PASSIVE SOLAR/EARTH SHELTERED OFFICE/DORMITORY
COOLING SEASON THERMAL PERFORMANCE*

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ABSTRACT

Continuous detailed hourly thermal performance measurements have been taken since February 1982 in and around an occupied, underground, 4000 ft$^2$ office/dormitory building at the Oak Ridge National Laboratory in Oak Ridge, Tennessee. This building has a number of energy saving features which have been analyzed relative to their performance in a southeastern U.S. climate and with respect to overall commercial building performance. This analysis documents cooling season performance, as well as effects of earth contact, interior thermal mass, an economizer cycle and interface of an efficient building envelope with a central three-ton heat pump.

The Joint Institute Dormitory obtains a cooling energy savings of about 30% compared with an energy-efficient, above-grade structure and has the potential to save as much as 50%. The proper installation of the overhang, interior thermal mass, massive supply duct system, and earth contact team up to prevent summertime overheating. From May through September, this building cost a total of $300 (at 5.7¢/kWh) to cool and ventilate 24 hours per day.

Besides thermal performance of the building envelope, extensive comfort data was taken illustrating that at least 90% of the occupants are comfortable all of the time according to the PMV measurements.

INTRODUCTION

The cooling season thermal performance of this energy-efficient, earth-sheltered building was closely monitored through the 1982 and 1983 summer months. This continuously conditioned building is used for office and dormitory space at the Oak Ridge National Laboratory (ORNL).

The building cross section is shown in Fig. 1. The roof, north wall, and part of the east wall are earth covered.

The building envelope consists primarily of poured concrete and masonry construction. All walls have 7.5 cm (3 in.) of polystyrene foam board insulation fastened to the outside of the building. The roof consists of precast concrete sections covered by 5 cm (2 in.) of poured concrete, membrane, 7.5 cm (3 in.) of extruded polystyrene insulation, a 7.5-cm (3-in.) gravel seam, filter paper, and earth sloping from 0.76 to 0.46 m (2.5 to 1.5 ft).

The whole building saves about 30% of the energy used during both the heating and cooling seasons compared with a DOE-2.1A building simulation model using identical weather parameters and a well-built, above-grade structure with similar interior usage patterns and ventilation air change as the JID.1,2 The above-grade building model used for comparison has metric R values (RSIs) of 4.6 h·m²·°C/W (R = 26 h·ft²·°F/Btu) for the roof and 2.5 h·m²·°C/W (R = 14 h·ft²·°F/Btu) for the walls. It has the same total glass area, but the glass is redistributed with 50% of the total glass on both the north and south sides; the overhang on the south side is 0.6 m (2 ft) instead of 1 m (3.5 ft).

A second comparison of the JID cooling season performance was made with an actual well-built, energy-efficient, above-grade building exposed to the same 1982 meteorological conditions. The results of this comparison show that 30% energy savings during the cooling season over efficient, above-grade structures is a reasonable estimate for a climate such as that in Oak Ridge.

The building used for this comparison is the TECH House III, located 20 miles from the JID site.3 This structure is a well-insulated house with 167 m² (1800 ft²) of gross floor area, walls with an RSI of 3.9 (R = 22),
a cathedral ceiling with an RSI of 3.9 (R = 22), a flat ceiling with an RSI of 7.4 (R = 42), floors with an RSI of 3.9 (R = 22), and double-glazed windows. This unoccupied building is monitored for ongoing heat pump field performance testing; its interior electric usage is approximately the same per unit floor area as that of the JID.

The JID’s south-facing wall consists of 75% glass with an extended overhang; the glass area is 19% of the floor area. However, even with full shading, the south facing windows transmit 40% of the daily sensible cooling requirements because of ground reflectance, sky radiation, and temperature differences between inside and outside air. The mechanical package in the building has a total cooling capacity at 35°C (95°F) of only 10.5 kW (36,000 Btu/h) or 28 W/m² [9 Btu/(h·ft²)] of gross floor area. The peak hourly power requirement for mechanical cooling is 4.3 W/m² [1.3 Btu/(h·ft²)] of floor area. For the 1982 and 1983 summer months the JID thermostat was set in order to keep the occupied space thermally acceptable at all times to at least 90% of the people.

The climate surrounding this building in the summer is normally hot and humid. In June, July, and August the 1982–1983 average cooling degree day (DD) totaled 545 DD base 18°C (965 DD base 65°F).

The heat pump indoor blower operates continuously. Supply air ducts are located within the wall footings. Most of the exhaust air is vented through two fan ports in the roof, one in the restrooms and a second in the kitchen. The air change rate varies from 0.4 air changes per hour with no exhaust fan operation to 0.7 air changes per hour with one fan.

A rated 12.3-kW (3.5-ton at 95°F) heat pump and enthalpy-controlled economizer provide space cooling to this building. The measured cooling output of the installed heat pump unit was about 20% below rated capacity; this was caused mainly by duct installation problems.

THERMAL COMFORT MEASUREMENTS

The PMV in the building was determined by a thermal comfort meter equipped with a transducer capable of sensing human response to the thermal environment. The thermal comfort meter was periodically placed in different locations throughout the building. The typical office occupant metabolism level was set at 1.2 met and dressed in a summertime clo value of 0.8. The relative humidity varied between 40 and 60% as sensed by a dew point meter in the return duct.

Figure 2 shows typical PMV measurements taken during the warmest part of the day throughout the summer months at three different locations within the JID. The dashed line in each plot represents typical conditions measured between June 1 and August 31, 1983. The solid lines represent maximum observed PMV in each zone.

The PMV in the summer season varies from 0 (neutral) to 0.5 (90% of the occupants satisfied), which is within the comfort zone specified by ASHRAE 55-1981. The bottom plot shows the building’s south-facing offices, with 75% of the south wall glazed, remain at a PMV of 0.1, except during the day when
the windows transmit heat into the space. The PMV rises from 0.1 to 0.3-0.5, peaking at around 4:00 p.m. The top plot shows the north-facing offices, which are surrounded on three sides by earth, remain closer to a PMV of 0.1 for most of the day and night.

PMVs for dormitory rooms in the southeast zone of the building with half the south wall glazed, but shielded completely from direct sunlight, show a slight rise in the middle plot of Fig. 2 from 0.1 to around 0.15-0.3.

Late in August the direct light begins to enter the extensive south-facing windows and even with 38°C (100°F) outside air temperatures, the building and the 3-ton heat pump keep the space below a 0.5 PMV. Data taken on August 23, 1983, show this (Fig. 3). The top plot shows the outside air temperature rising to almost 38°C (100°F). The middle plot shows the heat pump measured sensible cooling. The unit is running continuously from 1200 to 1700. The bottom plot shows that PMV peaks at 0.5 around 1400 and then drops back. The rapid drop between 1500 and 1600 was caused by cloud cover and afternoon showers.

Continuous PMV measurements taken in this building show very little short-term fluctuation of PMV due to compressor cycling. Supply temperature fluctuations are not noticeable, primarily because of the extensive coupling of the inside thermal mass and the supply duct.

A well-built, energy-efficient building not only saves energy, but can be held to tighter comfort standards even with drastically different inside surface temperatures, such as 22°C (72°F) at the floor and 32°C (90°F) at the south-facing windows. Occupant performance is related to comfort. A decrease in performance of mental tasks occurs with increasing thermal dissatisfaction. Most offices cannot afford any thermal comfort productivity penalty.

WHOLE-BUILDING COOLING SEASON ANALYSIS

Energy Usage

Some cooling is required in this building from May through September. In 1982, with a typical cooling season of 655 DD base 18°C (1180 DD base 65°F), the building used 5000 kWh for cooling at a cost of $285 assuming 5.7¢/kWh, and in 1983 with an above average cooling season of 724 DD base 18°C (1304 DD base 65°F), the building used 5487 kWh at $313. The direct cost of running the circulating fan is about $15 per month. During the cooling season months, 40% of the total electric energy consumed by this building is used for providing mechanical space conditioning.

During the day the office space is occupied intermittently. Throughout both cooling seasons, the total number of people using the building at any one time typically varied from three to seven. Throughout the summer months, the monthly non-space-conditioning energy use averaged about 4.5 kWh/m².⁴

Field Measured Heat Pump Performance

The heat pump sensible cooling output is determined by measuring the return and supply air temperatures and flow rate.⁴ The latent cooling is
determined by measuring the volume of condensate collected from the evaporator coil. The nominal cooling capacity and energy efficiency ratio (EER) rated at Air-Conditioning and Refrigeration Institute (ARI) conditions of 35°C (95°F) outdoor air temperature are 11.7 kW (40,000 Btu) and 7.7. The measured heat pump performance suggests that at steady-state operating conditions, the installed heat pump produces only 80% of the rated total cooling capacity, and the resulting EER is about 20% below the ARI-tested performance.

The poor heat pump performance is caused by how the unit is coupled with the building envelope. Figure 4 shows a percentage breakdown of the measured sensible and latent heat output for 1 h at 35°C (95°F) ambient air compared with the ARI-rated output at similar conditions. The short-fall in measured cooling performance is estimated based on a variety of factors which cause deviation from the laboratory test conditions. The largest single cause for the low output is that the evaporator fan provides only 67% of the manufacturer's recommended air flow. This low air flow is believed to result from restrictions in the supply duct located in the concrete footings of the building.

The lower air flow past the evaporator coil is estimated to reduce the cooling output at rated conditions approximately 8% from the manufacturer's data. Another 8% loss results from a combination of air leaks from the return duct and economizer, conduction losses due to wet insulation on the floor of the heat pump housing and missing insulation on the return duct, and the radiative loading of the sun. The surface temperature of the heat pump housing in the afternoon with full sun has been measured as high as 68°C (153°F).

The cause for the remaining difference between measured and ARI-tested performance is unknown, although part of the remaining shortfall in cooling performance could be due to the location of the heat pump on the west side of the building and the fact that it is surrounded by the building and retaining wall. With the afternoon sun, this location heats up above ambient conditions, causing the heat pump to use a higher condenser inlet air temperature than measured by the electronic thermometer collecting site ambient air temperatures.

The average seasonal energy efficiency ratio (SEER) for delivering only sensible cooling is around 4.5. The value is low, not only because of the installation shortcomings mentioned above, but also because of the continuous circulating fan.

When cooling is not needed in the afternoon hours, the sun shining down on the heat pump housing located on the west side of the building results in the circulating fan picking up a heat load of as high as 1700 W/h (6000 Btu/h). Part of this heat gain is due to the fan power (400 W). However, the fact that this represents about 25% of the heat pump maximum sensible cooling capacity illustrates the significance of this unwanted heat flow.

A more efficient mechanical design for the building would be to use a split heat pump system. The inside unit could circulate air without picking up heat, and the economizer could be reconfigured so the inside fan unit could also pull in outside air for ambient cooling when conditions were acceptable.
During the summer months, a dominant heat load to the building is from internal electric usage. The daily value fluctuates according to the building occupancy, although on a monthly basis it is fairly constant. The building envelope is well shaded from the direct sunlight and shielded from the wind so the remainder of the heat gain is proportional to the inside and outside temperature difference.

The monthly heat pump energy use from May through September for both 1982 and 1983 is plotted against monthly cooling DD in Fig. 5 along with the linear least squares regression. The cooling DD base 20°C (68°F) was found to provide the Y intercept closest to 300 kWh, which is the constant monthly consumption for the circulating fan. This suggests that the balance point for the building is 20°C (68°F). The slope of the regression line is 4.3, indicating that 4.3 kWh is required for every cooling DD base 20°C (68°F).

The correlation coefficient for the regression equation shown in Fig. 5 is 0.96. In general, the equation is capable of predicting monthly heat pump energy requirements for the building within ±20%. The least squares fit of heat pump energy consumption and cooling DD represents a data fit to a steady-state heat transfer model that suggests that the cooling load is simply a function of the average temperature difference between the inside and outside air.

**Economizer Performance**

The economizer is coupled in series with the heat pump and is positioned on the return duct side of the heat pump. An enthalpy controller senses the air temperature and moisture surrounding the unit. If the enthalpy is below the set points, outside air is pulled in to cool down the building air and mass with ambient cooling. Earth-sheltered homes are usually designed to minimize exposure to the wind, resulting in lost opportunity for natural cross ventilation; an economizer helps enhance ambient cooling by increasing the ventilation rate.

A larger fraction of economizer cooling takes place in early and late summer, ranging from 40 to 70% as compared with 0% when the temperature remains relatively high during midsummer nights.

The physical location of the economizer hinders the maximum use of ambient cooling for many of the same reasons the heat pump performance is impaired. The heat pump and economizer are surrounded by mass, that absorbs heat from the sun and from the heat pump condenser coil all day and into the night. Then, when the ambient air finally cools down enough to provide some cooling assistance, the economizer senses the surrounding warm radiating mass and keeps its dampers closed. However, the high humidity in the area restricts the economizer cycle operation throughout most of the summer.

Nighttime ventilation coupled with extensive structural thermal mass can provide significant annual and peak energy savings in commercial buildings. However, in those parts of the country with high humidity, this option is severely restricted. Building mass needs to be flushed with outside air not permitted to enter the occupied space.
A close examination of the heat pump efficiency and economizer performance suggests that when whole-building comparisons are made, differences in the mechanical plant must be considered. Very efficient heat pumps installed in residences near the JID have SEERs exceeding 8, and the heat pump at JID has an SEER of around 6. A very efficient building envelope and mechanical package do not necessarily produce an optimum whole-building design. Careful coupling of the two systems is necessary to reach the whole-building energy efficiency potential.

ENERGY SAVINGS COMPARED WITH ABOVEGROUND BUILDINGS

An above-grade, energy-efficient residential building used for comparison to the JID is the TECH House III, located 20 miles from the JID site. It was very carefully monitored throughout the 1982 summer season. The interior electric and occupancy usage of the TECH house III is approximately the same as that of the JID, when normalized to a unit floor area per month value (4.5 kWh/m²).

Comparing only the heat pump energy consumption the TECH House III with that of the JID reflects a 30% savings for the JID. If the JID heat pump were performing at the higher SEER measured in the TECH house, the electric energy savings would be 50%. Additionally, if the continuous circulating fan were unnecessary, the electric energy savings would exceed 60%.

The DOE-2.1A building simulation model was used to model both the JID and an aboveground structure. The annual savings for the entire year, both cooling and heating, was about 30%.

In addition to the annual energy savings, the peak cooling requirements are cut almost in half. The TECH house has an installed cooling capacity equivalent to 57 W/m² (18 Btu/ft²) compared to the JID's 31 W/m² (10 Btu/ft²).

The increased cost for going below ground in residential construction is estimated at about 12 $/ft² using Knoxville area labor. For comparison, the same floor plan placed in an aboveground structure would result in the underground JID structure saving 60% in cooling and heating energy. This results in an annual electric energy savings of about 500 $/year based on 5.7$/kWh, or a simple payback of 95 years, not accounting for the other environmental amenities inherent in underground construction. If the cost of energy were to triple to 17$/kWh, this would produce a simple payback of less than 30 years.

BUILDING ENVELOPE PERFORMANCE

The data acquisition system installed in the building permits an insight into those sources of heat entering the building which require removal. For instance, the fraction of sensible cooling caused by the heat entering the building from the earth-covered roof and bermed walls can be determined.

Figure 6 shows the largest source of heat in the building is internal loads (electric usage and occupants). The internal electric heat source represents about 50% of the total sensible heat gain to the building. The second largest heat source is the south-facing windows. The glazing aperture
is fully shaded from direct solar insolation, yet the sky radiation and ground reflectance still contribute about 40% of the total heat gain. Less than 10% of the sensible heat gain enters the building through the outside walls and earth-covered roof over a typical diurnal cycle.

The sensible cooling comes predominantly from the heat pump (53%). The economizer removes an average of about 9%. The economizer provides a much more substantial cooling contribution in the swing season. The weeks used for characterizing the cooling season energy balance are all from June, July, and August. A significant fraction of the heat is absorbed by the berm'd walls and floor (15%). This contribution is much greater in the first half of the cooling season than the last half since the surrounding earth temperature in the berm lags roughly a month behind ambient air temperature, and the earth below the floor lags about 3 months. The unmeasured and unaccounted residual energy varied from -9 to 28% on a weekly heat balance period. Part of the residual results from occupants opening windows predominantly in the evening.

Energy balances for time periods of 1 day or longer mask what really happens throughout the diurnal cycle. The peak cooling load occurs in the afternoon because of the extensive use of the building during this period, maximum solar-loading, and large inside-to-outside air temperature differences. Figure 7 shows an energy balance for a 1-h period at 4:00 p.m. with full sun and outside air temperature of 32°C (90°F). The heat gain exceeded the heat pump sensible cooling capacity by 50%, and the inside air temperature remained stable. The thermal comfort within the space was maintained. This excess heat was absorbed by the mass inside the building.

By far the dominant source of incoming heat was the south-facing windows (60%). The internal electric loads for this 1 h are only 15% (0.4 W/ft² or 1.3 W/m²) of the total heat gain, and ventilation accounts for about 16%. The opaque envelope components contribute only 9%.

**Slab Floor**

The floor is an insulated slab with 0.02 m (1 in.) of rigid insulation board placed underneath the poured concrete. Throughout the 1982 summer the average earth temperature 1 m below the floor surface was 19°C (67°F), and in 1983 it was 22°C (71°F). The average heat flow out of the building and through the floor fluctuates very little; this average is about 1 W/m² [0.3 Btu/(h·ft²)].

The heat flow through the slab floor with well-insulated footings appears to be accurately modeled by assuming steady-state heat transfer using average weekly temperatures. However, some uncertainty exists in the estimation of the temperatures to use for the soil below a similar building without thermocouple wells installed below the floor. In this building, a temperature profile taken on the south side of the building would underestimate the soil temperature all summer, and a soil temperature profile on the north side would overestimate the soil temperature until the middle of August. Figure 8 shows such temperature profiles for the JID as a function of depth, time, and location. The floor provides both diurnal thermal storage and a continuous sensible cooling load of approximately 0.4 kWh (1320 Btu/h).
This earth-sheltered building is in contact with the earth on three sides, and the soil temperature immediately adjacent to the building envelope varies as a function of envelope component and time. Figure 9 shows the average weekly temperatures of the soil adjacent to the floor, roof, and midheight of the bermed walls. For comparison, the ambient air and undisturbed earth temperature at a depth of 5 m are also provided.

The peak storage occurring at 1600 coincides with the peak daily cooling hour, and the heat is released back to the space at night. The evening ventilation air and occasionally the economizer carry much of this heat out of the space. If the 0.02 m (1 in.) of insulation were not present, even more sensible cooling could be provided by the floor. An estimate, assuming no insulation, suggests the net sensible cooling would triple to about 1.2 kW (3960 Btu/h).

On the average, the floor provides an estimated 11% of the sensible cooling for the building. The presence of 1 in. of insulation penalizes the building in the cooling season. If the floor provided an additional 22% of the sensible cooling, it would reduce the cooling cost by about 24 $/year. However, without insulation, more heat would be lost through the floor in the winter, and the estimated increase would be about $50. Thus, the insulation in the floor at current electric rates of 5.7¢/kWh saves about 25 $/year. This accounts for the floor loss only and not for increasing supply duct losses during the winter.

Bermed Wall

Figure 9 shows that the average temperature of the north wall between the soil and the wall construction remains below the average ambient air temperature until August. From then to the end of the cooling season, the berm itself does not provide any significant sensible cooling. However, Fig. 10 shows that a desirable thermal short exists between the bermed wall and the floor slab. About 18% of the heat going into the wall travels down the wall to the floor slab and eventually into the cooler earth below the building. This was determined by using the average measured temperatures surrounding the north wall to determine the boundary conditions for a finite difference model.6

The bermed wall construction consists of a 10-in.-thick poured concrete wall with 2-7/8 in. reinforcing rods running vertically on 0.4-m (16-in.) centers, providing a high conductive path between the wall and floor foundation. The wall is fully insulated between the concrete and the earth with 0.08 m (3 in.) of Styrofoam, and the floor slab is insulated with only 0.02 m (1 in.). More heat could be dissipated to the earth berm with less insulation, especially in the first half of the summer cooling season.

Throughout most of the summer, the bermed wall provides a sensible cooling load of about 0.15 kWh (500 Btu/h). However, in late August, the wall actually contributes a small amount of heat to the building space. No condensation forms on the back wall or on the floor. On the average, the bermed wall provides 5.3% of the sensible cooling provided to the building.
The net heat gain from the roof is very small. In some commercial buildings the roof sensible heat load is usually the largest single envelope component contribution. Figure 11 is a comparison of the measured temperatures taken on the JID roof and a conventional office roof system located in Oak Ridge, Tennessee. The conventional roof system is standard concrete deck with fiberglass insulation board placed on top, covered with a membrane and gravel ballast. The maximum surface temperature above the insulation is 54.4°C (130°F) on the conventional roof compared with 22°C (73°F) just above the insulation in the JID.

Figure 11 suggests that the peak heat flux penetrating this roof most likely coincides with the peak cooling load for the entire building. The earth-covered roof system actually supplied a small element of sensible cooling [0.26 kW (900 Btu/h)]. An additional 3.5 kW (1 ton) of cooling capacity would be needed to accommodate the additional heat gain coinciding with the building cooling load coming through a roof with the same R-value without earth covering. On the average, the conventional roof system temperature just above the insulation is 31°C (86°F) in contrast with the JID, which averages about 27°C (80°F) throughout the summer.

The roof system neutralizes the radiant gain from the sun and results in very little net heat entering the building. The heat that does penetrate the roof system is out of phase with the whole-building cooling load. During the daytime hours, the grass cuts the radiative load, and the soil reduces the roof surface temperature amplitude, resulting in a lower effective temperature difference across the roof.

The effect of the thermal mass capacity of the soil attenuating the temperature fluctuations is apparent. Throughout 1983 the soil was very dry. This had a number of consequences; one was that vegetation did not transpire as much. This is a lost cooling effect. Secondly, the conductivity of the soil remains relatively low, resulting in better insulating capabilities.

CONCLUSIONS

This underground building saves 30 to 50% of the purchased energy needed in well-built above-grade buildings during the cooling season. In spite of the fact that 75% of the south wall contains glass, largely for passive solar heating, extensive thermal comfort measurements show that the JID building remains comfortable. Peak cooling load is reduced by about one-half because of the extensive thermal mass in and around the building and the extensive shading.

Of the energy needed for cooling, 50% is a result of internal electric loads, and 40% comes from sky radiation and ground reflectance through the south-facing windows. The opaque thermal envelope is almost completely neutralized.

The floor and bermed walls provide about 15% of the sensible cooling needed by the building throughout the summer cooling season. The earth-covered roof tracks the average daily temperatures. The high solar radiation
loading is completely offset by reflection, vegetative evapotranspiration, and nighttime reradiation to the night sky. What little heat does penetrate this earth-tempered roof system is out of phase with the building peak cooling loads. The earth-covered roof alone reduces the peak cooling load requirement by at least 25%.

An efficient building envelope and an efficient heat pump do not necessarily produce an optimum whole-building configuration. The coupling between the mechanical equipment and the envelope must be carefully considered. The location of the heat pump on the west side of the JID, surrounded by a massive retaining wall penalizes the heat pump performance. The hot afternoon sun creates a hot pocket from which the heat pump must pull air for the condenser coil. A second penalty is the building requirement for continuously circulating air. A fan pulls the circulating air through the single-unit heat pump housing where it picks up heat. On mild, sunny afternoons, the heat picked up from the heat pump housing can be higher than all other heat gains to the building.

A split heat pump system with the outside coil located on the roof would have been a preferable design. An efficient heat pump installation could reduce the summer cooling cost about 20%. The economizer pulls in outside air for cooling at night when the enthalpy is below the enthalpy of the inside air. In climates with high humidity during the warmer summer months, very little direct ambient cooling is possible without raising the dew point above recommended conditions. This was the case in the JID; most of the economizer cooling occurred during the beginning and the end of the cooling season, although the seasonal contribution of the economizer amounted to 17% of the total sensible cooling supplied by the heat pump.

REFERENCES


5. H. Shapira et al., Cost and Energy Comparison Study of Above-and Belowground Dwellings, ORNL/CON-91, Oak Ridge National Laboratory, August 1983.

Fig. 1. Joint Institute Office and Dormitory.

Fig. 2. JID thermal comfort measurements in three locations.

Fig. 3. Thermal comfort at 32°C (100°F) peak outside temperature.

Fig. 4. JID heat pump steady-state performance at 35°C (95°F) outside air temperature.

Fig. 5. Monthly heat pump energy usage vs cooling DD – May-September 1982 and 1983.

Fig. 6. Average energy flows around JID for summer of 1982.
Fig. 7. Peak hourly energy balance showing 30% of the incoming sensible heat stored in thermal mass.

Fig. 8. Earth temperatures tautochrones as a function of depth at three locations: south side, below, and north side of building.

Fig. 9. Average weekly soil temperatures surrounding the JID envelope.

Fig. 10. Response factor analysis reveals a desirable thermal short in the bermed wall.

Fig. 11. JID roof temperatures compared with those of conventional roof systems.