Engineering

Approach

Attached is a paper that various students involved in the project are currently working on. We have reached out to transportation experts, concrete experts and various other experts throughout the build and design phases of the Triple Dome Home Project. We have had an engineer sign off on our building, and we are about to have our final inspection. Our engineering team has done a great job at collecting data, at working with experts in their field and applying new market-leading technologies to our build. One example of this is the SPAN smart panel, which will allow the homeowners to control all the outlets from within the house from their mobile device. James Niedens has been doing research on modular thin shell structures. His research has been on maximizing extreme loading for all loadings (soil and structure with other dead loads and other live loads like snow). Another research that has been done is the berming of the structure and how that heat flux and thermal envelope.

One of our students Sofia, has had a great deal to do with this paper that she coauthored with a faculty here at BYU. The paper addresses the efficiency of the home and its performance, as well as some documentation. That paper will be attached below.

Systems and Component Design

Regarding the component selection of the Triple Dome Home, Fiberglass was used as the primary material to reinforce the concrete structure. One significant advantage of fiberglass over rebar is its corrosion resistance. Fiberglass is immune to these issues, unlike steel rebar, which can rust and corrode over time. Another benefit of fiberglass is its lightweight nature. This can reduce labor costs and make working in tight or challenging spaces more convenient. This will significantly help with transporting the Triple Dome Home to California safely.

Fiberglass is also non-conductive, which can be beneficial in structures with electrical wiring. In addition, as an insulator, and will not interfere with electrical systems. In terms of design flexibility, fiberglass has the edge over rebar. It can be easily molded and shaped to fit the specific needs of a project, while rebar is typically limited to straight or curved lengths.

When choosing appliances for our home, it was essential to consider energy efficiency. Where functional devices certified by Energy Star were chosen, these appliances have met strict guidelines for energy efficiency. As a result, they can help you save money on your energy bills.

One passive strategy used was custom-made windows with a low 0.22 U-value. The many windows in the design take advantage of natural lighting and ventilation without sacrificing energy efficiency. Also, adequately sealed, and insulated windows can help reduce drafts and air leaks, leading to significant energy savings.

A PVC membrane is applied to the exterior of the concrete walls as an envelope. It is a waterproofing material to protect concrete structures from water damage. This is important because water damage can lead to cracks, leaks, and other structural issues. The membrane is also flexible, which allows it to move with the concrete as it expands and contracts due to changes in temperature and humidity.

The Triple Dome Home will be bermed. This will create a visual interest in the landscape, providing privacy and directing water runoff. Berms will be constructed using various materials, including soil, rocks, and plants, and can be designed to complement the house.

The house is designed with the occupant's comfort in mind. Therefore, every aspect of the house provides an energy-efficient and sustainable space that will serve the occupant's needs and contribute to the occupant's well-being. The energy produced comes from 2 solar panel structures, carrying 19 panels each. The panels are sized according to the house's needs.

Efficiency and Performance (Attached Paper)

Documentation (Attached Paper and Plans)

Innovation

The Concrete Dome home is composed of many new ideas. Innovation begins with the dome style since it defers from normal houses. The dome home is also mobile which is innovative since the house is being built as one structure but will be separated to transport. Other innovations include the fiberglass replacing most of the rebar, using concrete as finish inner surface and having an envelope which is a membrane. The profile of the house which is attached in the paper shows that concrete is in the inside. The foam is the middle surface protected by the membrane. This makes a huge contribution to thermal conservation making the house more efficient.

A lot of research was done to find new and sustainable design structures. The research has shown that dome structures are energy efficient and that has helped the team to develop a design. There was more research on how to replace the rebar with fiberglass. In addition, there was research to select the appliances to reduce the energy consumption and water consumption. We have replaced most of the rebar within our dome with fiberglass rebar, and that also was easier to install, to bend and to work with than your typical rebar.

Passive Thermal Performance of Earth-Sheltered Thin-Shell Concrete Dome Structures

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***Abstract*—The objective of this research was to evaluate an insulated concrete thin-shell dome structure for thermal flux with various depths of soil coverings. Computational thermal analysis was performed to model temperature fluctuations inside a representative section of an experimental concrete dome structure during typical winter and summer seasons in northern Utah. The results are compared against the baseline of a traditional insulated wood-framed building envelope and indicate that thermal flux is significantly reduced in the earth-sheltered concrete dome structure with foam on the outside of the concrete. The addition of soil dampens the amplitude of the flux and increases the time lag between maximal exterior and interior temperatures.**

***Index Terms*—concrete dome, lag time, sustainability, thermal analysis, thermal flux**

I. Introduction

Approximately 70% of global anthropogenic greenhouse gas (GHG) emissions are related to energy consumption, primarily due to carbon dioxide (CO_2) produced from burning fossil fuels [1]. Recently, buildings have been shown to be responsible for 32% of global energy consumption and 19% of greenhouse gas emissions [2]. Because increasing GHG levels play a significant role in climate change [3], reducing GHG emissions associated with the built environment is warranted.

Significant attention is devoted to supplying the built environment with electric power generated from renewable sources, therefore reducing GHG emissions by *cleaning* electric power production. While addressing energy production is important, the research reported in this paper is oriented toward *reducing* energy consumption in the built environment through optimized building envelope design in the form of ”passive structures.” Passive solar design involves optimizing the orientation and layout of a building to maximize solar exposure and leverage the availability of stable ground temperatures. It also involves using materials with high thermal mass to store heat and incorporating various additional design features (shading, insulation, natural ventilation, etc.) to regulate indoor temperature [4]. Passive structures can provide comfortable indoor living conditions while limiting the use of active (energy-consuming) mechanical systems and reducing total energy consumption through passive heating/cooling systems [5]. Heating, ventilation, and air conditioning (HVAC) systems are the largest energy-consumption category in most structures, accounting for about half of all building energy used [6].

This research is centered on a type of passive building envelope comprised of a concrete thin-shell ”dome” with an integrated exterior insulation layer and an applied soil (earth-sheltered) layer. Through computational thermal modeling [7]–[9], the objective of the research is to evaluate an insulated concrete thin-shell dome structure for thermal flux with various depths of soil coverings. The results are compared against the baseline of a ”traditional” insulated wood-framed building envelope. The following sections provide background information, explain the methods utilized in the research, discuss the results, and offer conclusions based on the findings.

II. Background

This paper integrates existing research in passive structures, concrete thin-shell domes, and earth-sheltered structures as described in the following sections.

A. Passive Structures

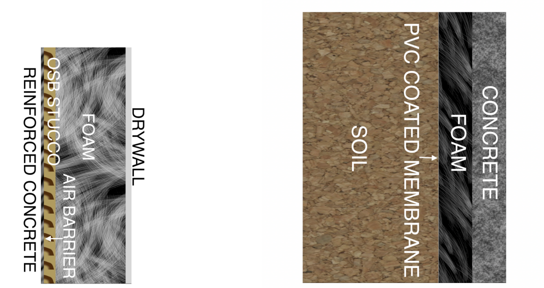
Passive structures and basic principles of passive solar design have been present for centuries. Ancient cultures employed passive structure design by siting their buildings in favorable locations that maximized solar energy and/or protected them from over-exposure while capturing stable ground temperatures maintained within the earth itself [10]. However, as various forms of energy have become available and societies have come to rely on abundant affordable energy access, fundamental principles of passive design have received less emphasis as mass production of buildings and new architectural styles have been accommodated.

Modern interest in passive solar design re-surged for a period during the 1970s and 1980s, as a result of the energy crisis of the 1970s, and passive structure design was supported in the United States by significant Department of Energy funding to combat the crisis [11]. As negative impacts on climate change from high levels of GHG emissions are becoming globally concerning, interest in responsible resource use, including energy efficient passive solar buildings, is growing.

B. Concrete Thin-Shell Domes

Concrete structures have demonstrated capacity in passive building performance resulting from a comparatively high thermal mass available to stabilize and regulate indoor building temperatures [3]. Concrete thin-shell dome structures pair optimized geometries with the high compressive strength of concrete to enclose more space with less material. Curvilinear geometries more uniformly distribute loads, allowing for reductions in concrete quantities necessary to construct thin-shell dome buildings [12]. The effect of using less material per unit of constructed surface area (and enclosed volume) naturally reduces the economic and environmental impact of such structures.

The most common method of constructing concrete thin-shell dome structures includes a monolithic closed-cell spray polyurethane foam (SPF) insulation layer on the exterior of the concrete shell [13]. Insulating the exterior surface of the concrete with SPF further enhances the passive thermal performance of these structures by reducing conductive heat transfer and improving the thermal mass effects to maintain consistent temperatures across diurnal cycles (fluctuations in temperature that occur within a 24-hour period, typically due to higher temperatures during the day and lower temperatures during the night). A structure with high thermal mass and an exterior thermal insulation layer is effective at moderating the impact of temperature extremes, thereby reducing energy consumption from HVAC systems otherwise needed to provide comfortable interior temperature levels [14].



(a) Wood Profile (b) Concrete Profile

Fig. 1: Thermal material profiles for a typical wooden residential structure and a concrete dome structure.

C. Earth-Sheltered Structures

Earth-sheltered structures are buildings with an earthen mass integrated in the outside surfaces of the building envelope to minimize temperature flux [15]. Earth-sheltered structures have historically made dwellings habitable in areas with daily temperature extremes [10]. The Earthship, a type of earth-sheltered structure utilizing many passive design elements, has even proved effective in climates with dynamic seasonal extremes [16].

This research extends the work of previous researchers by integrating principles of passive building design with insulated thin-shell concrete domes. The study sought to quantify the thermal performance of insulated concrete thin-shell dome structures with varying depths of soil coverage.

III. Methods

The stated research objective was addressed through computational thermal modeling. The problem configuration and material properties, principles of transient thermal analysis, and relevant numerical methods are described in the following sections.

A. Problem Configuration and Material Properties

Computational thermal analysis was performed to model temperature fluctuations inside a representative section of an 80-sq m (approx. 850-sq ft) experimental insulated concrete thin-shell structure located at the Brigham Young University campus in Provo, UT. A similarly sized traditional structure, an insulated wood-framed building envelope typical for the same location, was also modeled as a comparative baseline. Figure 1 presents a cross section of each building envelope.

Tables I and II show the data necessary for thermal analysis for each layer of the insulated concrete dome structure and the typical insulated wood-framed structure, respectively. For concrete, thermal conductivity and density values were determined directly from specimens

TABLE I: Material Properties for Concrete Dome Structure

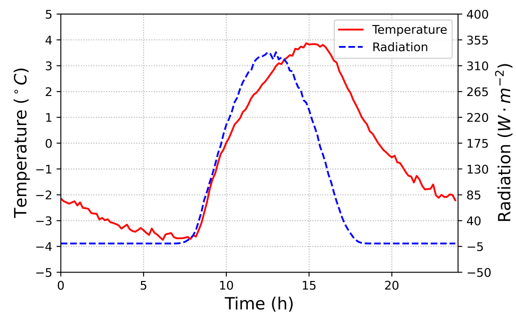
Material	Thickness (in)	Thickness (m)	Density (kg·m^{-3})	Thermal Conductivity (W· m^{-1}·°K^{-1})	Specific Heat (J·kg^{-1} · °K^{-1})	Emissivity (unitless)
Concrete	3	0.0762	2215	2.711	1000 [17]	-
Insulation (SPF)	3	0.0762	38.4 [18]	0.022 [18]	2100 [19]	-
PVC Membrane	0.02	0.000508	1300 [20]	0.23 [20]	970 [20]	0.9 [21]
Soil (Sandy Clay)	variable	variable	1400 [22]	2.45 [23]	1459 [23]	0.9 [24]

TABLE II: Material Properties for Typical Wooden Structure
*Asterisk denotes materials that are alternated within different portions of the structure

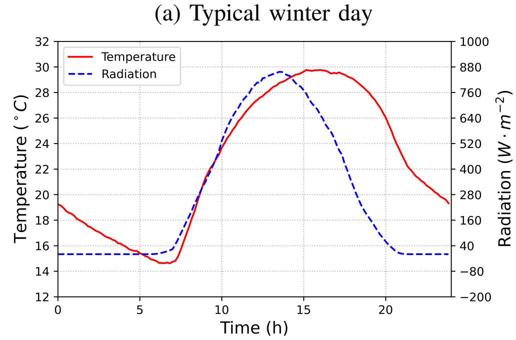
Material	Thickness (in)	Thickness (m)	Density (kg·m^{-3})	Thermal Conductivity (W· m^{-1}·°K^{-1})	Specific Heat (J·kg^{-1} · °K^{-1})	Emissivity (unitless)
Fiber-Reinforced Concrete Board	0.5	0.0127	1400 [25]	0.62 [25], [26]	1080 [25]	0.8 [27]
HPPE-Fiber Barrier	0.006	0.1397	35 [28]	0.033 [28]	1600 [29]	-
Structural OSB	0.5	0.0127	619 [30]	0.097 [30]	1552 [30]	-
Fiberglass Insulation*	5.5	0.1397	55 [31]	0.035 [31]	830 [32]	-
Wood (Pine)*	5.5	0.1397	540 [32]	0.151 [32]	1380 [32]	-
Drywall	0.5	0.0127	770 [33]	0.24 [33]	950 [34]	-

that were cast during dome construction and cured for 28 days.

Climatic data were collected from the Utah Climate Center's AG Weather data set for Lindon, Utah [35], in which average temperature and radiation readings are given on 10-minute intervals for each day of the year between 2010 and 2022. Typical values for winter and summer seasons, which included temperature extremes of interest in this research, were then computed from data reported between December and February and between June and August, respectively. Radiation includes average contributions from only shortwave solar radiation, rather than any longwave radiation. Graphs of temperature and radiation on typical winter and summer days are shown in Figure 2.



(a) Typical winter day



(b) Typical summer day

Fig. 2: Temperature and radiation data for typical winter and summer days based on averages of 12 years of data from the Utah Climate Center station at Lindon, Utah [35].

B. Transient Thermal Analysis

Transient thermal analysis through a typical flat composite wall with variable thermal behavior between different layers is described by

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\kappa}{\rho C_p}\frac{\partial T}{\partial x}\right). \quad (1)$$

Here, κ is thermal conductivity, ρ is density, and C_p is specific heat. Between layers, conduction governs heat transfer. At the boundary with the interior wall, heat is transferred through convection via

$$-\kappa_i \frac{\partial T}{\partial x}\bigg|_{x=L} = h_i(T|_{x=L} - T_{i_\infty}), \quad (2)$$

where κ_i is the thermal conductivity of the material at the surface of the interior wall, h_i is the heat transfer coefficient of this surface, and T_{i_∞} is the air temperature in the interior of the structure—taken to be $20°C$. The internal heat transfer coefficient, h_i, is taken as a constant 2.2 W· m^{-1}·°K^{-1} as per ASHRAE's alternative surface heat transfer coefficient recommendations [36, p. 19].

For the boundary representing the exterior wall, heat is transferred both by convection and radiation using a similar Robin-type boundary condition:

$$-\kappa_o \frac{\partial T}{\partial x}\bigg|_{x=0} = h_0(T_o - T|_{x=0}), \quad (3)$$

where κ_o and h_o are the respective thermal properties on the outer surface. The external heat transfer coefficient is taken as $h_o = 21.6$ W· m^{-1}·°K^{-1} [36, p. 17]. T_o is the so-called "sol-air" temperature, described by

$$T_o = T_{o_\infty} + \frac{\lambda q_{sol}}{h_o}, \tag{4}$$

where T_{o_∞} is the time-dependent outside temperature, q_{sol} is the time-dependent solar radiation, and λ is the absorptivity of the surface material. All materials are assumed to be "gray surfaces," so absorptivity equals emissivity, or $\lambda = \epsilon$.

The heat flux at the inside surface of the structure wall, q_i, is given by

$$q_i = h_i(T|_{x=L} - T_{i_\infty}). \tag{5}$$

Here, a positive flux indicates that heat is entering from the exterior, while a negative flux indicates that heat is instead leaving from the interior. The average flux from some start time t_{start} to an end time t_{end} is

$$\bar{q}_i = \frac{1}{t_{end} - t_{start}} \int_{t_{start}}^{t_{end}} q_i \, dt, \tag{6}$$

and the average absolute flux, which describes energy expense needed to maintain the constant indoor temperature, is

$$|\bar{q}_i| = \frac{1}{t_{end} - t_{start}} \int_{t_{start}}^{t_{end}} |q_i| \, dt, \tag{7}$$

The lag time of a thermal configuration, Φ, is the time difference between the maximal interior and exterior temperatures of the structure, or

$$\Phi = t\Big|_{\max T|_{x=L}(t)} - t\Big|_{\max T|_{x=0}(t)} \tag{8}$$

The decrement factor, DF, is the difference in the maximal and minimal temperatures of the interior of the structure divided by the difference between maximal and minimal temperatures in the exterior of the structure, or

$$DF = \frac{\max T|_{x=L} - \min T|_{x=L}}{\max T|_{x=0} - \min T|_{x=0}}. \tag{9}$$

While the heat flux rate measures how heat travels between the interior and exterior, the time lag and decrement factor indicate how heat is stored in the system [37]. As a result, each is of interest.

C. Numerical Methods

For this research, one-dimensional transient thermal analysis was performed using a custom Python script. An implicit backward Euler scheme was used to discretize the time domain, while a central difference method was used for the spatial discretization. As a result, a tridiagonal system of equations must be solved for each time iteration, but the method is unconditionally stable. The initial temperature for the model was taken as $T(x, 0) = T_{i_\infty}$, after which the model was run until the temperature difference between identical times for two successive dates was below $1e-4$. A constant time step of $\Delta t = 10$ seconds and spatial resolution of $\Delta x = 10$ mils (0.01 inches, converted to metric) are used.

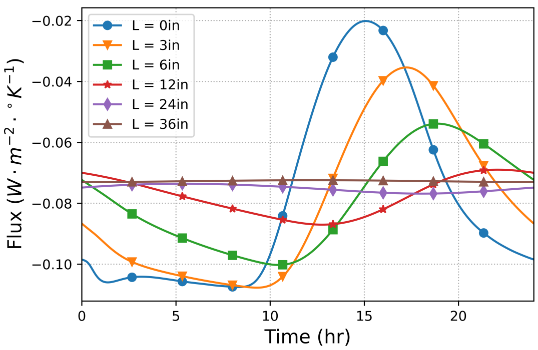
IV. Results and Discussion

Computed results for typical days in the winter and summer seasons are provided in Table III, including the thickness of the proposed soil layer, time lag, decrement factor, average heat flux at the interior wall, and average absolute heat flux at the interior wall. For comparison, these values are also computed for the thermal configuration of the baseline structure. The true value of computed quantities for the insulated wood-framed baseline structure would be a weighted average of values for the studs (10% of the structure) and the insulated space between the studs (90% of the structure).

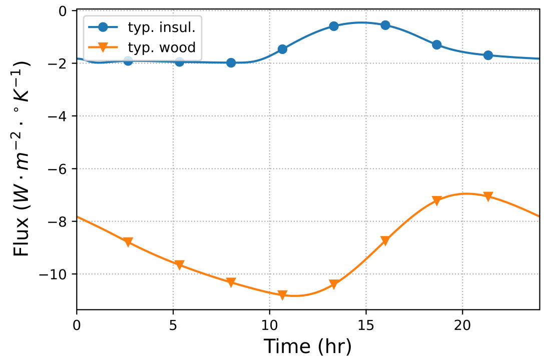
Graphs of computed heat fluxes for both the concrete structure and the baseline structure for typical days in winter and summer are shown in Figure 3, in which a large difference in magnitudes of the flux between structures is apparent. The results corroborate previous research [38] that also demonstrated that an insulated concrete dome structure is significantly more thermally efficient than a traditional structure. Indeed, the heat flux for the concrete configuration is at least an order of magnitude smaller than that of the traditional structure, largely attributable to placement of the SPF on the outside of the concrete. Indeed, Figure 4 shows that by simply reversing the placement of the concrete and SPF, the heat flux of the concrete structure increases to ranges comparable to those of the traditional structure for a typical summer day; the heat flux for typical days in other seasons also comparably increases. Thus, place-

TABLE III: Lag Time (Φ), Decrement Factor (DF), Average Heat Flux at the Interior Wall ($\bar{q}_i$), and Average Absolute Heat Flux at the Same Wall for Varying Wall Thickness (L) and for the Wooden Studs (TW) and Insulated Space between the Studs (TI).

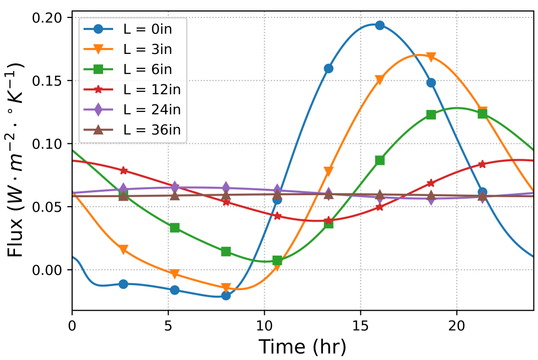
Season	L (in)	Φ (hr)	DF	$\bar{q}_i$ (W· m^{-2}·°K^{-1})	$\lvert\bar{q}_i\rvert$
Winter	0	1.95	0.00160	-0.09	0.09
	3	2.63	0.00200	-0.08	0.08
	6	4.30	0.00175	-0.08	0.08
	12	7.93	0.00069	-0.08	0.08
	24	15.2	0.00012	-0.08	0.08
	36	22.2	0.00002	-0.07	0.07
	TW	6.36	0.08889	-9.21	9.21
	TI	1.02	0.03124	-1.53	1.53
Summer	0	1.94	0.00166	0.08	0.09
	3	2.79	0.00213	0.07	0.07
	6	4.70	0.00184	0.07	0.07
	12	8.17	0.00078	0.07	0.07
	24	15.0	0.00013	0.06	0.06
	36	21.8	0.00003	0.06	0.06
	TW	6.97	0.09862	6.63	6.63
	TI	1.01	0.03199	1.10	1.31



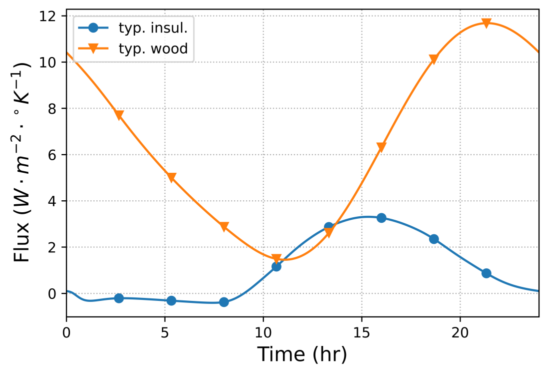
(a) Typical winter day: concrete



(b) Typical winter day: traditional



(c) Typical summer day: concrete



(d) Typical summer day: traditional

Fig. 3: Variation in total heat flux on the interior wall of a concrete structure (left) and traditional structure (right) during a typical day (use of different scales for the concrete and traditional structures reflects large differences in magnitudes of flux).

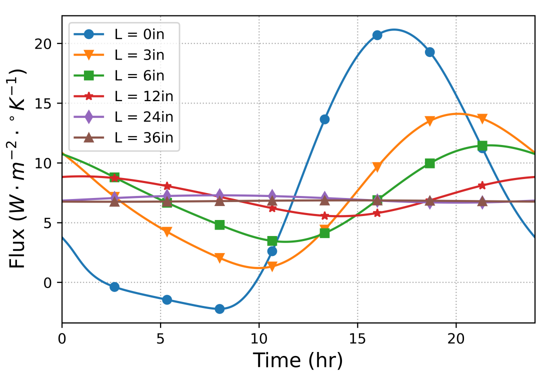


Fig. 4: Heat flux for a typical summer day for the concrete profile in which the SPF is placed on the inside of the concrete, with magnitudes of flux similar to those of a traditional structure.

ment of SPF on the outside of the concrete is critical for improving the thermal response of the concrete structure.

With the addition of soil, the flux further diminishes and reduces in amplitude (as indicated in part by the decrement factor), while the time lag increases significantly. The results indicate that a 12-hour time lag may be achievable through the use of 460 mm (18 in.) of soil.

Though these results clearly demonstrate the potential passive solar value of an insulated concrete thin-shell dome structure, a number of assumptions were made that should be validated and/or honed to improve the fidelity of the results. In particular, material properties need more careful study and may be more accurately modeled as functions of temperature and/or moisture. Furthermore, geometry was not taken into account even though the curvature of concrete dome structures may affect thermal behavior. A full three-dimensional analysis informed by experimental measurements would help clarify the effects of these assumptions.

V. Conclusion

The objective of this research was to evaluate an insulated concrete thin-shell dome structure for thermal flux with various depths of soil coverings. The results are compared against the baseline of a traditional insulated wood-framed building envelope. The results indicate that thermal flux is significantly reduced in the concrete dome structure with SPF on the outside of the concrete.

The addition of soil dampens the amplitude of the flux and increases the time lag between maximal exterior and interior temperatures. Future research should be performed to incorporate material properties as functions of temperature and/or moisture and account for structure geometry in a full three-dimensional analysis informed by experimental measurements.

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