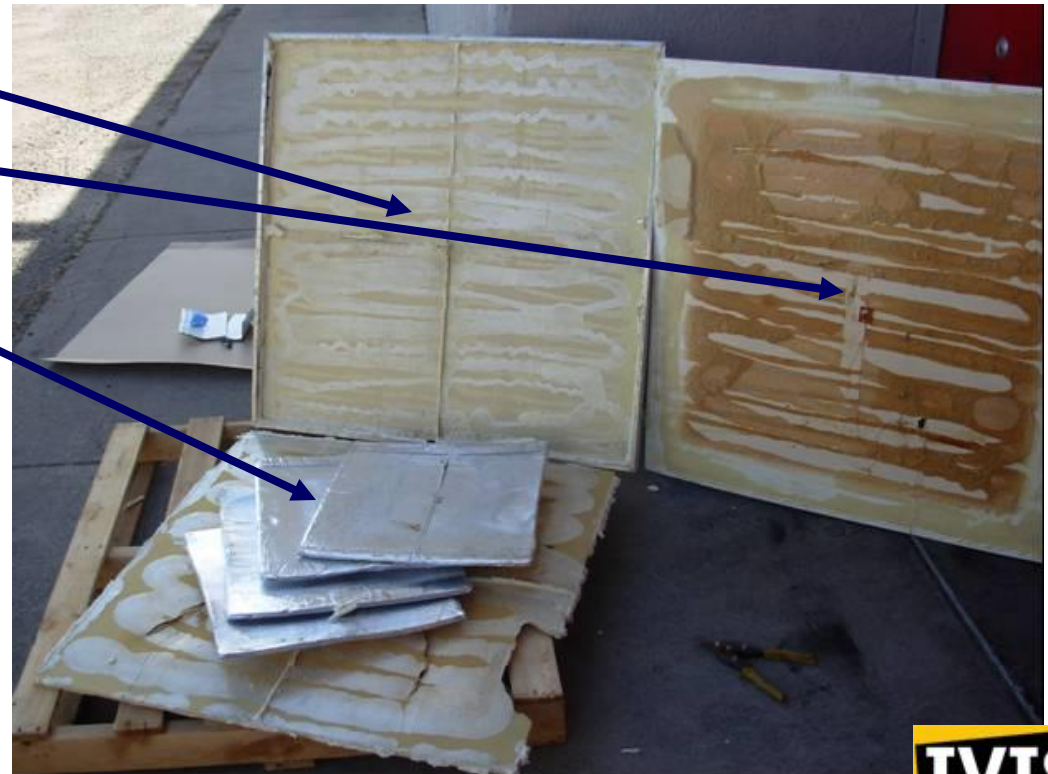
Post thermal excursion analysis

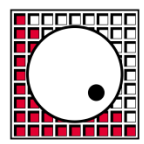
- Hot side PU showed significant thermal degradation as compared to cold side
- All VIPs were intact! Pressure was measured and found to be between 10 and 13 mbar despite the hot side excursion

Cold side PU

Hot side PU

VIPs





Summary

- For long-life building applications, only nanoporous core materials such as silica are appropriate because of the difficulty of maintaining water vapor pressure below 1 mbar for cores with larger pores (foam/fiberglass).
- Assuming that water vapor is not an issue (i.e, core yields good thermal performance in the ~20 mbar range such as for some silica panels), 80 °C accelerated testing indicates lifetimes well over 30 years with minimal (<20% thermal performance degradation depending on the barrier material).
- This study seems to be the first long term, accelerated testing on thermal cycling of VIPs in an integrated system.
- Thermal cycling means that VIP system design is an important factor in VIP lifetime.