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Cold Climate Considerations: An Evaluation of Envelopes for Rapidly Deployable Shelters

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ABSTRACT HEADING

Rapidly deployable shelters (RDS) are shelters that can be erected in a short amount of time, without the assistance of heavy equipment, are transported in a reduced volume form, and contain all their planned fixtures when packaged. RDS are utilized and deployed across many fields including: the military, disaster relief housing, emergency management, oil and mining operations, and field research. Due to increasing development and deployment activities in cold climate regions, a major issue is the lack of cold climate capable RDS on the market. For traditional buildings in cold climates, more than 70%, on average, of a structure's annual energy consumption is used for space heating and this percentage is even higher for a typical RDS. Currently, a majority of cold climate RDS deployments are based on modular building systems with containerized shelters being the primary choice for RDS. Therefore, the Cold Climate Housing Research Center, Inc., National Renewable Energy Laboratory and the University of Alaska's, Alaska Center for Energy and Power have conducted research on containerized shelter building envelope needs for cold climate RDS. An effective building envelope should 1) cost-effectively reduce building energy usage; 2) acknowledge embodied energy tradeoffs; and 3) be capable of withstanding field condition deployments. Preliminary evaluations on multiple insulation options currently on the market have been conducted ($/ft2/R-value for one inch thickness). Two insulation options that pursue different optimization priorities were selected and lab evaluations are being carried out. .. Results of these evaluations will inform construction of a demonstration prototype. Data gathered from the evaluations and prototype will inform proposed cold climate RDS design requirements for several stakeholders. These requirements will ultimately reduce the energy impact of RDS in cold climates going forward.

INTRODUCTION

Rapidly deployable shelters (RDS) are shelters that can be erected in a short amount of time, without the assistance of heavy equipment, are transported in a reduced volume form, and contain all their planned fixtures when packaged. There are many applications for RDS, including military, disaster relief housing, emergency management, oil and mining operations, and field research. Some examples of RDS include containerized shelters, tents, hangar, and panelized/flatpack shelters.

In recent years there has been an increasing development, exploration, and deployment activities in cold climate regions around the world. However, there is the lack of RDS that suitable for use in cold climate regions currently on

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the market. According to, on average 70% of a traditional building structure's annual energy consumption is used for space heating in cold regions. This percentage value would be higher in RDS and even higher if a RDS is not properly adapted for a cold climate region because a shelter with low R-value for its insulation means a higher wattage is required to heat the shelter.

Currently, the majority of RDS on the market that claim to be adapted for cold climate regions have the properties of being containerized and have a modular building system (MBS). The term "Containerized" means the entire shelter comes in one rigid package that is ready to move into once it is set on the ground. In general, containerized shelters are designed to conform to International Organization for Standardization (ISO) shipping specifications for ease of transport. Due to the specific ISO regulations, containerized shelters are very constrained by space, which often results in poorly insulated for cold climate conditions.

MODULAR CONSTRUCTION

Regulatory

One of the main regulations of MBS is that they are constructed to be International Code Council (ICC) compliant for the local jurisdiction of their destination. This means that RDS that have MBS are built to standards just like on-site constructed building systems. Since there are no specific construction codes for modular constructions in the United States, this means that the International Building Code (IBC), International Residential Code (IRC), and the International Energy Conservation Code (IECC) dictates the general construction process. (J. Wilson 2019) The finishing touches and final compliances are then deferred to local code authorities where the RDS is deployed. (J. Wilson 2019). Modular buildings can be constructed to be relocatable or permanent; the choice dictates the pertinent building code section that the system must follow. Even if they are used for residential purposes, MBS are not required to meet the US Housing and Urban Development code for manufactured housing (International Code Council 2020b). Canadian MBS are constructed under a similar regulatory process through the National Building Code framework (Modular Building Institute 2020b). Regulatory requirements can be specific to a jurisdiction and an MBS manufacturer may create a line of buildings that is only meant to be deployed in a certain geographic region, such as the Black Diamond Group's Britco line of products, which is manufactured for code compliance in the Canadian province of British Columbia and their BOXX modular line, which is manufactured for use in all other Canadian provinces (Black Diamond Group 2021).

Industry Financial Model

Modular building companies own more than 90 percent of the available relocatable units in North America, and the industry is driven by companies leasing units for temporary use across different industries such as education, healthcare, commercial, security, and humanitarian (Modular Building Institute 2020a). The building-code environment can prevent units from being relocated to inappropriate locations if the local authority with jurisdiction does not approve the design. The temporary use by the client and the depreciation of the unit for the owner disincentivizes high performance or above-code construction for energy efficiency or decarbonization.

TYPES OF DEPLOYABLE MODULAR BUILDING SYSTEMS

Relocatable MBS are built to be deployed quickly, broadly, and/or repeatedly and have been historically utilized in cold climates by extraction industry companies for worker facilities (Modular Building Institute 2020a). The three commonly used MBS are conventional, modified shipping containers, and panelized structures

Conventional

Conventional MBS that are relocatable in North America are similar in construction to manufactured homes, as they are completely constructed offsite, wood-framed with an IBC compliant building envelope, and moderately customizable in their footprint. The complete construction of the unit before site delivery can complicate transportation to remote sites, and they are not constructed to be stackable for transportation or combinable in the field (J. Wilson 2019).

Modified Shipping Containers

In recent years, the desire to modify intermodal steel shipping containers for building applications has led to an increase in their use as relocatable MBS. These shelters are built to ISO standards and are desirable due to their durability, structural integrity, and inherent ease of shipping (Shen et al. 2019). The appeal of using shipping containerized shelters is the ability to easily make it modular and connect one another to make one big shelter. The downside is the container must be modified for human occupancy. This entails installing a fenestration and HVAC system, which can render the ISO structural analysis obsolete and require additional structural and life safety analysis before occupancy is allowed (International Code Council 2019). The rigid size of containers can vastly limit the applicability of modular ability, e.g., installation of insulation, interior framing and/or finishes.

Panelized Structures

Panelized shelters attach prefabricated panels on a steel frame and can be customized depending on the deployment of the structure (Modular Building Institute 2020c). Panelized MBS shelters are more commonly found in Europe than North America. These types of shelters tend to not be built to ISO structural ratings but can be pre-engineered to be stackable for specific site conditions. The panelized building product methodology allows flexibility in choosing unit combinations, transportation, exterior finishes, insulation, HVAC penetrations, and fenestration depending on its final deployment.

DESIGN CRITERIA

Thermal

The thermal performance of MBS shelter is important for cold climate regions. There are no high-performance standard for MBS shelters for Alaska. This allows manufactures to build shelters to the least strict options from any relevant building codes that apply. Although the manufacturer is following a code, it does not necessarily mean the shelter would be appropriate for high energy performance given the climate where its located. Therefore, this may lead companies to falsely claim their single MBS style is suited for cold climate conditions and falsely promote their ability to make MBS shelters adapted to cold climate conditions. For example, if a typical factory-built modular building is constructed completely offsite and slated for deployment in the US state of Alaska, then the manufacture must comply with the 2012 IBC and can withhold the requirement of meeting any iteration of the IECC. Alaska is a large state with significant regional variation in heating degree days. An example of this is Juneau and Utqiagvik with respective winter design temperatures and heating degree days (HDD) of 8F/8,335 HDD and -42F/18,467 HDD, respectively (University of Alaska Fairbanks Geophysical Institute 2021; U.S. Environmental Protection Agency 2019). Therefore, the more north in latitude a shelter is going to be deployed needs to be suited for a higher heating degree days.

Structural and Life-safety

Structural and life-safety need to be considered in shelter design. In cold climates the shelter should be designed to withstand seismic events, snow loads, and high winds. To assure they are safe, structures require analysis and approval by the authority with jurisdiction before allowing occupancy (International Code Council 2020a).

Foundation

In addition to significant regional differences in heating degree days, the terrain of cold climate regions vastly differs based on the latitude. For example, Alaska in the north has solid or continuous permafrost characterized by poor drainage with many thaw lakes and ponds covering up to 50 percent of the surface (Nations). While the terrain in the south terrain slowly changes from discontinuous to sporadic and finally absence of permafrost. Therefore, skids and pilings/blocks are the best option for foundations for shelters built in regions in the north with continuous permafrost due to the unstable soil of the active layer and the amount of snow. Wheeled chassis/skis/pilings/block or placing the shelter on directly the ground is acceptable for locations with stable soil.

Moisture Management

Effectively managing water in bulk, moisture, and vapor form is critical to the durability of a relocatable MBS. Sloped roofs, rain screens, and gutters are atypical envelope measures for dealing with bulk water in relocatable MBS. An air-tight envelope and engineered HVAC system need to be specified to handle the sensible and latent loads of the destination in conjunction with the outside air needs of the occupancy type. The structure's ability to handle diffusion via vapor retarders in varying climate areas needs to be considered; an appropriate assembly for one region may have durability risks in another if the building is relocated.

ENVELOPE SYSTEMS

The majority of RDS that claim to be adapted for cold climate are containerized shelters, and therefore, the physical size of the shipping containers is the most limiting design factor. The thermal envelope of a shelter takes up space. Adding more insulation reduces usable space but insulation is imperative for cold climate use. Various of envelope systems were studied to determine which, if any, are suitable for cold climate containerized shelters. Four types of insulation were considered: foam (EPS and XPS), polyisocyanurate (also called polyiso, ISO PIR, and PIR), aerogel and vacuum insulated panels (VIPs). The insulation types were evaluated based on their R-value, cost, longevity, durability, environmental impact, and construction technique. Figure 1 shows the carbon payback or the period the period between initial harvest and the point in time were the overall carbon balance equals the carbon storage before initial harvest, taken into account carbon debt and avoided fossil fuels for different insulation types (Mitchel et al., 2012). The two insulation types that are currently being evaluated in the lab are polyisocyanurate foam and VIPs. Ultimately, the deciding factor for the choice for the experiment is the environmental impacts. The polyiso was chosen in this case since it had the lowest carbon payback out of all the foam options.

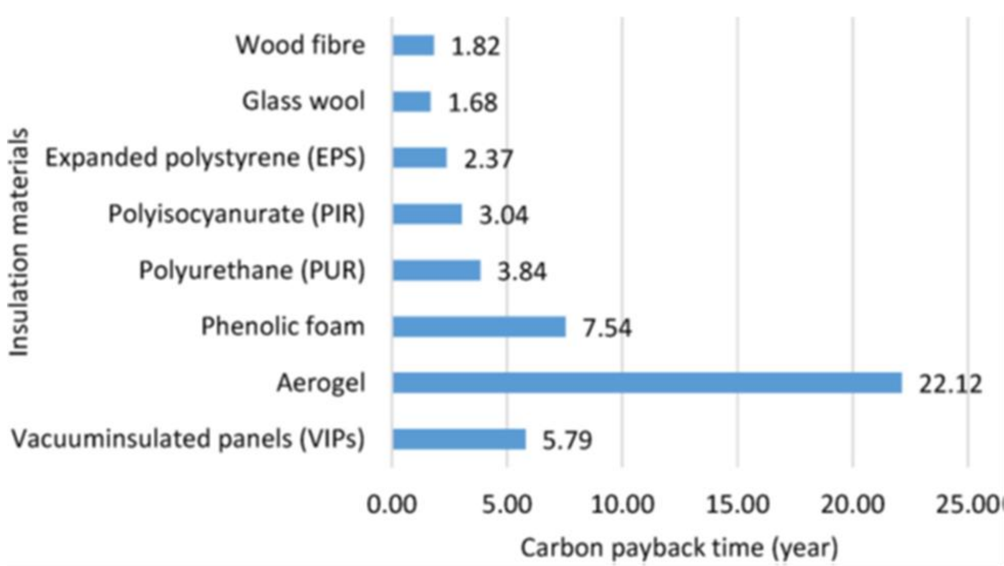

Figure 1 *The carbon payback time of insulating the solid wall of pre-1919 Victorian house stock with a pre-retrofit U-value of 2.1 W/(m2·K) (Li and Densley Tingley 2021)*

Polyisocyanurate

Polyisocyanurate, pertaining to modern residential and commercial construction, is a thermoset rigid closed-cell foam insulation. The foam material is made of three main constituents: methylene diphenyl diisocyanate (MDI), a polyester-derived polyol (organic compound), and pentane (volatile hydrocarbon). During manufacturing, the MDI and polyol components are applied at a mixing head, along with a catalyst and a blowing agent. The blowing agent boils in the fast-curing mixture and introduces bubbles as the mixture is mechanically formed/pressed to a specific thickness before hardening. When facer laminations are applied, the laminates are applied as the mixture enters the form/press.

Pentane is the current standard blowing agent for PIR foam board manufacturing, favored for its zero-ozone-depletion and relatively high thermal resistance characteristics. The chemical and thermal properties of the PIR foam products have a relatively higher established in-service R-value and modulus of elasticity (stiffness) than most other foam board insulations.

PIR foam board is available in varying thicknesses and with a variety of facer laminates, including fiberglass, organic materials (felt or other permeable fabrics), and metallic foils as well as with no facer materials. The most common PIR foam board laminate for building construction practices today is aluminum foil-facers on both sides.

Longevity and durability. Recent studies conclude that lab-aged PIR foam board insulation undergoes microstructural changes, including cellular elongation, increase in cell wall thickness, condensation of blowing agent, and diffusion of air in and blowing agent out of cells. A decrease in blowing agent up to 85% was measured. This lowers the R-value of PIR over time (Berardi 2019).

R-Value. Current manufacturers of PIR foam board insulation, such as R-Max, Dow Thermax, and Hunter Xci, advertise an R-value of between 6.3 and 6.7 for a 1-inch-thick foil-faced sheet and optimum cost per R-value per ft^2 at 2 inch or thicker panels.

Recently, industry recognized leaders in building technology for commercial, institutional, and residential applications, such as the Building Science Corporation (BSC) and the National Roofing Contractors Association (NRCA), have conducted extensive research and testing on new and aged PIR insulation under various climate conditions (Building Science Corporation 2013; Graham). Their most recent studies indicate that the actual performance of current-generation PIR insulation produced by several major manufacturers are significantly and consistently lower than the advertised R-values and are furthermore negatively affected by age of the product (off the shelf and installed) and the in-service temperature. Table 1 shows polyiso per inch thickness for aged samples at different mean temperatures (Building Science Corporation 2013; Graham).

Table 1. R-value, per inch thickness (2-inch specimens)

Sample Number	25 F	40 F	75 F	110 F
1	3.765	4.757	5.774	5.118
2	3.909	4.719	5.444	4.958
3	4.737	5.350	5.371	4.810
4	3.506	4.509	5.828	5.227
5	4.221	5.269	5.522	4.929
6	3.775	4.854	5.889	5.247
7	4.431	4.878	5.058	4.581
Average (mean)	4.049	4.905	5.555	4.981
Standard deviation	0.432	0.302	0.297	0.239

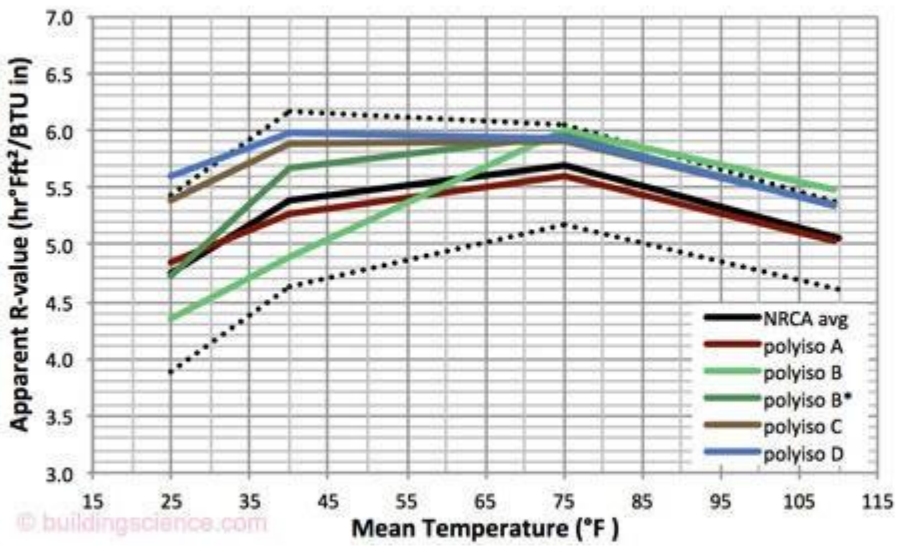

Figure 2 *R-value of PIR foam at different mean temperatures from (Building Science Corporation 2013)*

Construction Techniques. To combat the decrease in thermal performance at lower temperatures NRCA recommends thicker layers be applied for lower temperature climates. Additionally, a hybrid insulation approach could be administered. Other insulation types that are less responsive to cold may be applied to the outside of the PIR layer to increase the temperature where the PIR is in service.

Moisture Control. Like most other exterior rigid foam board insulation applications, the primary challenge in controlling moisture with PIR is at the interface of the foam and structural sheathing. PIR is generally perceived to be less permeable than other foams and thus poses more of a challenge. In a study conducted on the hygrothermal performance of PIR, results concluded that PIR with no facer outperformed both extruded polystyrene insulation and any other PIR with facer plies (Iffa, Tariku, and Simpson 2020). The results also indicated that thicker insulation had higher hygrothermal performance because it helped to keep the interface warmer.

Vacuum Insulated Panels

Vacuum insulated panels (VIPs) are a relatively new insulation technology that is used in building, refrigeration, and shipping/temperature-controlled packaging industries and can provide a ten-fold improvement in insulating value when compared to traditional materials of the same thickness. Recently they were also evaluated for insulating trains (Wernery et al. 2021). Vacuum insulated panels consist of a core material that is evacuated to a low pressure (a fraction of atmospheric pressure) before being sealed inside an impermeable envelope or membrane. The envelope or membrane allows for the internal core to be in vacuum, however, the disadvantage is its frangibility.

The core materials of vacuum insulated panels available on the market typically consist of either fiberglass or fumed silica (va Q tec; Panasonic). Some Chinese VIPs available on Alibaba.com appear to be manufactured with aerogel cores. Researchers have evaluated panels with other core materials as well, such as organic materials (Wang et al. 2020), but these do not appear to be commercially available at present, and may have some hurdles to overcome before reaching similar insulating properties to those of fiberglass and fumed silica panels.

Longevity and durability. Different longevity studies found different outcomes. De Masi, Ruggiero, and Vanoli found that 5 years after VIP panels are installed, thermal conductivity increased by 10%; or if the trend is linear, roughly 2% per year (2020), for 10mm thick silica-based panels enclosed in an envelope with an aluminum layer. That was the same result as found by Molleti, Lefebvre, and van Reenen two years earlier (2018), for two 12mm silica-based VIP panels protected by polyiso sheathing in a roofing application. In contrast, an earlier study did not find any degradation after five years for 20mm thick silica VIPs (Johansson, Adl-Zarrabi, and Sasic Kalagasidis 2016). A company contacted with an inquiry about their VIP panels used primarily in the shipping industry, with a very short lifetime expectancy, said they see a degradation of 15% over the course of a couple years (personal communication, 2021).

Construction Techniques. Building applications at present appear to focus on floors and roofs, since both have limited lifetimes in the minds of customers, and the insulation can be replaced when these are getting retrofitted. Some construction techniques were document in the Cold Climate Housing Research Center's report on VIPs in 2018 (Vacuum Insulated Panels). Additional research is being conducted into all aspects of vacuum insulated panels, such as making the envelopes non-metal (Chang et al. 2021).

The limitations of VIPs include:

- their fragility – if they are punctured, their insulating value returns to that of its un-evacuated core;
- limited lifetime – current VIPs on the market claim lifetimes of between a few years (those used for shipping and refrigeration/freezer applications) and 50-60 years (building VIPs, top of the line)
- edge effects due to typical metallic layer within the enveloping membrane decreasing the effective insulating value (but without it the pressure within the core increases much quicker, so any building VIP at present would be expected to have a metallic layer in order to have a longer lifetime;
- decreasing insulation effectiveness over time due to internal off-gassing as well as molecules slowly migrating across the envelope, resulting in limited lifetime;
- and lack of adjustment on site – any cutting of the VIP to size would destroy the vacuum inside the panel and increase the thermal conductivity.
- High cost compared to other insulation products

R-Value. The R-value of VIPs are all dependent the material used in the core and impermeable envelope or membrane on the outside. Table 2 summarizes the panels that are currently available on the marketplace.

Table 2. Summary of some of the panels available on the market presently

Manufacturer name	Name of product	Country of Manufacture	Description	R-value/inch (aged)	Durability	Longevity
Avery Dennison Hanita	ThermaVIP	Israel	VIP encapsulated in polyurethane (Fiberglass)	R~45 delivery. After two years, ~R-30/inch	Fragile, though video on website shows more durable than other	Short
Panasonic	U-Vacua	Thailand	(Fiberglass)	R~60/inch center of panel, R~30 inch effective at delivery	Fragile – keep away from sharps	"determined to have a center of panel R-value greater than 12 to 60 years"
Panasonic	Advance-R	Thailand	(Fiberglass)	R~60/inch center of panel, R~30 inch effective at delivery	Fragile – keep away from sharps	~70% of initial R-value after 50 years
ThermalVisions	Threshold50	USA	(Fiberglass)	R~50/inch initial decreasing 1.5% per year	Fragile – keep away from sharps	Potentially 20 years
KevoThermal		US & UK	(Fumed silica)	R~40/inch at delivery R~20/inch aged	Fragile – keep away from sharps	
va-Q-tec	va-Q-vip F	Germany	(Fumed silica)	R~33/inch center; ~R-30/inch effective; ~R-20/inch incl. aging and edge effects	Fragile – keep away from sharps	Up to 60 years

LAB TEST

For the lab test, two 4x4x4 foot boxes were constructed, one with VIPS and the other with polyisocyanurate insulation. The boxes were placed outside and metered to evaluate their thermal performance in Fairbanks, Alaska temperature conditions. The boxes were placed on a stand that raised them 2’3” above the ground to ensure proper air circulation and even heat loss through the envelope. To ensure no sunlight reached the boxes, the boxes were placed between the building and a radiation shield.

To get a performance rating of the insulation, radiator heaters were placed in the boxes and set at a constant 70°F to replicate a typical heated shelter during the heating season. The heat was controlled by a thermostat, had a manual on/off switch to ensure minimal chances of failure and an adjustable wattage. The wattage was set to 400 for the VIPs and 700 for the polyiso according to the predicted R-value from the manufacturers. Since the polyiso had a lower R-value, this meant that it required a bigger heater which potentially lead to more temperature swings during collection. On the first round of data collection, it was noted that there was too much of a temperature swing, which made it difficult to calculate the R-value and was not a good representation of the performance. Therefore, the decision was made to lower the interior temperature to 60°F to reduce the temperature swings. The experiment is planned to run from October 2022 to January 2023 to partially represent a sub-arctic heating season.

FUTURE WORK/CONCLUSION

Since the experiment is still on going, the data have not been analyzed and cannot be summarized at this time. The collected data will be used to evaluate the energy use performance of the box prototypes, which will give a good understanding of how the insulation performs in the sub-arctic heating season. Once the data has been analyzed, then the box prototypes will be able to inform proposed cold climate RDS design requirements for several stakeholders. These requirements will ultimately reduce the energy impact of RDS in cold climates going forward.

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