Thermal Capacity and Potential for Freezing of a Passive Solar Hangar

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Background

The planned *Solar Hangar,* located at 3314 Airport Road, Boulder, Colorado 80301, will be a concrete structure with a steel roof. The six inch thick concrete walls are insulated externally with three inches of rigid polyisocyanurate foam and a stucco covering. The steel deck roof is externally insulated with six inches of polyisocyanurate foam and a PVC covering. The four inch thick concrete slab floor is insulated with four inches of rigid foam. There are no interior partitions except for a rest room, which will be added later. There is no electrical or gas heating systems. All heating and cooling are natural solar gain and chimney effect ventilation.

Winter solar energy gain is received through a large south facing window, measuring four feet by 78.5 feet, which, added to the lower double-hung windows equates to 381.5 square feet (35.4 m^2) of south facing glazing. The heat energy from the solar gain is expected to be captured within the mass of the concrete floor and walls.

Hypothesis

The heat energy stored in the thermal mass of the structure is sufficient to maintain a minimum temperature greater than 0° C (32° F) over prolonged periods of limited solar gain and negative 28° C (-20° F) outside air temperature.

Energy from Solar

Winter Solar energy available = 4.5 kilowatt-hour/meter^2 per day, or
16,200 kiloJoules/meter^2 per day

Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	2.4	3.3	4.4	5.6	6.2	6.9	6.7	6.0	5.0	3.8	2.6	2.1	4.6
	Min/Max	2.1/2.7	2.8/3.5	3.7/5.0	4.8/6.1	5.1/7.2	5.7/7.8	5.6/7.4	5.2/6.6	4.0/5.5	3.1/4.2	2.3/2.8	1.9/2.3	4.3/4.8
Latitude -15	Average	3.8	4.6	5.4	6.1	6.2	6.6	6.6	6.3	5.9	5.1	4.0	3.5	5.4
	Min/Max	3.2/4.4	3.8/5.1	4.3/6.2	5.3/6.8	4.9/7.3	5.5/7.6	5.6/7.4	5.3/7.1	4.6/6.7	4.0/5.8	3.4/4.6	2.8/4.1	4.9/5.7
Latitude	Average	4.4	5.1	5.6	6.0	5.9	6.1	6.1	6.1	6.0	5.6	4.6	4.2	5.5
	Min/Max	3.6/5.1	4.2/5.7	4.4/6.5	5.2/6.7	4.6/6.8	5.1/6.9	5.2/6.8	5.1/6.8	4.6/6.8	4.2/6.4	3.9/5.2	3.2/4.8	5.0/5.8
Latitude +15	Average	4.8	5.3	5.6	5.6	5.2	5.2	5.3	5.5	5.8	5.7	4.8	4.5	5.3
	Min/Max	3.9/5.6	4.3/5.9	4.4/6.5	4.8/6.2	4.1/6.0	4.4/5.9	4.5/5.9	4.6/6.2	4.4/6.6	4.2/6.5	4.1/5.6	3.5/5.3	4.8/5.6
90	Average	4.5	4.6	4.3	3.6	2.8	2.6	2.7	3.2	4.0	4.6	4.4	4.3	3.8
	Min/Max	3.6/5.4	3.7/5.2	3.5/5.0	3.0/4.0	2.3/3.1	2.2/2.8	2.3/2.9	2.7/3.6	3.1/4.6	3.4/5.3	3.7/5.1	3.4/5.2	3.4/4.1

(Source: NREL Solar Radiation Data Manual page 46)

Total average energy gain thru hangar's windows per winter day = 563,760 kiloJoules
Cloudy days provide about 10% or 56,376 kiloJoules per day

The solar energy entering through the windows will be captured in the thermal mass of the walls and floor, and other objects within the hangar. Although air in contact with the thermal mass will transfer some of the heat energy, most of the energy will radiate to other objects inside of the structure, and back, producing a common temperature at all objects.

Heat Capacity of Thermal Mass

The heat energy held in the thermal mass of the building will vary slightly throughout the seasons. Summer temperatures will be regulated by the ambient air temperatures with very little gain through the south windows. Winter temperatures of the thermal mass will be regulated by the gain from the southern glazing during the day and losses through the walls and roof during the night. Additional energy loss will occur when the aircraft door is open. Most of the open door loss will be through radiation from the walls that have a view of colder objects outside of the door. Convective heat loss through air exchanges while the aircraft door is open will depend on the time interval between door openings.

How much energy will be held in the mass of the walls and floor?

Concrete walls = 3,169.75 ft^2 at 6” thick equals 1,584.87 ft^3 or 44.884 m^3
Concrete floor = 3.807.25 ft^2 at 4” thick equals 1,269.08 ft^3 or 35.936 m^3
Mass of concrete => 2,400 kg per cubic meter
Concrete thermal energy capacity = 0.96 kJ/kg-degree Kelvin
Mass of concrete = 193,968 kg

Energy stored in building concrete at:

	22.2° C	(72° F) =	54,411,125 kiloJoules
[below grade temperature]	12.2° C	(54° F) =	52,549,147 kiloJoules
	0.0° C	(32° F) =	50,273,436 kiloJoules
	-28.9° C	(-20° F) =	44,894,364 kiloJoules

Volume of air within the hangar = 1,886.66 m^3
Density of air varies with temperature – about 1.23 kg/m^3
Mass of all interior air is about 2,500 kg
Energy capacity of air = 1.005 kiloJoules/(kg * K)

Energy stored in interior air:

	22.2° C	(72° F) =	662,736 kiloJoules
[below grade temperature]	12.2° C	(54° F) =	662,478 kiloJoules
	0.0° C	(32° F) =	662,099 kiloJoules
	-28.9° C	(-20° F) =	659,056 kiloJoules

Heat Energy Flow

Assuming worst-case conditions, what is the rate of heat energy flow leaving the building? As the thermal masses lose energy, their temperature will decrease, which will reduce the rate of energy transfer. The greater the difference in temperature between the thermal mass and the outside air, the higher the rate of energy transfer (higher power).

Energy transfer to the outside air will be:

1. From the thermal mass of the walls, through the polyisocyanurate insulation and into the outside air.
2. From the thermal mass mostly of the floor, through the polyisocyanurate roof insulation and into the outside air.
3. From the thermal mass of the floor, through the polyisocyanurate insulation and into the ground.
4. Air exchanges from the thermal mass of the interior air heated through convection with contact between the air and the interior walls and floor.

Energy transfer temperature points will be used to calculate energy levels to determine average transfer rates. The amount of energy lost from the thermal masses between 22.2° C and 12.2° C will be used to determine the average energy transfer rate while the energy sink under the floor is positive. Then the amount of energy lost from the thermal mass between 12.2° C and -28.9° C will be used to determine the average energy transfer rate while the energy sink under the floor is negative. The energy lost through air exchanges will be added to the losses through the building enclosure.

Conditions

Building interior temperature	22.2° C	(72° F)
Below grade temperature	12.2° C	(54° F)
Exterior temperature	-28.9° C	(-20° F)
Air changes per hour = 1	60,000 kg per day	
Cloudy day Solar gain	10% of sunny day or 51,037 kiloJoules per day	

The heat energy losses will be calculated in two stages. Stage one is between 22.2° C and 12.2° C, and stage 2 is between 12.2° C and 0° C.

Stage 1 Heat Energy Transfer

The amount of energy transferred to the air from the 22.2° C walls and floor depends on the difference between the mass temperature and the air temperature within the building. As the interior air cools the transfer rate decreases. Here we will do an energy balance between the structural masses at 22.2° C and at 12.2° C, at such temperature where the earth will then start providing heat to the building interior.

Convective heat transfer between concrete and air = 12 Joules/m^2*second*K
Total area of walls and floor = 662.3 m^2
After one air exchange the delta T is 50.3° C
Heat energy from walls and floor transferred to air = 1,439,151 kJ/hour at the delta T.
The energy capacity of the air at 22.2° C is 662,736 kJ, which would allow the fresh air temperature to rise to wall temperature in less than 30 minutes.
The energy loss from the concrete through air exchanges is determined by the number of air exchanges per day. At 24 air exchanges per day the energy lost will be 88,333 kiloJoules for the temperature drop to 12.2° C.

As the walls and floor lose energy to the exterior their temperature lowers. Between the concrete temperature of 22.2° C and 12.2° C the building will lose 226,917 kiloJoules per day.

Stage 2 Heat Energy Transfer
Once the structure reaches 12.2° C the ground will be warmer and heat will flow from the ground into the hangar.
Between the temperatures of 12.2° C and 0° C the building structure will lose 149,753 kiloJoules per day and the air will transfer out 82,149 kiloJoules per day.

The solar gain through cloudy skies will be about 51,037 kiloJoules per day.

Conclusion
The worse-case situation was a constant day and night temperature of -28.9° C (-20° F) and cloudy skies, although it would be extremely rare to maintain a temperature that cold and have cloudy skies, since cloud cover tends to keep temperatures higher at night.
Daily heat loss through the wall and roof insulation would be 376,670 kiloJoules.
Daily heat loss through air exchanges would be 170,482 kiloJoules.
With the solar gain the net loss would be 496,114 kiloJoules per day.
The temperature of the building would reach freezing in 8.34 cloudy days of -28.9° C.

Selected situations:

Ambient temperature	**Sky cover**	**Time to freeze in days**
-28.9° C (-20° F)	Cloudy	8.34
-28.9° C (-20° F)	Sunny	112.5
0° C (32° F)	Cloudy	50.94
0° C (32° F)	Sunny	Never

The National Weather Service records for the Denver/Boulder area, from 1872 to present, show that there has never been more than two consecutive days of minus 20 degrees F or lower. The longest sub-zero cold spell on record was set in 1983 at 115 hours. The Solar Hangar would take over eight days of minus 20 degrees F to freeze. The possibility of the Solar Hangar freezing at minus 20 degrees F is vanishingly small. Freezing at higher temperatures, over longer periods of time would require less Solar gain over the longer periods, which is very remote since sunny days are the norm in order to have colder, cloudless nights.

The Solar Hangar is not expected to ever freeze under normal operations of the building, and historical meteorological data.