Gen3 Long Life High Performance Vacuum Insulation Panel for Construction Applications

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Theme 2: VIP Innovations- Product Development

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Abstract:
VIP have for some years been trialed as a mainstream building insulation material for floors, walls, and roofs. This is especially true for constructions that limit the available thickness. The purpose of this paper is to propose a new VIP called Gen3 that can serve as the bedrock of the building envelope insulation system for thickness limited construction applications. The requirements for successful construction applications are reviewed and compared to the capabilities of Gen3. These are 1) the ability to provide an effective R56.8 (10 RSI or 0.10 U) from a panel about 2 inches thick; 2) maintain that R-value with stability over the 50 to 100 year service life of the building; 3) survive both the construction and service environments; 4) be affordable to the builder contractor and building owner; and 5) the VIP must be scaleable and manufactured with reasonably simple methods to attain the needed economy. All of these requirements must be present if the VIP is to be successful and considered "building worthy".

Glass fiber cores offer the most advantage and are the prime focus of this paper. The COP (center of panel) R-value depends on the specific core material chosen and its design pressure. A core insulation heat transfer model clarifies the relationship of core density and fiber diameter index to the COP R-value. Gen3 VIP employs an hermetic stainless steel foil envelope to maintain vacuum. Results from a three dimension thermal model show the ability of the Gen3 design to meet the proposed R 56.8 target at practical thicknesses and sizes. Comparisons to multilayered metallized aluminum foil envelopes are not made due to the author's opinion that these envelope constructions are not yet to a state of development to provide R-value stability over the 50 to 100 year life of the building without refitting.

To demonstrate the predicted longevity of the Gen3 VIP design, thermal data from 14 year old stainless steel foil Aura® VIP are presented. Concepts are presented to protect the stainless steel foil envelope from damage during installation at the construction site and during service. Expected pricing of Gen3 is compared to an established target for construction in the UK of £30/m² ($4.00/ft²).

Gen 3 is a feasible and proprietary new VIP product design requiring solid partnerships and financial backing in order for it to become a production reality. An estimate of tasks, pilot line construction, and the timeline for manufacturing indicate that this product could be available in trial quantities within the year following completion of all agreements and confidentialities. The technology is robust and well known to the author. The majority of issues have either been resolved or validated in the author's Gen1 and Gen2 VIP designs.

In summary, the elusive target of a thin 0.1 U-value panel for opaque construction without panel refit over the life of the building appears to be within striking distance using the information presented. (The author is the inventor of the Owens Corning 75 R/inch (COP) Aura® Gen1 stainless steel foil VIP used in refrigerated appliances.)

1. PANEL THERMAL PERFORMANCE

1.1 Theoretical COP R per inch for glass fibers

A theoretical model has been prepared by the author to show the response of COP R per inch to the major factors. This model is for laminar glass fiber cores and incorporates the fiber/gas mean free path interactions, radiation blocking and solid fiber to fiber conduction components. The major response factors are fiber diameter index (fineness) and core density. Units shown for fiber index are HT (hundred thousandths of an inch) and for core density lb/ft^3. A 3D response plot at 100 m Torr pressure is presented in Figure 1 shows R per inch (US) over a wide range of these factors. What can be seen is that the R per inch rises as fiber index is reduced and core density increases. This reflects the mean free path effect. A maximum R per inch of over 90 is evident. Note the drop off that occurs when the fibers are of such fineness that they are less effective in absorbing or scattering the infrared thermal radiation. Maximum COP R per inch can be optimized through careful balance of fiber index, compressive strength and cost. Details of the fiber theory model are beyond the scope of this paper. A separate paper on this subject can be obtained by contacting the author (1).

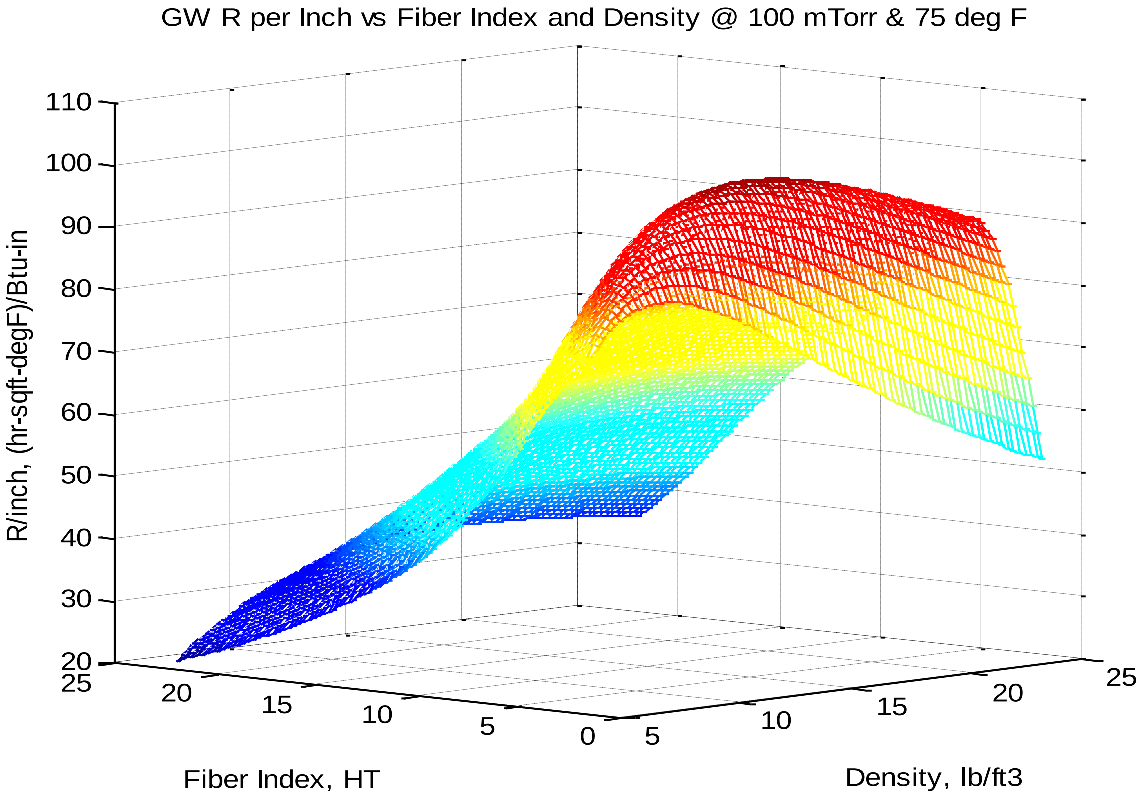

Figure 1. Response Plot for Glass Fibers

1.2 Test COP R per inch versus model

R per inch data from the Owens Corning ASTM C 177 vacuum guarded hot plate tester

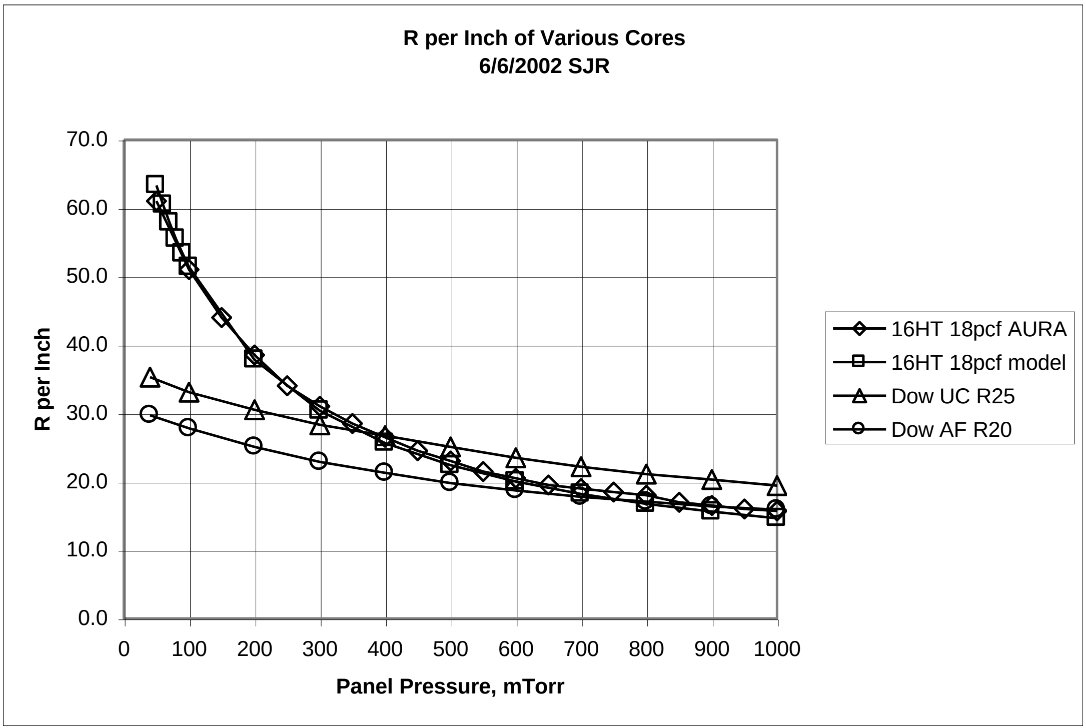

Figure 2. R per Inch versus Panel Pressure Test Data and Model

for Aura® glass fiber vacuum cores are shown in Figure 2. Good agreement with the author's model at 16 HT and 18 pcf is shown indicating that the important physics have been captured. Open cell Dow Instill® foam literature data is also given for comparison. All glass fiber data is reported at 75 deg F mean temperature with a 40 deg F temperature driving force across the samples (1, 2, and 3).

1.3 Theoretical Effective R value Performance (R_e) for Gen3 VIP

1.3.1 3D Model

The Gen3 VIP design employs a long service life hermetic envelope made from conductive stainless steel foil. This requires an accounting of the heat shunting around the envelope to arrive at an estimate of the panel's effective insulating value or R-value (R_e). Thus, for metal foil envelope panels the COP R per inch times thickness overstates panel thermal performance. Two different steady state thermal model types were created to estimate the impact of stainless foil on thermal performance. A one-dimensional parallel heat flow model of Gen3 (4) along with a 3D heat transfer FEA model of Gen3 were created to describe this behavior (5). SolidWorks COSMOSWorks® 2006 software was used to provide the 3D outputs. A quarter section 3D VIP model was employed considering the symmetry inherent in the model and to reduce the mesh complexity and computation time. The 1D model was useful in guiding the general direction of the 3D results but has been shown by the author to severely understate R_e of foil panels (2).

The details of the 3D models (IPS) are given. A rectangular shell envelope was created in SolidWorks that was 3.0 mils thick. This envelope was then cut extruded to form a quarter section of the Gen3 VIP size to be studied. The solid insulation part conformed to the interior of this shell and was exactly 1.0 inches thick. In CosmosWorks the boundary condition for the top face of the envelope was 55 degrees F connected by a convective film coefficient. The boundary condition for the bottom face of the envelope was 95 degrees F connected by a convective film coefficient. The same convective film coefficient was used for each of the face sides. A recommended film coefficient of 1.0 Btu/hr/ft^2/degF was obtained from the ASHRAE Fundamentals Handbook and that was multiplied by 1.5 in order to be conservative (6). The remaining external vertical faces of the model were adiabatic. The properties of each material are given in the Appendix. Parts were bonded together with no contact resistance between them. The Sparse Solver option was chosen. The finest mesh possible was run for all cases, typically 0.35 inches with tolerance of 5%. Sparse Solver is especially useful to run thermal models where the material properties are vastly different as they are here in these examples.

1.3.2 3D Model Outputs

An example of the temperature output from a one inch thick 24 inch by 48 inch quarter scale model run is shown in Figure 3. This plot shows the cold top face up. The heat shunting around the edges can be seen.

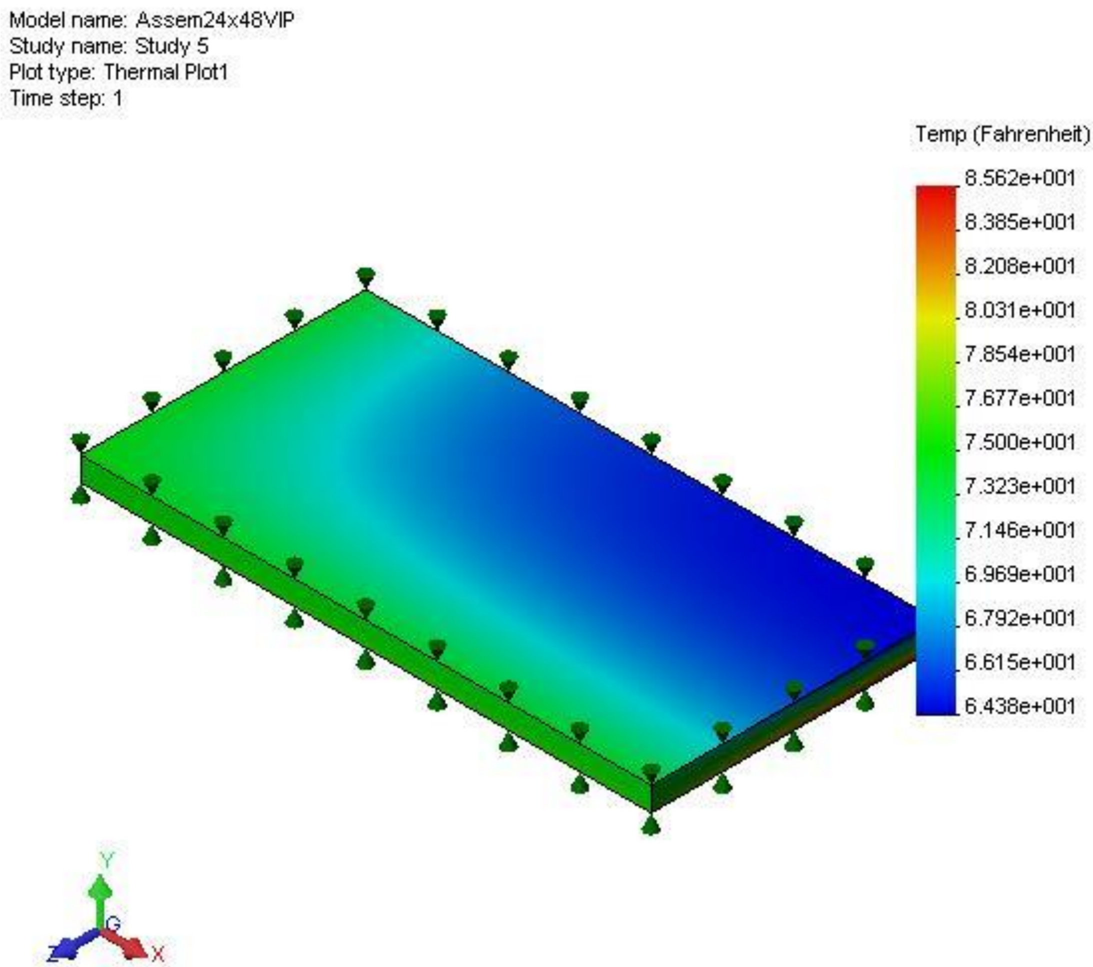

Figure 3. CosmosWorks Temperature Output for a 24”x48” Gen3 VIP with 3 mil Thick Stainless Foil

An example of the resultant heat flux vector output from a one inch thick 24 inch by 48 inch quarter scale model run is shown in Figure 4. This plot shows the cold top face up.

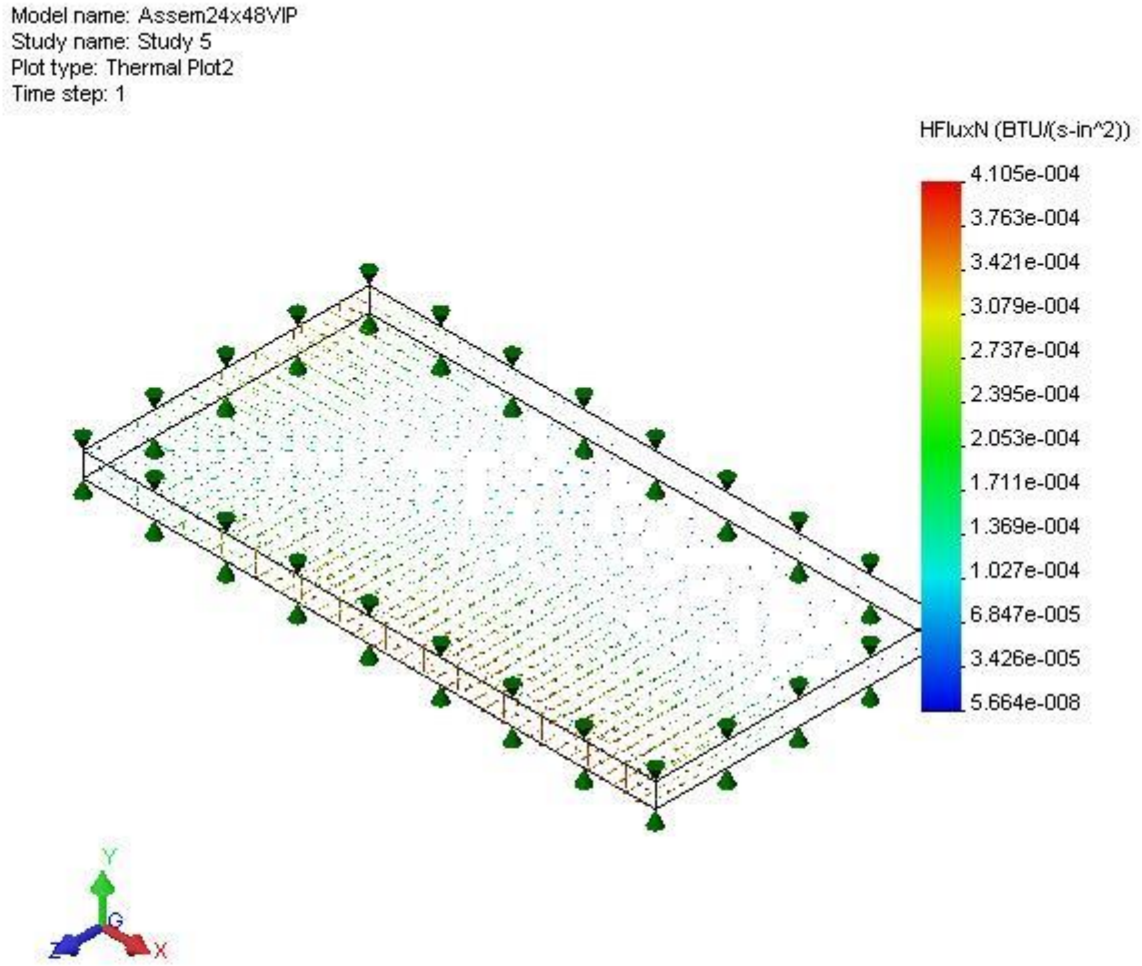

Figure 4. CosmosWorks Heat Flux Vector Output for a 24"x48" Gen3 VIP with 3 mil Thick Stainless Foil

Once all the model cases were run the resultant total heat flows from the top and bottom faces could be gathered from the post-processing software output in CosmosWorks. This total heat flow was then multiplied by 4 to obtain Q in units of Btu/hr. The difference between top and bottom Q was found to be less than 0.5%. The effective R-value, R_e, was computed by equation 1 for each case.

$$(1) \quad \mathbf{R_e} = \mathbf{(AREA) \ x \ (\Delta \ T)/Q}$$

AREA is the total panel top or bottom area, and ΔT is the temperature difference (40 degF). A summary of all 9 of the cases run for this paper are presented in Table 1 including the zero points. Aspect ratio of 1 indicates that is a square panel. Values for other aspects ratios are also shown.

Table 1. Summary of 3D Cases Run Showing R_e Values Obtained

Aspect Ratio	Side, in	Side, in	Area,Ft2	Re
1.0	0	0	0.0	0.0
1.0	12	12	1.0	20.2
1.0	18	18	2.3	26.6
1.0	24	24	4.0	29.5
1.0	30	30	6.3	31.9
6.0	0	0	0.0	0.0
6.0	6	36	1.5	22.1
2.0	18	36	4.5	27.0
2.7	18	48	6.0	29.2
2.4	20	48	6.7	30.5
2.0	24	48	8.0	32.9

A plot of R_e versus Gen3 panel area is shown in Figure 5. The 1D model is given for reference and note that it is substantially lower than the 3D model outputs. Note also that R_e increases with increasing panel size as would be expected. At infinite panel size R_e will reach COP R of 75. Note also those aspect ratios higher than 1 have slightly lower R_e since there is more "edge effect" in these panels.

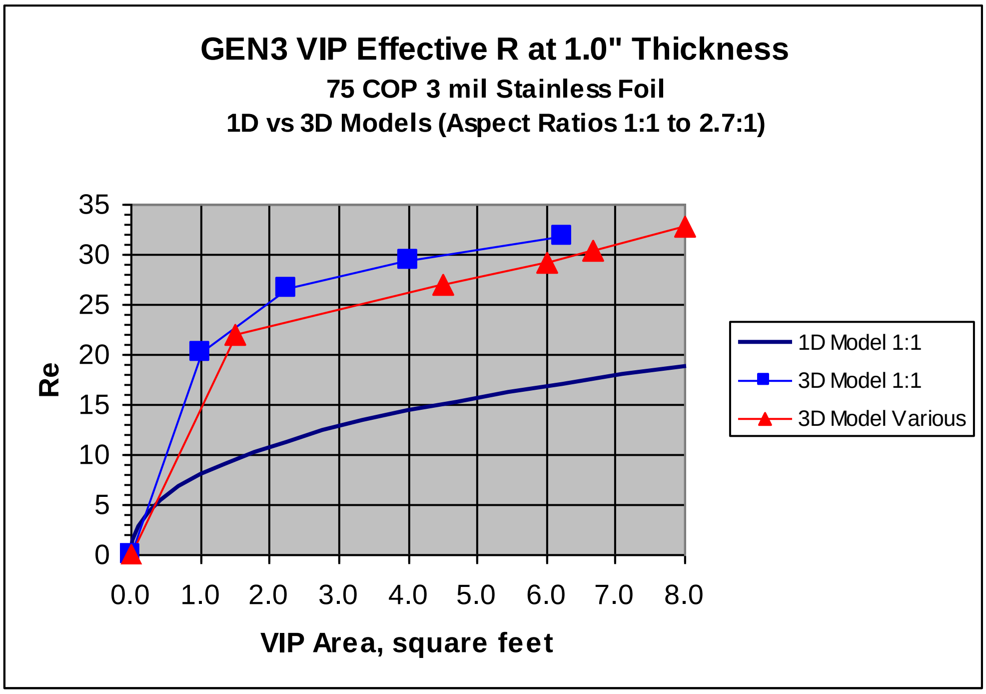

Figure 5. R_e Versus Size for 3D and 1D Gen3 Models

1.3.3 3D Model Extrapolations for Practical Gen3 VIP Sizes

The desirable target for R-value and thickness is the one often cited in the UK of 56.8 R (US) at a maximum thickness of 2.0 inches (50.9 mm) (7). That value corresponds to an RSI of 10 or U (SI) of 0.10. From Figure 5 it was seen that this target cannot be reached for a Gen3 VIP that is 1.0 inches thick unless it is much larger than 8 square feet in size. Output from the cases run at aspect ratios above 1 were used to extrapolate to thicknesses and sizes that would meet the target. This output is given in Table 2.

Table 2. Summary of 3D Cases Run Showing R_e Values Obtained

Width, in	Length, in	Re/inch	Inches for 56.8	Area, ft2
18.00	36.00	27.00	2.10	4.50
18.00	48.00	29.20	1.95	6.00
20.00	48.00	30.50	1.86	6.67
24.00	48.00	32.90	1.73	8.00
24.00	54.00	34.56	1.64	9.00
24.00	60.00	36.22	1.57	10.00
24.00	66.00	37.88	1.50	11.00
24.00	72.00	39.55	1.44	12.00
24.00	78.00	41.21	1.38	13.00
24.00	84.00	42.87	1.32	14.00
24.00	90.00	44.53	1.28	15.00
24.00	96.00	46.19	1.23	16.00

In order to create Table 2 the assumption is made that the thicker VIP will have similar edge effect to the 1 inch thick model cases run. The cases shown in light green highlight are actual cases run whereas the cases shown in light yellow are the extrapolations made using a linear fit of R_e versus area for all aspect ratios run. Panel sizes shown are considered to be "practical" from a construction point of view. To summarize then it appears that the ability to meet the 56.8 R (US) target is possible at thicknesses below 2.0 inches with practical size panels.

Experimental performance validation of the 3D models presented here is paramount in determining any bias between model and actual performance. Additionally, the exact sizes of Gen3 VIP for a particular application will depend on the voice of the customer (VOC), production efficiencies, and cost.

1.3.4 Benefits of Stainless Steel Foil

The stainless steel production foils shown are considered by its manufacturer to be hermetic (pinhole free) whereas only 1.0 mil aluminum foil and above is considered by its manufacturer to be hermetic (8, 9). Thus, the case is presented that stainless steel foil envelopes such as that used in Aura® VIP can provide excellent thermal performance at 3.0 mils thickness and advance the possibility of very long life if designed and built properly. Low metal thermal conductivity is the reason that stainless steel foil envelopes perform so well. Aluminum foil envelopes made from 1.0 mil thick foil suffer from poor thermal performance. That is because the thermal conductivity of aluminum is over 14 times that of type 201L stainless. A simple way to look at the differences between stainless foil and aluminum foil is to calculate the product of thermal conductivity K and foil thickness T. Achieving the lowest practical K x T will result in better R_e performance between the two. For example K x T for a 3 mil 201L stainless foil is 339. The 1 mil aluminum foil K x T product is 1629 almost 5 times larger. The author has run models that bear out the poor thermal performance of 1.0 mil aluminum foil envelopes.

2. GEN3 VIP PREDICTED LONGEVITY

2.1 Aged Aura® VIP Thermal Data

The longevity of Gen3 VIP is expected to follow that of the Owens Corning Aura® VIP. The stainless steel envelope, core heat cleaning treatment, and gettering processes of Gen3 are similar. It was with the author's great appreciation that personnel at the Owens Corning Science and Technology Center agreed to test and release data from Aura® VIP panels that were over 14 years old for this paper. The design of Aura® at the time of production included a specification that the COP R per inch achieve 75 or greater. Any drop off from 75 would indicate that the envelope did not remain hermetic or that some outgas of the core materials had occurred. The data are presented in Table 3 (10).

Table 3. Thermal Performance of Aged Stainless Steel Foil Aura® VIP

TR#: 90550
Date: 7/2/2009
Tester: Mark Mantonya
Method: ASTM C518
Equipment: Fox 1,2,3 LaserComp
Meter Area: 10"x10"
Material: **Aura Panels from 1995**
No.Layers Tested: 1

OWENS CORNING SCIENCE & TECHNOLOGY CENTER
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Granville, Ohio 43023-1200
740.321.5000

Sample I.D.	Total Test Thick. in.	Test Temp Hot, °F	Test Temp Cold, °F	Test Temp Mean, °F	K-Value BTU·in / hr·ft^2·°F	R-Value hr·ft^2·°F/ BTU	Machine	R/in
Aura Panel 1	1.10	95.03	55.03	75.03	0.01551	70.92	Fox 1	64.47453
Aura Panel 2	1.11	95.03	55.03	75.03	0.009909	112.02	Fox 3	100.9184
Aura Panel 3	1.09	95.03	55.03	75.03	0.009765	111.21	Fox 4	102.4066
Aura Panel 2	1.10	95.03	55.03	75.03	0.01197	91.81	Fox 1	83.54219
Aura Panel 1	1.10	95.03	55.03	75.03	0.01039	105.77	Fox 3	96.24639

AVERAGE 89.5176
AGE 14 years+

A total of three panels of size 20 inches wide by 24 inches long were randomly selected from the Owens Corning sample archives by Jerry Parks of Owens Corning. Three LaserComp FOX heat meter k testers were used and two panels were retested on different machines. The averaged or individual COP R per inch data indicate that all three panels remained at or above the as manufactured specification of 75. Thus it can be concluded that the construction of these panels have proven to be hermetic for the 14 year time period. It is forecast from these data that Gen3 VIP R value will remain stable for long periods from this evidence so long as the construction is similar to Aura® VIP.

2.2 Photograph of Aura® VIP

Figure 5. Aura® Production Stack of Five 16 inch X 20 inch VIP

2.3 Post Production, Construction, and Service Impacts on Life

Initial panel survival through the construction phase depends on how well the required protective enclosure for the Gen3 VIP is designed. The conditions or events that would cause an obvious puncture of the envelope include those that might occur during post production packaging, warehousing and storage, or at the construction site. Tool impact or a dropped panel might cause a puncture. The section on "Protective Enclosures" addresses a method that is useful in reducing these types of punctures. A puncture or loss of vacuum failure is evident by a very obvious loss in panel stiffness. If this occurs the R per inch of the glass core will revert to a COP R per inch of 4 and must be replaced as it cannot be repaired in the field.

It can be argued that more subtle VIP failure might be caused by a pinhole that might occur due to the environmental conditions surrounding the panel within the insulation cavity of the building. These include crevice corrosion from moisture, thermal stresses and strains from the imposed and ever changing temperature gradients, and movement of the envelope due to small changes in atmospheric pressure loadings.

Crevice corrosion of stainless steel foils was studied early in the Aura® VIP development program. These tests showed that the type 201L annealed stainless foil envelope can withstand long term water immersion without breach of the envelope (2). In addition, extremely corrosive environments may require the use of protective epoxies or other suitable coatings to improve the corrosion resistance.

Accelerated testing applying all conditions likely to affect the performance integrity of the panel will shed light on the robustness of the Gen3 VIP design package and allow for necessary iterations to achieve the intended goals. Of particular importance is to define the loads imposed by the building during its service life.

However, it can only be stated at this point of development that Gen3 VIP will have a static service life at least equivalent to the Gen1 Aura® VIP design if properly protected from these external influences.

3. GEN3 VIP PROTECTIVE ENCLOSURE, SLEEVE, AND STANDARDIZATION

3.1 Concepts

In order for a production Gen3 VIP to survive the conditions mentioned it will be necessary to design a suitable protective enclosure. The enclosure provides protection and panel interlocking. This enclosure must not degrade Thermal Engine performance or result in an increase in overall VIP dimensions that make it incompatible with the allowable confined space. Enclosure cost and simplicity are important factors as well.

Thin sheets of tempered aluminum or other hard materials like plywood may be suitable to protect the faces (only) of the VIP while keeping the panel weight down. Hot melt glues can be used to bond onto the foil surface since they have been successfully used in past Aura® VIP.

The edges are the most important and fragile areas and will require the most design thought. A thin foam perimeter extending to the edge of the foil of equal thickness to the VIP will provide the necessary protection and serve to square off the panel. A production step that encloses the VIP can be envisioned that will incorporate both the protective sheeting and the foam edging. It is further envisioned that the edge design can serve to either interlock the panels to each other or simply be butted up to each other.

Once the protective enclosure is built into the Gen3 VIP it is foreseen that a further protective perimeter packaging sleeve will be needed prior to panel boxing and packaging. This sleeve made of a durable and returnable plastic or plastic foam material will serve to further protect the VIP during packaging and during transit to the warehouse or job site. During the unpacking of the box the sleeve will be attached and then can be removed when the panel is finally installed into position.

Jobs at the construction site will require a variety of panel sizes in order to properly cover the wall, floor, or ceiling application exactly. The vision of Gen3 VIP is to make only a limited number of standard size panels and then produce custom sizes as needed to complete the job. This will keep the cost down and balance the needs of the customer.

3.2 Other issues

Gen3 VIP are recyclable. The basic materials of the design include glass fiber, stainless steel, and the enclosure materials. The sleeve is a part returnable to the manufacturer.

4. PRICING

It is too early to discuss pricing details as this information is considered proprietary and developing. What can be said for comparison purposes is that the Gen1 Aura® VIP was selling in the neighborhood of $4.00 per square foot for small size panels of 0.75 inch thickness. The innovations inherent to the Gen3 VIP design focus on achieving the stated target of £30/m² ($4.00/ft²) or lower as possible (7). The material costs, labor and process point to a favorable realization of this target.

5. CONCLUSIONS AND NEXT STEPS

Gen 3 is a feasible and proprietary new VIP product design requiring solid partnerships and financial backing in order for it to become a production reality. An estimate of tasks, pilot line construction, and the timeline for manufacturing indicate that this product could be available in trial quantities within the year following completion of all agreements and confidentialities. The technology is robust and well known to the author. The majority of issues have either been resolved or validated in the author's Gen1 and Gen2 VIP designs.

6. ACKNOWLEDGEMENTS

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8. APPENDIX OF TERMINOLOGY, CONVERSION FACTORS, AND THERMAL PROPERTIES

Foil thickness T 1.0 mils = 25.4 microns
Foil thickness T 1.0 mils = 0.001 inches
Length 1.0 inches = 25.4 mm
Length 1.0 inches = 2.54 cm
Length 1.0 foot = 0.3048 m
Fiber diameter 1.0 HT = 0.254 microns
Area 1.0 square foot = 0.0929 m^2
Density 1.0 lb/ft^3 = 16.0179 kg/m^3
Density 1.0 pcf = 1.0 lb/ft^3
Pressure 1.0 Torr = 1000 m Torr
Pressure 1.0 Torr = 133.322 Pa
Pressure 1.0 m Torr = 0.13332 Pa
Temperature 75.0 degF = 23.89 C
Delta Temperature Δ 1.0 degF = 0.555 K
R-Value 1.0 R (US) = 0.1761 RSI
U-Value U (US) = 1/R (US) and U (SI) = 1/RSI
Resistivity 1.0 R per inch = 6.9348 mK /w
Thermal conductivity 1.0 Btu-in/(hr ft^2 degF) = 0.1442 w/(m K) = 144.2 milli-w/(m K)
Convective heat transfer film coefficient 1.5 Btu/hour/$foot^2$/degF = 2.89E-06 Btu/s/in^2/degF (150% times ASHRAE Factor)
Heat flux 1.0 Btu/hr/$foot^2$ = 1.93E-06 Btu/s/in^2
Aspect ratio = dimensionless ratio of the longer side of the VIP to the shorter side
Gen3 fiber glass thermal conductivity = 1.333E-2 Btu-in/hour/ft^2/degF
K of 201L stainless steel thermal conductivity = 113.02 Btu-in/hour/ft^2/degF
K of Aluminum thermal conductivity = 1629.4 Btu-in/hour/ft^2/degF