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Performance of Vacuum Insulation Panels in Building Energy Conservation

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ABSTRACT: *In this study, building energy simulations were performed to explore the application of Vacuum Insulation Panels (VIPs) for building insulation. The simulations were done to compare the use of traditional building insulation to the use of VIPs in relevant areas of a building. Also, the study was extended to investigate the outcome if the same building is located in different geographical areas and climates. The results show that in moderate to cold climates VIPs can account for an overall building energy savings of up to 10%. In warmer months, particularly in the warmer climates, the savings were found to be insignificant. This implies that in hot climates the energy savings is not much. For winter months in colder climates energy savings were found to be in the range of 10% to 16%. Thus VIPs have the potential to save energy in moderate to cold climates, especially during the coldest months of the year and can be a valuable application for green buildings located in areas that have more of such weather conditions.*

KEYWORDS:*-Building energy conservation, green buildings, thermal energy transfer, vacuum insulation panels*

I. INTRODUCTION

Conservation of energy has become very important as energy costs continue to rise. Consequently, building energy conservation has emerged as a key area of research and development. The operation of buildings in the United States alone uses almost forty percent of the nation's annual energy supply [1]. Related information on Europe's annual energy supply also show that building space heating and cooling demands about the same percentage of energy consumption. Many materials and applications have been used to insulate buildings. There have been some improvements in recent years as new materials are emerging with some having better insulating properties but with higher cost. A recent example is Vacuum Insulation Panels (VIPs). This is an effort to implement vacuumed space in thermal boundary walls for substantial insulation. Studies have shown that for the same thickness, the thermal resistance of an evacuated insulation is up to ten times better than conventional insulation materials such as fiberglass, polyurethane and polystyrene.

Related research on VIPs include Kaynaki [2] which reported a study to determine optimum thickness of building insulation and its effect on energy consumption. Xiao et al. [3] explored the influence of wall insulation thickness on building energy consumption. Other than climate, building type, and indoor heat gain, external wall insulation were found to have about the most influence on energy consumption in buildings in the study. The results show that the increase in insulation thickness helps reduce building energy consumption. Friess et al. [4] investigated the impact of building insulation on building energy consumption. The study showed that with appropriate external wall insulation alone energy savings can be up to 30%. Korolija et al. [5] used EnergyPlus to explore how to select an appropriate HVAC system and provided guidelines for selecting HVAC systems for UK office buildings. Bojic et al. [6] investigated possibilities for decreasing the energy used in a Serbian home that was not thermally insulated and found that the single best refurbishment procedure was insulating the external walls. Hens and Wouters [7] and Petersson [8] studied the effect of insulating roofs and ceilings on building energy consumption and found that energy consumption was greatly reduced with improved ceiling insulation.Johnasson [9] did a literature survey on VIPs and recommended promising areas for future applications. Fricke et al. [10] investigated the thermal properties and some applications of VIPs and concluded that understanding thermal transport in VIPs is necessary for its further applications. Brunner and Simmler [11] studied application of VIPs to buildings and also, compared the findings to laboratory simulations.

A VIP flat roof construction was studied for three years. The results were used in predicting the service life of VIPs. Alam et al. [12] explored VIPs' use in building construction by reviewing their contemporary developments and possible future directions. Conclusions from the study and future directions included needing to develop ways for VIPs to last longer and lower market prices.Tseng and Chu [13] studied the effects of adding polyethylene (PE) in polystyrene (PS) foaming material on the cell structure and heat transfer of VIPs. Results from the study show that adding 2 to 5% PE altered the cell structure and reduced the heat transfer through the VIP whereas adding more than 5% did not improve the heat transfer performance further. Kwon et al. [14] studied three thermal transport mechanisms of a number of filling materials for VIPs with special emphasis on the solid conduction. The results show that due to the relatively long thermal path, solid conductivities of the fiber and staggered beam insulation are lower than those of foam and powder. The study also found that fiber and staggered beam structures demonstrate promise as filling materials for VIPs. In this present study, a typical residential building constructed with traditional building insulation materials was interfaced with the EnergyPlus program. Computer simulations were performed to study the energy demand by the building. Thereafter, simulations were also performed for the same building to study how the effect of applying VIPs as a building construction material to relevant areas of the building will affect the energy consumption. Areas investigated included external wall insulation and ceiling. The results of the energy demand by the building for the two different cases were compared. The study was extended using the same building to study the comparison for different geographical areas and climates of this country, namely the northeast, the northwest, the southeast, the southwest and the mid-region (mid-west). The results of the study were summarized and discussed. Based on these, recommendations were made for the best applications of VIPs.

II. THERMAL ENERGY TRANSFER THROUGH THE VIP

Vacuum Insulation Panels can be described as an evacuated open porous material located inside a multilayer envelope [12]. A vacuum within the core eliminates convection heat transfer and reduces conduction heat transfer. Figure 1 is a schematic of the VIP. It is composed of three parts, namely, an inner core, the barrier envelope, and

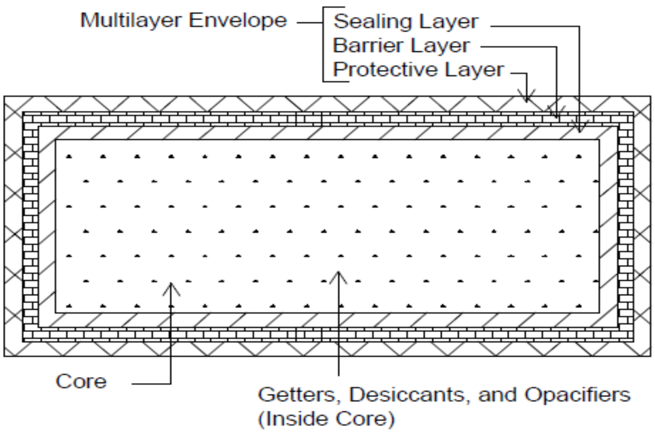

Figure 1: Schematic of a VIP

getters. The inner core is made of low conductivity porous material that has the purpose of maintaining the physical support of the panel under vacuum conditions. The porous cells in the material are connected thus forming a network that makes it possible for all the gases to be evacuated. The barrier envelope is composed of non-permeable thick metal sheets of multiple layers. The functions of the multiple layers are for protection and sealing, with a barrier in between. Getters are chemicals within the VIP that collect gasses that do slip through the membrane. Compared to most common building insulators such as, fiberglass, mineral wool, VIPs have a potential to have up to eight times higher thermal resistance to heat transfer [11]. Performance of conventional insulators is limited by gas conduction inside the porous materials.Thermal energy transfer through the VIP is by solid conduction, radiation and gaseous conduction. The structure and material properties of the core control solid conduction. Thermal radiation energy transfer is dependent on the structure and optical properties of the core.

The gas conduction also depends on the gas pressure. Collision between the gas particles limits efficient heat transfer at a high pressure where the mean free path of the gas molecules is much smaller than the size of the pores. Gas conduction is also determined by the thermal conductivity of the non-convective gas. The effective thermal conductivity k_{eff} of the VIP can be written as:

$$k_{eff} = k_s + k_r + k_g \qquad (1)$$

In this equation, k stands for thermal conductivity and the subscripts s, r, and g stand for solid, radiation and gas respectively.

The theory of gaseous thermal conduction is based on the concept of temperature jump or discontinuity. For two parallel plane surfaces at temperatures T_1 and T_2, separated by a small distance L, Kwon [14] gives the energy flux q_g between the surfaces as:

$$q_g = \frac{k_g}{L + 2\beta}(T_1 - T_2) \qquad (2)$$

In this expression, β is described by the equation,

$$\beta = \left(\frac{9\gamma - 5}{2\gamma + 1}\right)\left(\frac{2 - \alpha}{\alpha}\right)\lambda$$

(3)

where, γ is the specific ratio of the gas, α is the thermal accommodation coefficient and λ is the mean free path for the gas. VIP is a thin material and so the heat transfer through the central core can be modeled as a one-dimensional plane parallel medium. The radiant energy transfer is given by the expression [15]

$$q_r = -\frac{16\sigma T_m^3}{3\sigma_e(\nabla T)} \qquad (4)$$

where, σ is Stefan Boltzmann constant, T is absolute temperature, T_m is the mean of the boundary temperatures and σ_e is Rosseland mean extinction coefficient defined as:

$$\frac{1}{\sigma_e} = \int_0^\infty \left(\frac{1}{\sigma_{e_\lambda}}\right)\frac{\partial e_{\lambda_b}}{\partial e_b}\,d\lambda \qquad (5)$$

In this expression, e_b is total emissive power of a blackbody, $e_{\lambda b}$ is the spectral emissive power and λ is the wavelength of the thermal radiation. It is also important to include the heat transfer at the edges of the VIP due to conduction. The barrier material for the edges are required to have low water vapor and gas permeability and should surround the evacuated core completely. Schwab et al. [16] gave the expression for the overall or effective thermal transmittance U_{eff} for the barrier laminate that completely covers the evacuated core of the VIP as:

$$U_{eff} = U_{cop} + \frac{L_p}{A_s}\psi_{vip,edge} + \frac{1}{A_s}\sum_{i=1}^{N}\chi_{vip,corner,i}$$

(6)

where L_p is the perimeter of the panel or circumference, N is the number of corners, A_s is the surface area of the panel, $\psi_{vip,\,edge}$ is the linear thermal transmittance of the edge and $\chi_{vip,\,corner}$ is the corner thermal transmittance. For this equation, Tenpierik and Cauberg [17] stated that the center of panel thermal transmittance U_{cop} for conventional insulation materials including their environment can be expressed as:

$$U_{cop} = \left[\frac{t}{k_{cop}} + \frac{1}{h_i} + \frac{1}{h_o} \right]^{-1}$$
(7)

where t is the thickness of the panel, k_{cop} is the thermal conductivity of the panel, h is the heat transfer coefficient and the subscripts i and o stand for inside and outside respectively. Usually, the third term on the right hand side of equation (6) can be neglected by assuming that the corner thermal bridge effect is small compared to the effect of the thermal edge.

III. BUILDING DESCRIPTION AND PROCEDURE

The house used for this study was designed for 2000 square feet, (about 186 square meters), which is typical for today's average family residential building. Figure 2 illustrates the floor plan for the building used in this study. The building has three bedrooms, including a large master suite, two bathrooms, an average sized

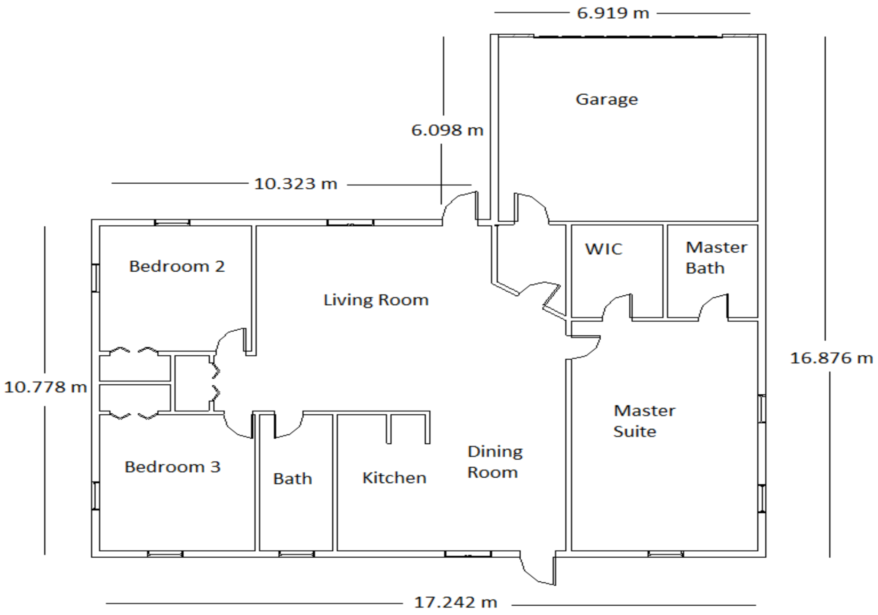

Figure 2: House Floor Plan

kitchen, a dining room and a large living room. Also included in the building are, a two car garage and a typical attic space. All aspects of the construction are considered to be very typical. Exterior and interior wall studs were designed with 16-inch spacing on center. Exterior walls are composed of wood siding, a layer of insulation, and plasterboard from exterior to interior. Interior walls are considered to have just plasterboard on both sides. The roof consists of a few layers from exterior to interior, asphalt shingles, and plywood. The ceiling is composed of a layer of insulation and plasterboard from the exterior to interior. The windows used consist of three layers with exterior layers made of 3mm thick glass, and the interior consisting of 6 mm of air. Exterior doors are also basic and made of wood. The garage door is made of a material similar to the steel siding. Energy for the garage was not modeled because typically, the garage is not served by the HVAC system in most family residential buildings.All of the equipment in the house that uses electricity were divided into three groups, namely, lighting, heating and cooling, and others. An electric heat pump system was implemented for the building. The heating and cooling was run on the same schedule not only to ensure that temperatures were always within a comfortable range but also to maintain the same standard for the different regions studied. The set point used for heating was 20°C (68°F) and that for cooling was 24°C (75.2°F). Other equipment/appliances implemented in the model included a hot water heater, four ceiling fans, one vacuum cleaner, a clothes dryer, a clothes washer, one video game system, one HD receiver, a Blu-ray player, three cell phones,

two computers, one tablet, two clock radios, one stereo player, two TVs, one coffee making machine, a microwave oven, a dishwasher, and a refrigerator/ freezer combo. Tables 1 and 2 show the relevant properties for the materials implemented in this study. While Table 1 shows the R-values for the building materials, Table 2 shows the thicknesses and relevant thermal properties for the fiberglass batting and the VIP used.

Table 1: R-values for Typical Building Insulation Materials [14]

R-Values for Typical Building Insulation Materials		
Material	$m^2 \cdot K/(W \cdot in)$	$ft^2 \cdot °F \cdot h/(BTU \cdot in)$
Fiberglass Blanket	0.55-0.76	R-3.1 – R-4.3
Rockwool Blanket	0.52-0.68	R-3 – R-3.85
Blown in Fiberglass	0.44-0.65	R-2.5 – R-3.7
Blown in Cellulose	0.52-0.67	R-3 – R-3.8
Spray Foam Open Cell	0.63	R-3.6
Spray Foam Closed Cell	0.97-1.14	R-5.5 – R-7
Foam Board	0.63-0.95	R-3.6 – R-5.4
VIPs	5.28-8.8	R-30 – R-50

Table 2: EnergyPlus Data for Fiberglass Batting and VIPs

Material	Thickness (m)	Conductivity (W/m-K)	Density (kg/m^3)	Specific Heat (J/kg-K)
Fiberglass Batting	0.066	0.04	12	840
VIPs	0.0254	0.005	190	800

The procedure adopted in the study assumed that the materials used in the building construction had uniform thicknesses. Material degradation over time was not considered. The following is a list of the steps taken in the procedure.

[1] Selection of the building and the contents.
[2] Construction of the model of the building in EnergyPlus environment. This included all of the building surfaces, fenestration, schedules, etc.
[3] Performance of simulations to fix any arising errors.
[4] Selection of the materials along with the properties necessary for the simulations.
[5] Performance of annual simulations with the working model based on the representative city and the weather data for the region being studied.
[6] Recording the results along with the associated data.
[7] Selection of a new representative city with its weather data for the new region and repeating steps 5 and 6.
[8] Continuing the steps 5 to 7 until simulations were completed for all the regions. It should be noted

here that the simulations were performed for five different regions of the United States. The study involved locating and studying the building energy demand in the following regions, namely, the Midwest, Northeast, Southeast, Southwest, and Northwest. These cities for the locations were Carbondale-Illinois, Boston-Massachusetts, Orlando-Florida, Phoenix-Arizona, and Seattle-Washington, respectively. The weather files for each city stored in the program, were used in the simulations.
Analysis of the results.

IV. RESULTS AND DISCUSSION

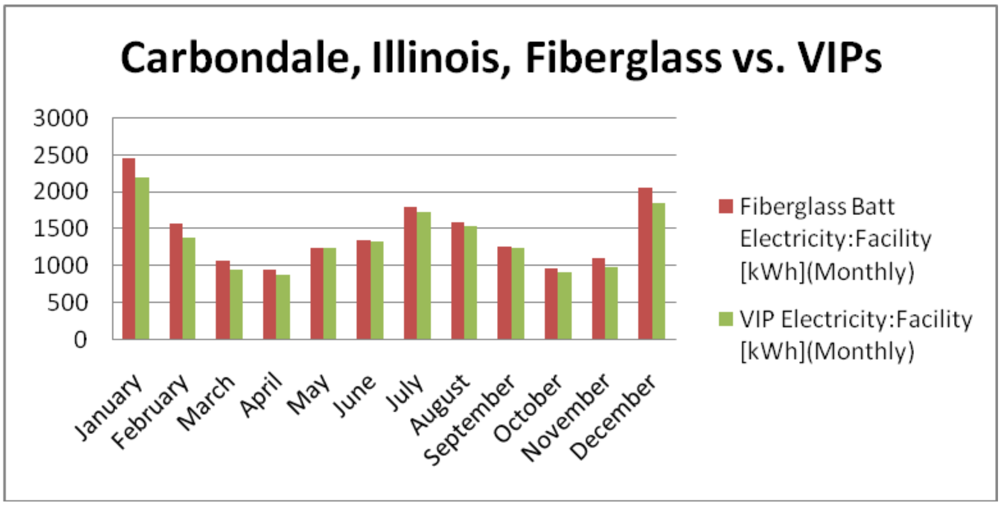

Figure 3 shows comparison of performance of fiberglass batting and the VIP in the building for Carbondale IL representing the mid-west region of the country. This illustrates the savings VIPs can provide

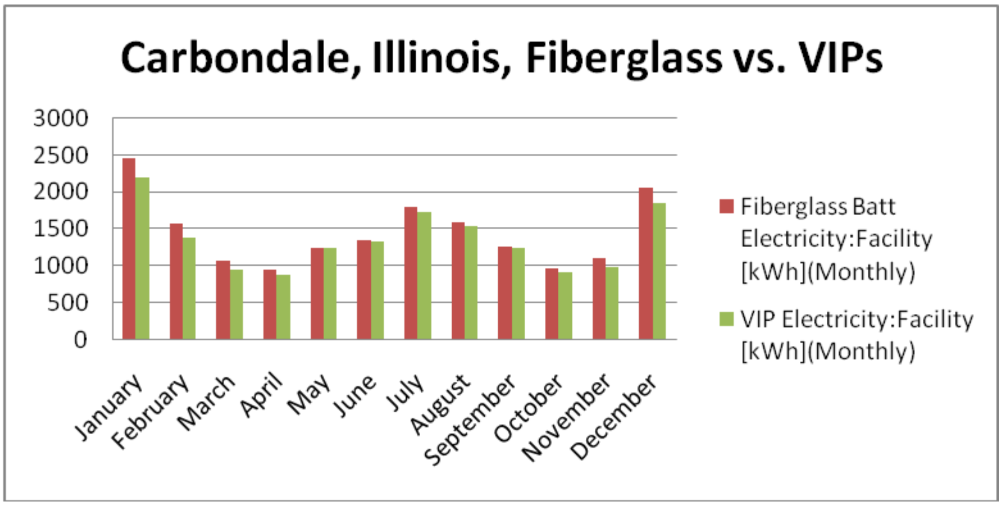

Figure 3: Results for Carbondale, Illinois, Fiberglass vs. VIPs

over fiberglass batting as wall insulation. As can be seen in the figure, electricity is saved every month. Figure 4 shows the savings broken down by month shown as percentages. The greatest savings can be seen to occur in the winter months. It can also be seen that in these colder months the electricity savings is always over 10%, peaking at 13%. This shows that VIPs are more effective during the winter months. During the summer, the hottest months, the savings are much lower than the winter savings. During the periods in-between, the savings are minimal.

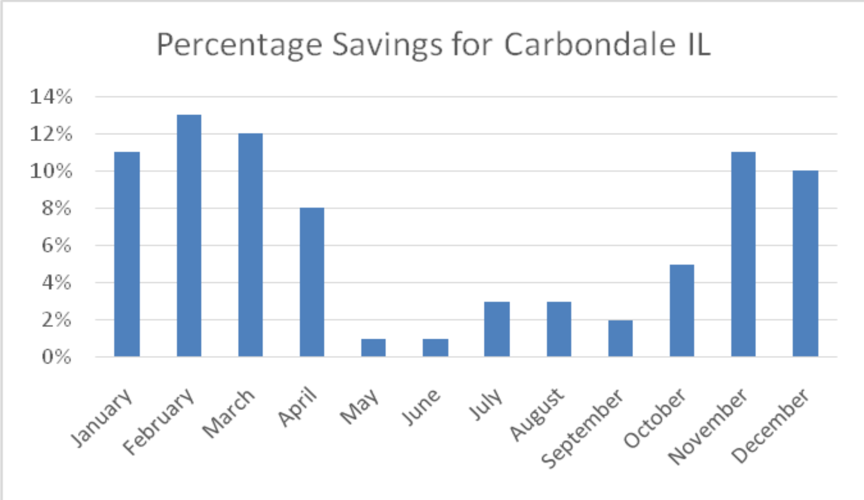

Figure 4: Percentage Savings for Carbondale, IL, Fiberglass vs. VIPs

Figure 5, compares the performance of the VIP to the fiberglass batting as wall insulation in Boston, Massachusetts. The total electricity usage showed an 8% savings with VIP over that with fiberglass batting.

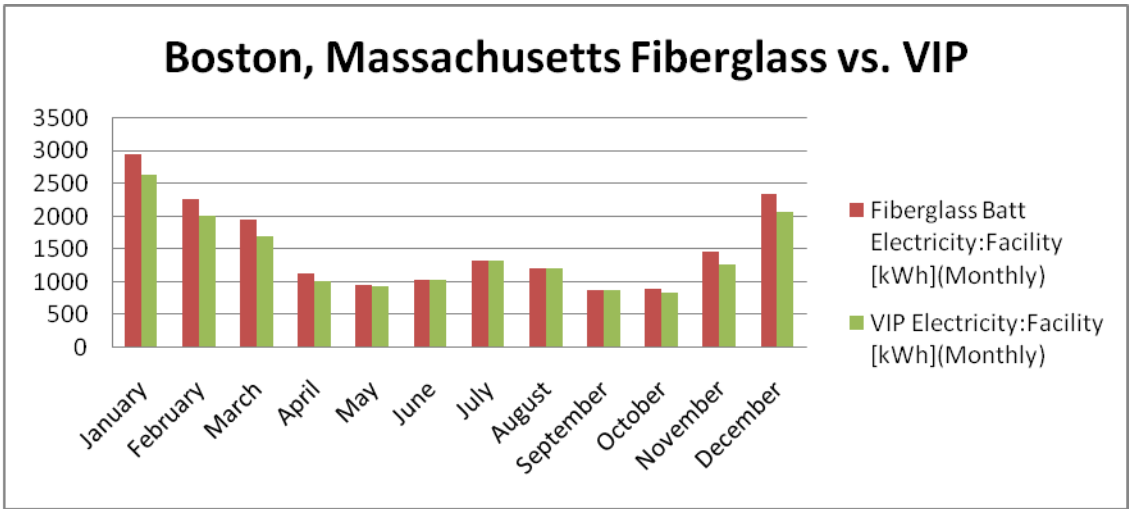

Figure 5: Results for Boston Massachusetts Fiberglass vs. VIP

The monthly energy savings when using VIPs instead of fiberglass batting are shown in figure 6. It is seen that throughout the warmer months there is virtually no savings, i.e., 1% or less for four months. For the winter, the colder months, there are significant savings. For six months out of the year, electricity usage was reduced by 10% or more.

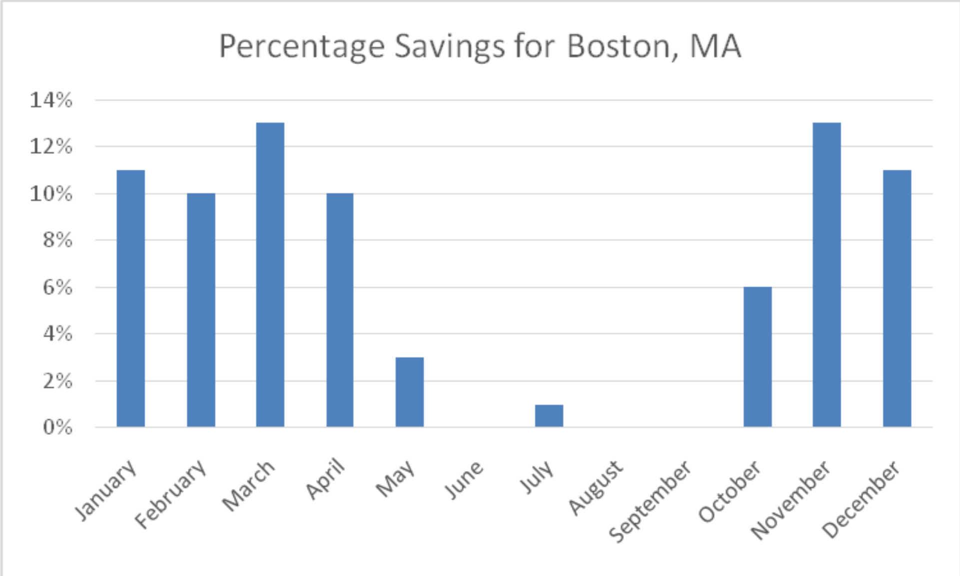

Figure 6: Percentage Savings for Boston, MA, Fiberglass vs. VIPs

Simulations were also performed for Orlando, Florida to investigate the performance of VIPs in houses located in the southeast region of the country. Figure 7 shows the results for fiberglass batting as wall insulation compared to VIP in that region.

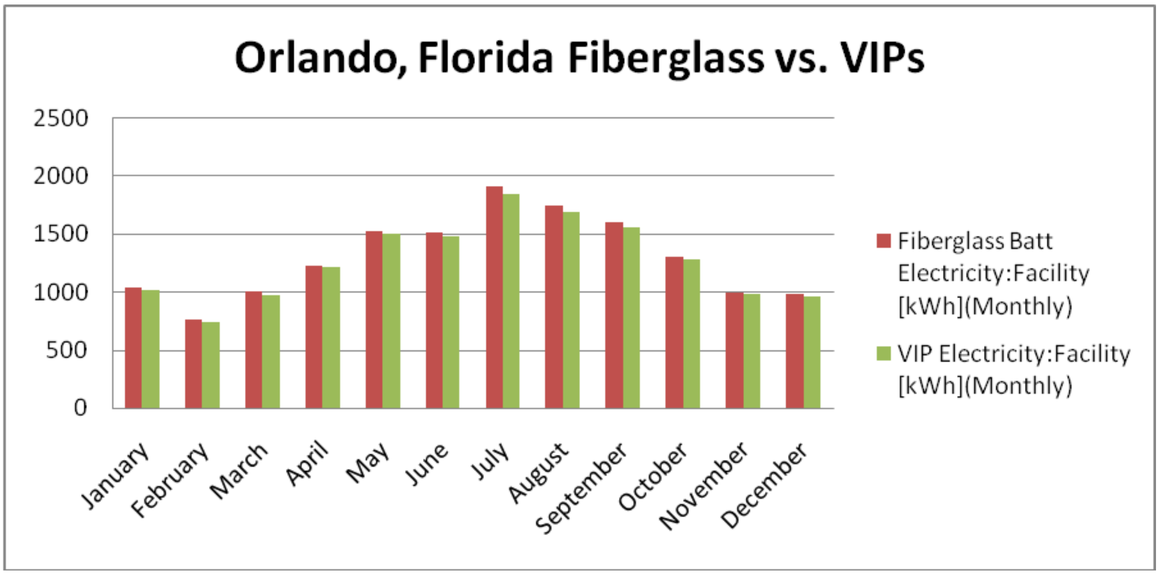

Figure 7: Results for Orlando, FL, Fiberglass vs. VIPs

In figure 8, the energy savings are broken down monthly, and shown in percentages. In a climate like Orlando, Florida, the high and low temperatures do not fluctuate as much as those in the more northern climates, and are warmer overall. The energy saved when using VIPs instead of fiberglass batting was never higher than 4% for a month. This implies that in this climate, and similar ones, VIPs do not have a large impact.

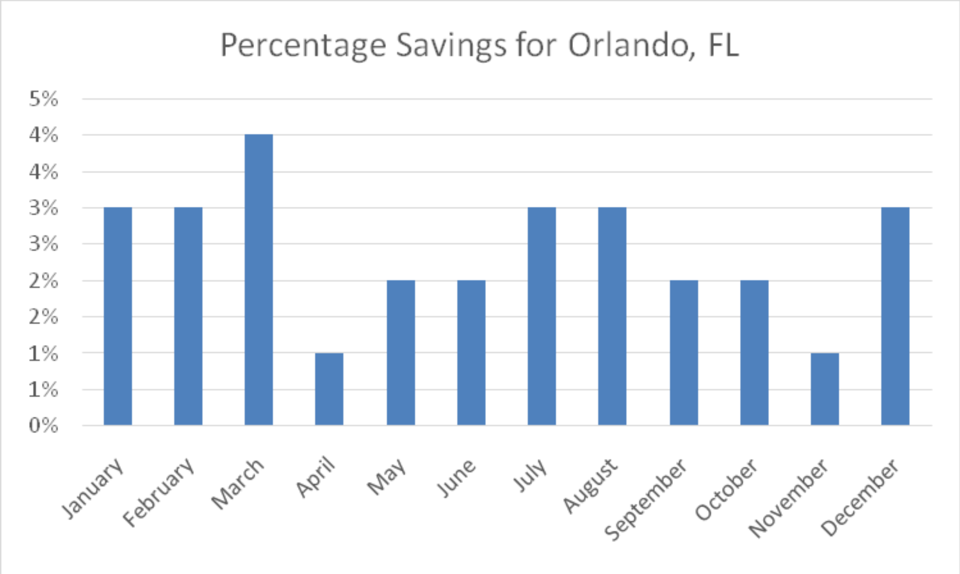

Figure 8: Percentage Savings for Orlando, FL, Fiberglass vs. VIPs

Simulations were also performed for Phoenix, Arizona to investigate the performance of VIPs in the southwestern region of the country. Figure9 shows the results for fiberglass batting versus VIPs in this

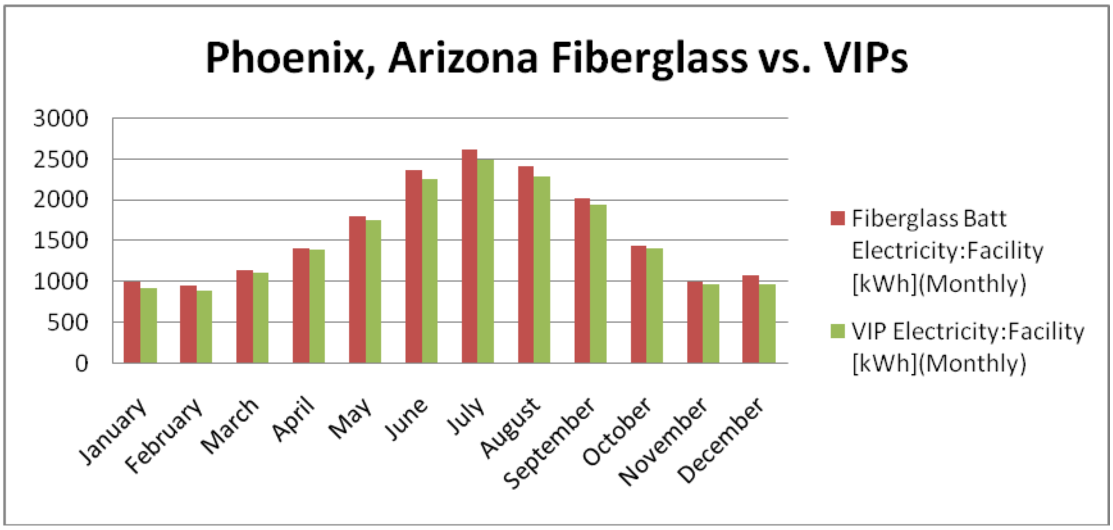

Figure 9: Results for Phoenix, Arizona, Fiberglass vs. VIPs

region. Figure 10, shows the energy savings broken down by month and reported in percentages. It can be seen that in the colder, winter months, there are some meaningful savings. In the three coldest months electricity used is reduced by 7% monthly. As for the rest of the year, savings are seen to be less significant. Overall, it can be concluded that electricity savings in Phoenix-Arizona are likely not significant enough to implement VIPs as wall insulation for the building. Simulations were also performed for Seattle, Washington

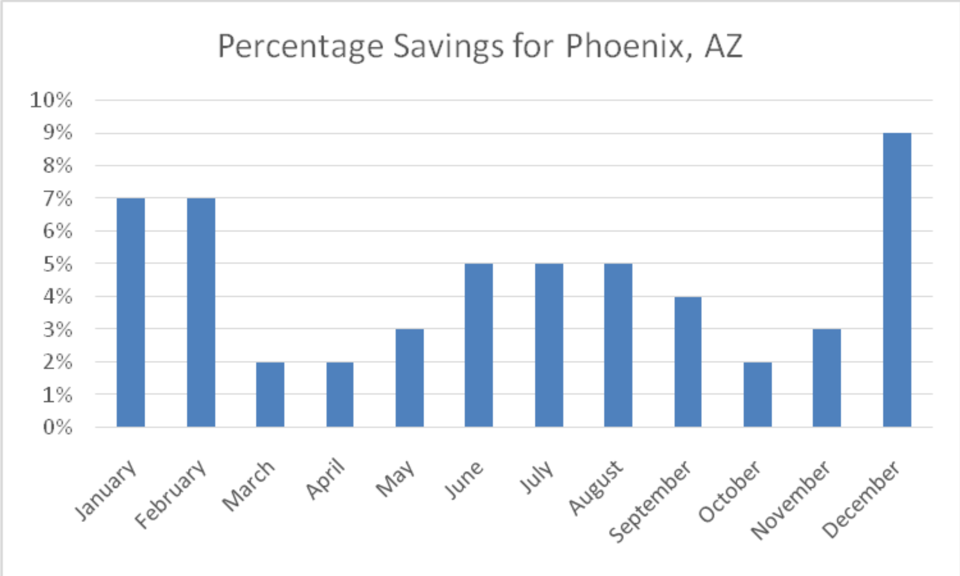

Figure 10: Percentage Savings for Phoenix, AZ, Fiberglass vs. VIPs

to investigate the performance of VIPs in houses located in the northwestern region of the country. Figure 1 shows the results for fiberglass batting as wall insulation versus VIP for this region. Monthly percentage savings for Seattle WA, are shown in figure 12. The savings in this region show to be the highest among all

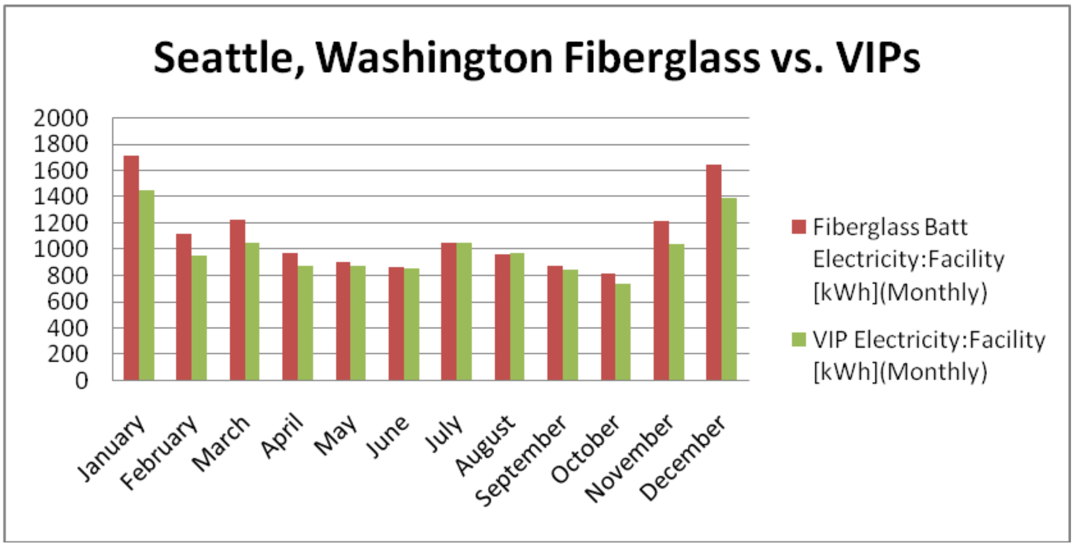

Figure 11: Results for Seattle, Washington, Fiberglass vs. VIPs

the regions studied. Monthly savings of between 14% and 16% were obtained for the months of October to April. During the warmer months (May to September), little or no savings, of between 0% and 1% were obtained. Thus the savings in the relatively colder months are seen to be quite significant.

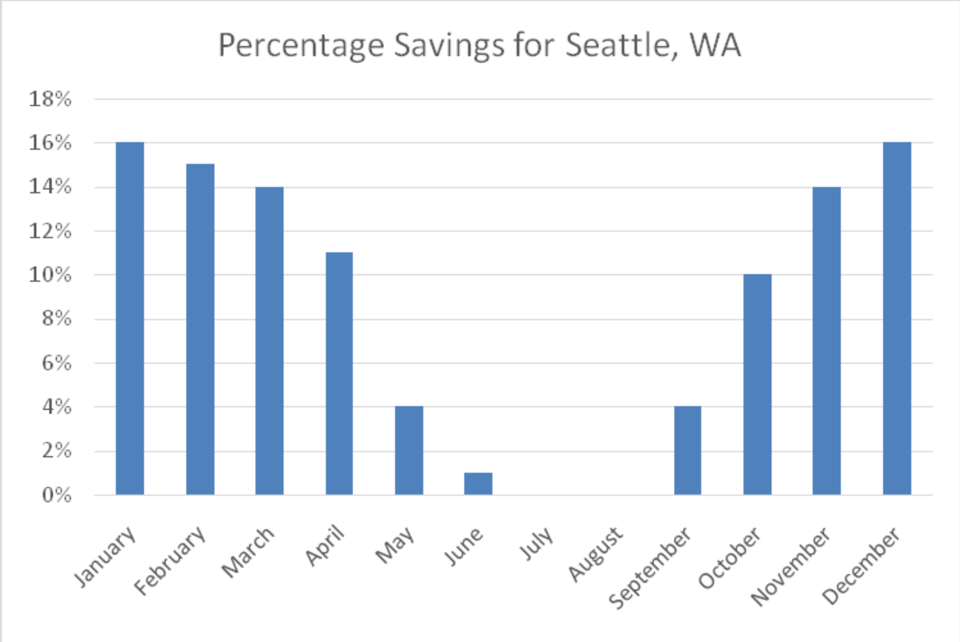

Figure 12: Percentage Savings for Phoenix, AZ, Fiberglass vs. VIPs

Simulations were also performed for each location to explore the application of VIPs as insulation in ceilings. The use of insulation in ceilings is important, as large heat loses or gains may occur there. Hence,

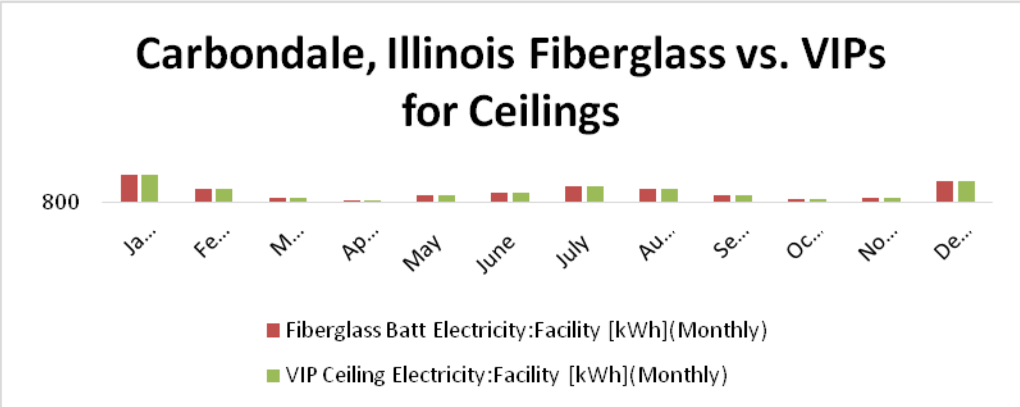

Figure 3: Results for VIPs as Insulation in Ceilings

it is important to have the right level of insulation in ceilings. Simulations were performed with fiberglass batting ceiling insulation in the building and compared to the use of VIP as ceiling insulation for all the five cities (regions) studied under wall insulation. The results for Carbondale, IL (the mid-west region) are shown in Figure 3. This data shows electricity energy use by month for both ceiling insulations. The graph clearly shows the minimal savings. Results were found to vary only slightly by location. Hence only the results for the mid-west region represented by Carbondale, IL are shown here. The savings show to be only less than half of a percent.

V. CONCLUSIONS

In this study, computer simulations were performed on a typical family residential building to study the energy demand by the building using conventional wall and ceiling insulation materials compared to using VIP as the insulation material. The application of VIP as wall insulation showed electricity savings ranging from 2% to 10%. The lowest savings were for the southeast and the southwest regions of the country, at 2% and 4%

respectively. With this result, it is not be recommended that VIPs be used as an energy saving option for these areas at this time. It is anticipated that the cost of VIPs will come down with time as more research is done on it. The other three regions of the country, namely, the mid-west, northeast and northwest regions, showed savings of up to 7%, 8%, and 10%, respectively. Thus VIPs could be effective energy savers as wall insulation material in these areas. The simulations performed by using VIP as insulation material for the ceiling in all the cities or regions showed only very slight energy savings. Thus is not recommended that VIPs be used at this time as ceiling material in these areas.Another important trend also emerged from this study. Savings in the colder months were found to be significantly greater than those for the warmer months. Savings were also significantly greater in colder climates. During the months with the hottest temperatures in the hottest climates the savings were found to be not much, i.e. zero to one percent. During the five coldest months in the three coldest climates, VIPs showed savings of at least 10% of energy use compared to fiberglass batting. Therefore for areas where relatively long cold months in the year, VIPs could be implemented for considerable energy savings.

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