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Thermal Envelope Field Measurements in an Energy-Efficient Office/Dormitory

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ABSTRACT

A 4000 ft^2 (345 m^2) earth-covered structure located at the Oak Ridge National Laboratory is the focus of a DOE-sponsored building envelope research project. Heating the office/dormitory building over the 1981-1982 heating season costs \$0.16/ft^2 (\$1.70/m^2), assuming \$0.057/kWh. The total cost for construction in 1980 dollars was about \$85/ft^2. The thermal integrity factor is 2.8 Btu/ft^2 · °F (0.016 kWh/m^2 · °C). A preliminary DOE-II model estimates the monthly electric energy needs for heating within 5% of field-data derived estimates. DOE-II building simulations suggest that this earth-covered, passively heated office dormitory saves 30% for space heating and 16% for cooling compared to an "energy efficient" above-grade structure. A preliminary winter energy balance has been generated from data collected in February and March which provides a fractional breakdown of thermal losses and gains. A number of the energy-conserving components' performances have been isolated: earth-covered roof, bermed wall, and nonvented Trombe wall. The earth covered roof system showed an overall thermal transmittance of 0.18 W/m^2 · °C (0.03 Btu · ft^2 · °F). The thermocouple wells located in the earth surrounding the building indicate that earth covering offers additional energy savings over earth berming. For one week in February the Trombe wall produced a 50% greater net thermal gain to the building then south-facing windows.

INTRODUCTION

The Joint Institute Office/Dormitory (JID) is an earth-covered, passively heated building containing 4000 ft^2 (345 m^2) of inside floor area. It is located at the Oak Ridge National Laboratory in eastern Tennessee. Construction was completed in early 1981, and the building was occupied in the spring. Manual electrical-energy submeter readings began in December 1981, and automated field-data acquisition began in February 1982. This report covers data collection from February to April 1982.

The building has a number of innovative energy-conserving concepts: an earth-covered roof, a bermed north wall, full perimeter insulation, a direct-gain passive solar system in the form of south-facing glazing amounting to 17% of the floor area, thermal mass, nonvented Trombe walls, and an economizer heat pump. One of the major objectives of this paper and the research program involving field-data acquisition is to present field-performance data on the building's energy-saving concepts, which can be used to evaluate their effectiveness.[1]

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To date, most of the performance on these features have been gained from simulation models, laboratory experiments, and very limited time and location field measurements. Data collected on JID will provide field data for at least a full year. The individual building conservation features cannot be considered independently of one another, indeed, in every building they are a part of the whole building system. A feeling for the performance of the whole building is established by a detailed energy balance completed to account for all major heat flows into and out of the building and to relate the performance of individual building-envelope components to auxiliary energy needs. Heating the office/dormitory during the 1981-82 heating season costs $0.16/ft^2 ($1.70/m^2) (assuming commercial rates of 5.7¢/kWh in Oak Ridge, Tennessee).

BUILDING DESCRIPTION

The formal name of the building is the Joint Institute for Heavy Ion Research. It is part of a national user facility. Visiting scientists from this country and foreign countries stay in the dormitory for short periods of time while conducting experiments involving the two accelerators that are the focus of the facility: a 25-MV tandem electrostatic accelerator and a cyclotron. The dormitory occupancy varies from 0 to 10 people, and the office space is occupied by anywhere from 2 to 12 people.

Figure 1 shows a floor plan of the building. The east wing contains the dormitory rooms, and the west wing contains primarily offices. The two are separated by a lounge and eating area. The four dormitory rooms on the south side have 3 ft by 10 ft (0.9 m by 3 m) windows over 3 ft by 11 ft (0.9 m by 3.6 m) nonvented Trombe walls.

The building envelope is primarily of concrete masonry construction, as shown by the building cross section in Fig. 2. All walls in contact with the air are covered with 3 in. (0.75 mm) of polystyrene. The roof consists of precast concrete covered by 2-3 in. (0.5-0.75 mm) of poured concrete to provide a smooth adhesive surface for the waterproof membrane, 3 in. (0.75 mm) of extruded polystyrene, filter paper, gravel, more filter paper, and 1.5-2.5 ft (0.46-0.76 m) of soil. The back wall is shown in Fig. 2 illustrating the 3 in. (0.75 mm) of styrofoam all the way to the footings. The north wall and part of the east wall are bermed. The remainder of the east and all of the west and south are exposed to the air.

The mechanical package in the building is a 12.3 kWh (3-1/2 ton) heat pump with an economizer cycle capable of providing ambient cooling when the enthalpy is low enough and cooling is needed by the building. A circulating fan is continuously used to avoid air stagnation and help thermal mixing in the building. The supply ducts are located in the concrete footings. The dual-return duct system pulls air from the top of all rooms in the building. The temperature in the building was maintained at about 20-21°C.

DATA ACQUISITION

The data acquisition system supports the objective of not only determining the performance of the whole building, but also providing tools from which to determine the energy-saving effectiveness of individual components and concepts.

Sensors

Electrical Energy Consumption. There are five electrical submeters in the building which monitor the heat pump, water heater, lights, receptacles, and kitchen appliances.

Ventilation. There are two ventilation fans in the building: one in the restroom and one in the kitchen. The restroom fan is a determining factor in the air-change rate of the building. If the fan is off, the air change per hour is about .5; if on, it is about .7. The fan's operation is controlled by the building occupants. A current sensor has been placed in the fan circuit, which is electronically checked every minute to determine the amount of time the fan is on.

Weather. The weather station consists of a wind sensor/generator, which converts speed into a corresponding AC voltage, a wind-direction transmitter, a relative humidity sensor/transmitter, and a shielded electronic thermometer to measure the ambient dry-bulb temperature. All of these sensors appear to perform very well, except the humidity sensor/transmitter. This instrument apparently measures well within 50-80% relative humidity, but very high and very low ranges produce unreliable data.

Rainfall is recorded with a rain gauge that uses a 8-in. (20-mm) diameter orifice and a tipping bucket mechanism coupled to a mercury switch.

Total direct and diffuse horizontal solar radiation is measured by two pyranometers. The sensors have had one calibration check with the values provided by the manufacturer and were found to agree within 2.5%.

Three pyranometer sensors are positioned behind south glazing to measure actual solar radiation transmitted through the glass. The silicon photodiode does not cover the full range of the solar spectrum, but the error introduced is less than ±5% under most conditions of natural daylight.[2]

Heat Pump. The heat-pump electrical energy demand to run the compressor, fan, electric-resistance strip heaters, crankcase heater, and controls is recorded separately on a Watt-hour meter. An ORNL-designed energy meter is necessary to measure the heat pump output. Three sensors are used: two averaging-resistance thermometers (one in the supply duct, another in the return duct) and a small anemometer.

Indoor Air. Indoor-air dry-bulb temperature is measured at four locations in the building. The sensors are shielded thermocouples which average the effects from convection currents and radiant energy exchange. Temperature differences between the south and north zones of the building as well as temperature differences between the east and west ends can be determined from these measurements. The dew point of the inside air is measured in the return duct, which represents an average building-humidity condition. The manufacturer indicates the accuracy to be within +1 to -2°F (.5 to 1°C).

Building Envelope and Thermal Mass. Thermocouples are attached inside and outside the building-envelope components in direct contact with soil. Additional thermocouples are positioned inside the building. These are useful for analyzing both the performance of the thermal mass and heat transfer through the envelope. Heat-flow sensors, incorporating a differential thermopile assembly that senses temperature difference across a calibrated conducting wafer, are mounted in the floor, rear wall, ceiling, and on both sides of one Trombe wall. For protection of the wafer during installation, a number of heat-flow sensors were precast into a small concrete slab.

The heat-flow sensors produce a self-generating millivolt signal and are sensitive to both radiation and conduction. Each wafer was calibrated at the factory, and the calibration was checked upon arrival at ORNL.

Earth. All of the earth temperatures are taken in the instrument plane, marked "AA", shown in Fig. 1. This is a north-south cross section of the building, extending into the surrounding earth to a distance at which the influence of the building should become negligible. The temperatures in the earth are measured in PVC-conduit instrumentation wells. Thermocouple sensors are held against the conduit inside the wall by foam insulation. The foam insulation also prevents convective loops from occurring in the wells when the ambient air temperature is very cold and the earth much warmer.

Collection. Sensor data is collected by a micro computer located in the northwest corner of the building. The data logger and two peripheral scanners have 100 active incoming sensor channels. Data is recorded for every sensor once an hour.

Those sensors that can fluctuate significantly during the hour (i.e., solar, heat flux, heat pump supply- and return-temperature) are scanned every minute, summed, and averaged. The logger has limited calculating capability, which has been used mostly to convert incoming signals to engineering units.

The initial data-collection design called for the data to be written to a data cassette and a paper tape on site. The cassettes store about one week's worth of data. Once the magnetic tape was full, it was transported manually to another tape player that was hard-wired to a large computing facility, read into the large computer, and edited into clean one-week data files.

In August a telephone modem was installed to provide a hard line from the data logger to the large computer. The data cassette is presently used for backup. The first two months of data transmission through the hard line have resulted in the loss of less than a day's worth of data.

WHOLE BUILDING PERFORMANCE

There are a number of different methods of describing how well the building is performing. This section presents four performance descriptions: the back of the envelope, energy balance (weekly and monthly), whole-heating-season performance, and computer simulation. Each technique offers a different insight.

The back-of-the-envelope approach simply measures the electricity used by the heat pump for an entire year. However, the objective of this research is to make available field-performance data on a number of energy-conserving concepts, and to fulfill this objective, a closer examination of the building components is necessary.

Before conclusions can be drawn on energy-conserving components, the link must be established between individual component performance and the whole building's performance. This link is in the form of a whole building energy balance.

A whole-building energy balance for one complete week is advantageous for a number of reasons. First of all the hourly data is stored in one-week blocks. A very convenient method of validating the data is to use the data to add up the building's heat gains for the week and compare them to the data derived heat losses. Secondly, an energy balance helps to determine if the major heat gains and losses can be accounted for in the building. Finally, an energy balance relates individual building components to each other.

A monthly energy balance provides slightly better accuracy than a weekly one. A number of building components, such as the floor and bermed walls, have heat-transfer lags longer than a week. By summing heat flows over a month, the thermal storage differences will be minimized.

The whole heating season represents a complete cycle of varying weather conditions. Once the building's performance is measured for an entire heating season, comparisons to other buildings and other construction practices are more reasonable. In addition, the building-component performances can be broken out and evaluated with regard to their performance in other buildings.

Back of the Envelope

To tell how well a building of this sort is performing, the study period should cover at least an entire heating and cooling season. From June 22, 1981, to June 22, 1982, the heat pump Watt-hour meter registered 19,050 kWh. This represents the electricity consumed by the heat pump and the continually operating circulating fan.

Energy Balance

The week of February 22-28, 1982, is used to display a weekly energy balance and March to display a monthly energy balance. The last week of February represents the first complete week of successful data collection, although it was warmer than a typical winter week in Oak Ridge. The average ambient air temperature for the week equaled 18°F (7°C). Figure 3 shows hourly data on the ambient dry bulb (1), solar insolation as sensed by a pyranometer located behind the south-facing glass (4), inside air temperature (2,3), and the heat pump (5) output.

The vertical axis in Fig. 3 represents hours, the horizontal axis, °C for those temperatures plotted, W/m^2 for the solar data, and W for the heat pump output. The ambient air temperature is plotted using a "1" in °C. The first few hours of the week were not logged; however, beginning Monday afternoon the temperature can be seen falling for the evening to around -4°C and rising the following day to 24°C. Later in the week the ambient air temperature rises much less during daylight hours.

Two inside air temperatures are shown in Fig. 3 one recorded in the south facing offices plotted with "2" and one in an office on the windowless north side plotted with "3". As expected, on warm, sunny days the south offices remain about 1.5°C warmer than the back; however, during the cold, cloudy fifth day the front offices are slightly cooler than the back.

The fifth piece of information plotted in Fig. 3 is the heat pump output in Watt-hours (Wh), ranging from a minimum of -2000 Wh to a maximum of about 10,000 Wh. The first four days show very little need for the heat pump plotted with a "5"; however, on the cloudy fifth day some heating is called for every hour. Those hours in which the heat pump is showing an actual net heat loss reflects the heat-pump-housing losses from both leakage and conductive heat transfer with the ambient air.

Building Thermal Gains

There are four significant sources of heat gain into the building in the winter: internal loads, the direct-gain solar system, the Trombe wall, and the heat pump. The data-acquisition system measures all four of these wintertime heat gains. Equations 1 - 5 show the heat-gain accounting.

$$G = IL + SW + TR + Q_H \text{ (kWh)} \tag{1}$$

where

IL	=	internal loads
SW	=	direct solar
TR	=	Trombe wall
Q_H	=	heat pump

Equation 2 shows the summation of internal electric loads that enters the building plus sensible people heat. A log is kept on daily occupancy in the building.

$$IL = \sum_{i=2}^{5} M_i - H_L - L_o + F_L + P_E - B_F - K_F + A_E \tag{2}$$

where

M	=	kWh meters
i	=	meter number (2-5 are for internal electric load)
H_L	=	hot-water energy lost through the drain
L_O	=	outside lights
F_L	=	circulating fan power (<450 Watts)

P_E = people sensible heat
B_F = restroom fan (250 Watts)
K_F = kitchen fan (250 Watts)
A_E = electric power consumption of data-collection system.

Direct solar gain is measured by two pyranometers located on inside window sills. The total measured radiative and conductive heat is used in Eq 3 to derive total gain.

$$SW = A \times Li \times SH \times SC \times HR \tag{3}$$

where

A = area of window
L_i = hourly solar insolation
SH = percentage of window in direct sunlight
SC = shading coefficient
HR = time period

The Trombe wall building gain is measured by the heat flow sensed by the heat flux meter on the inside wall and used in Eq 4.

$$TR = Q_T \times A_T \times SH \tag{4}$$

where

Q_T = summation of inside heat-flow sensor
A_T = Trombe wall area
SH = fraction of Trombe wall not shaded by overhang

The heat pump output calculation, Eq 5 is executed by the data logger and Q is printed out directly.

$$Q_H = \sum_{H=1}^{HR} \Delta T \times V \times k \tag{5}$$

where

ΔT = temperature difference across heat pump
V = velocity of air
k = calibrated constant accounting for duct size, specific heat, and density of air

Building Thermal Losses

There are seven significant heat losses in the heating season as shown by the steady-state Eq 6.

$$L = \sum_{i=1}^{5} U_i \Delta T_i A_i + Q_{iv} + Q_u \tag{6}$$

where

U_i	=	thermal transmittance of the envelope element measured over a long period of time (approximately one month) using heat flux and thermocouple sensors on the roof, bermed wall, outside walls, floor, and window
ΔT_i	=	averaged temperature difference across the element for the study period
A_i	=	element areas
i	=	envelope element (roof, bermed walls, floor, east and west walls, south wall, and south windows)
Q_{iv}	=	infiltration and ventilation heat loss.
Q_u	=	unaccounted losses.

The resulting weekly energy flows are shown in Fig. 4. Detailed calculations are shown in Appx A. The total heat losses measured and estimated for the last week in February totaled 1123 kWh compared to the heat gains of 1205 kWh. The fact that the heat losses came within 7% of the gains is probably as close a balance as one could expect given the element of error involved in monitoring an occupied building. The resulting energy balance for March is also shown in Fig. 4, and detailed calculations are presented in Appx B. The energy balance involves monthly average data in some of the calculations and monthly summations in other calculations, for example, solar insolation and heat-pump output.

Because of electrical difficulties, the data logger was down for a number of days in March. In addition, the data cassette failed to record data for a few more days. Calculations requiring average values for the month were carried out with the average values from those hours of available data.

The missing solar data were derived by using the sky-cover value provided by the local NOAA weather-collection station four miles from the building site. The sky-cover value was given as one (sunny) through ten (cloudy), and a corresponding daily Btu/ft^2 (W/m^2) was assigned those missing days by using good daily data with similar sky-cover values in March.

The missing heat-pump output was filled in by using the manual kWh readings for the heat pump and using a COP developed from other hours of heat-pump operation when accurate input and output data were available.

The total data-derived heat losses and gains for March were about 4100 kWh. The percentages of each gain and loss were very similar to the weekly balance in every category except for internal loads and heat pump contributions. In March, the internal loads were less, and the heat pump was needed to make up the difference. There are a number of features to the building and the rather extensive data-acquisition system that helped contribute to energy flow measurement accuracy: predictable infiltration and ventilation, a constantly circulating fan, heavy-thermal-mass construction, and an extensive data-acquisition system.

Blower-door, tracer-gas, and velometer measurements were used to determine the air-change rate. The blower-door and tracer gas tests predicted air change rates within 10% of each other.

The blower-door tests in January 1982 established that the building was very tight and that the ventilation fan when running would be the dominant contribution to air infiltration and ventilation.

A four-day indoor air sampling test was run, which found no radon problem in the building. The test revealed the radon levels under worst-case conditions never rose above 25% of the maximum acceptable concentration. Other indoor air pollutants will be sampled in the future; however, there are no odors present to suggest poor indoor air quality resulting from the .5 to .7 air changes per hour.

1981-82 Heating Season Performance

Because detailed data acquisition began in February 1982, and daily manual Watt-hour readings in December 1981, the determination of the first half of the heating season performance required an estimating routine using available performance data. This routine consisted of extrapolating the internal electric loads from January through March back into October and November. Available monthly master Watt-hour meter readings and one set of submeter readings in July were useful in developing the kWh submeter monthly usage for JID during the beginning of the 81-82 heating season.

The heat pump's monthly COP was estimated, and then the heat input to the building from the heat pump was calculated. Since the circulating fan runs continuously, the fan is subtracted from the COP calculation. Based on similar heating degree days the monthly COP for April is used in October, and February's measured monthly COP is used in November. The monthly COP estimate for December and January of 1.44 is based on the measured daily COP on cold days in February and March, which were representative of the median days in December and January.

A commonly used indicator for residential building comparisons with different weather conditions is the thermal integrity factor (TIF) Btu/ft^2 - DD (kWh/m^2 - DD). The monthly TIFs for the JID are shown in Fig. 5. The dormitory's performance compares quite well to other energy-conserving structures.

Ultimately, the generic usefulness of the detailed building thermal analysis lies in its comparison to theoretical models used by others to estimate building performance. The DOE-II building model was used to simulate the JID. Observations and measurements of the building internal loads, occupancy, and operating conditions were used as input to the model. The results of the base-case model are shown in Fig. 5. The weather used in DOE-II was 1962 Oak Ridge, which is considered a representative weather year. The building performance was normalized for weather by deriving the TIF.

The on-site data-derived TIF for each month of the 1981-82 heating season are compared to the DOE-II results in Fig. 5. For the months of November through March, the DOE-II model came within 5% each month of the TIF based on the field data.

The version of the DOE-II model used to simulate JID did not account for Trombe-wall gains or heat transfer through the floor. These features will be added in the future, although these two components do represent a very small fraction of the building heat flow, as shown in Fig. 4, and tend to cancel each other out.

Eventually DOE-II comparisons to field performance data will be made at the building-component level. However, at this point, it could be argued that on the whole-building level it does appear that DOE-II can simulate the thermal performance of JID. Therefore, a second model was built that has an identical floor plan, internal usage, etc. The building envelope was changed to approximate an energy-efficient, above-grade structure and used as a reference building for comparison. The energy efficient structure was given a roof with a thermal transmittance of 0.039 Btu/ft^2 (U = 0.22 W/m^2 · °C), walls rated at U = .41 W/m^2 · °C (R = 40.072 Btu/hr · ft^2 · °F), the same total glass area as JID but redistributed with 50% of the total glass on both the north and the south side, and no extended overhang on the south side. In other words, if the heavy direct-gain passive solar system, the Trombe wall, the earth-covered roof, and the bermed walls were taken away, DOE-II would suggest results of 42% more energy consumption for heating and 36% more for cooling. The remaining sections of this paper begin to dissect the building by examining more closely a few of the specific efficient features of interest.

EARTH TEMPERING

Earth-Covered Roof

A cross section of the earth covered roof system is shown in Fig. 2 along with the location of a few heat-flow sensors and thermocouples. The heat-flow sensor (HF2) is mounted in a 4 x 12 x 12 in. (0.1 x 0.3 x 0.3 m) concrete slab which has proven to be an extremely effective technique for protecting the sensor as well as providing good data.

The heat-flow sensor HF2 in the gravel layer of the roof and the two thermocouples TC1 and TC2 are capable of measuring the insulation performance insitu. By assuming steady-state heat transfer through the roof, which is reasonable over a long enough period of time, the thermal transmittance of the insulation can be measured and compared with the manufacturers' rated transmittance. Both Doug Burch and John Gustinis have found excellent agreement between steady-state theory and weekly averages for very heavy mass construction during the heating season.[3,4]

Figure 6 shows that the assumption of steady-state heat transfer over a one-week period does correlates well with average outside air temperatures. A similar plot was made using daily averages compared to steady-state heat transfer, and very poor correlations were found. The thermal mass of the roof accounts for the discrepancy over short periods of time.

The nine average weekly heat flows through the roof as sensed by HF2 are plotted in the top graph of Fig. 7 for February 22, 1982, to May 9, 1982. The second graph shows the $\Delta T(T_1 - T_2)$ across the styrofoam board. Assuming steady-state heat flow permits the calculation of the thermal transittance of the insulation. The manufacturer's rated U-value is 0.067 Btu/ft^2 · °F (0.38 W/m^2 · °C).

The bottom graph shows the resulting measured U-value for nine weeks. The dashed line illustrates the manufacturer's rating.

The U-value was determined by assuming steady-state heat transfer as described by Fourier. During the 10 weeks, the overall thermal transmittance of the insulation was 0.063 Btu/ft^2 · °F (0.36 W/m^2 · °C), which is within 10% of the manufacturer's rated value. For the entire roof system, the overall U-value was 0.03 Btu/ft^2 · °F (.18 W/m^2 · °C) compared to the steady-state series was resistance estimate of 0.05 Btu/ft^2 · °F (.28 (W/m^2 · °C). It might be conceived from this very limited period of roof-heat-transfer measurement that during the heating season, another 2 in. (5 mm) of styrofoam would give the same performance as the 1.5 - 2.5 ft of soil. This conclusion might be premature, since the period of examination consisted of the transition from the heating season to the spring-swing season.

Figure 8 is a weekly plot of the two heat-flow sensors (HF1 and HF2) in the roof, the two thermocouples TC1 and TC2, and the ambient-air temperature. The horizontal axis in Fig. 8 is in °C for the three thermocouple sensors and in W/m^2 for the two heat-flow sensors. Heat flow out of the building is denoted by a negative. The ambient air temperature is plotted with a "1"; the heat-flow sensor (HF2) in the roof's gravel seam is plotted with a "4"; and the inside heat-flow sensor (HF1) located on the ceiling is plotted with "5". Judging from the peak heat flow of HF1 after the lowest outside air temperature, the apparent lag time of the roof is about 11 hours. The last three days of the week provide a glimpse of the roof-system's performance under less fluctuating conditions. The inside heat-flow sensor HF1 ("5") shows more heat flow than HF2 ("4"). The thermocouple TC1 located above the insulation is plotted with a "2", and the thermocouple TC2 located just underneath the insulation is plotted with a "3". The average ΔT for the week is about 7°C.

The HF2 showed about 30% more heat flow into the span deck than was measured coming out of the roof at that same point. The explanation for this seems to be, first of all, that the unshielded HF1 sensor picks up artificially high readings from lights and people; however, this does not account for the whole difference. There is a slight average temperature gradient in the roof from south to north. The temperature is 1-2°C warmer in the south half of the roof than in the north. There is slightly less soil covering near the back of the roof than in the front. Conceivably, heat enters the span deck, and convective air movement and conductance through the span deck carries some heat toward the cooler north wall and through the insulation at the interface between the roof and back wall. Edge-loss arguments would support this theory. Installation of a few additional thermocouples and periodic infrared sensing on cold winter evenings should provide some data to substantiate the extent of this horizontal heat flow in the roof.

Rain had no significant effect on the heat-flow sensor or thermocouples in the roof, although heavy rains have caused the roof to leak on several occasions. Engineers involved in the design and construction of the building believe the leak is a result of improperly setting down the double-layer membrane at the point at which the roof and parapet wall interface. Instead of placing the first layer on a concrete surface all the way to the parapet wall, the foam canting was applied first and the membrane on top of it. The membrane is self healing when placed on concrete. However, with the installation as is, once water penetrates the membrane, water can migrate long distances underneath the membrane increases the chances of a leak.

Bermed Walls

Figure 9 shows isotherms in the berm behind the north wall and below the floor. The data for January show the air temperature at -2°C and the earth temperature near the building at 8-14°C. In March the top of the berm heats up, but a cold spot lingers in the center, which is caused by the soil below the berm remaining warmer throughout the winter and the air warming the top of the berm. The actual soil temperature below the floor of the building is 1-2°C cooler in March than in January which illustrates a two-month heat-transfer lag. In June the berm warms up. However, the soil temperature close to the building floor and lower bermed walls was lower than the inside air temperature and did provide an element of space cooling.

The instrument-plane thermocouples are useful in understanding the building-soil interface. Figure 10a shows average monthly earth tautochrones far enough from the building to have not been affected by the presence of the building. One set of earth temperatures versus depth is given for each month from January to June. This kind of information is used to estimate the effect of earth tempering on underground buildings. The horizontal axis represents temperature (°C) and the vertical axis, depth below the surface of the earth. The Δt between the building and soil as a function of depth can be compared to the monthly average Δt between the inside space and the ambient air temperature for any given month. For example, in March the Δt between the inside air temperature and the ambient air temperature is 10°C. The Δt between the inside air temperature and the soil depth of 2.7 m, which corresponds to the depth of the middle of the bermed north wall, is 8°C. Steady-state heat transfer would suggest that 20% less heat is transferred through the back wall at that point than would without the earth tempering.

Figure 10b shows the same information for the actual soil temperatures measured next to the building in the berm .5 m from the north wall. Looking closely at the curve for the month of March, the Δt at the 2.7-m depth corresponding to mid height on the back wall is 7°C. The effect of earth tempering is 30%. However, in January and February the thermocouples show that the berm actually cooled more quickly than a true subsurface-soil temperature profile. The use of available, undisturbed soil temperature profiles and steady-state heat transfer assumptions would produce erroneous heat loss estimates for a bermed wall. Figure 10b shows that in the months of January and February, actual temperature differences across the constructed north wall are greater than would be predicted by using an undisturbed soil temperature profile, as shown in Fig. 10a. This difference may also be partly caused by the porosity of the crushed stone located near the back wall.

The DOE-II model of JID was modified by removing the clay and gravel from the roof and the backwall. DOE-II base case was actually modeled by adding two feet of clay to the bermed walls, because the full berm could not be modeled accurately. DOE-II suggest that earth covering saves 19% during the heating season and 4% during the cooling season. In the month of March DOE-II would suggest that 19% less energy was lost through the roof and bermed walls as a result of the earth covering. By using the tautochrone information shown in Fig. 5.5b, and the average thermocouple readings just above the insulation in the roof. The increase in Δt across these surfaces would be approximately 4°C across the roof and approximately 7°C across the bermed wall. Using Eq. (6) to factor in areas the percent of predicted savings of earth tempering on JID is 23%.

TROMBE WALL

The Trombe-wall construction consists of double glazing, capable of withstanding very warm temperatures of up to 225°F (110°C) with the air gap between the two sheets of glass depressurized and backfilled with a gas desorbent to prevent condensation. Behind the glass is a 2-in. (5-mm) air space and then a 12-in. (30-mm) poured-concrete wall serving as the nonvented thermal mass. The surface is painted with a highly absorbent black paint which has recorded temperatures as high as 150°F (66°C) in February. The concrete wall is thermally decoupled on all sides by placing an insulating barrier between the wall and adjoining surfaces.

Temperatures as high as 90°F (32°C) have been recorded inside the Trombe wall with the peak temperature occurring eight to nine hours after peak solar collection at about 1:00 PM. The net gain of the Trombe wall in March suggests an efficiency of 17% defined as heat flow into the room compared to solar incidence measured behind the glass. This efficiency is low, largely because the designed operation calls for the reflector cover to be placed in the open position for the entire heating season, day and night. The advantage of this is that there is no need or cost for manual daily operation. The penalty is that about 17% loss at night after a good sunny day. The Trombe wall is instrumented with a pyranometer, heat flow sensor and thermocouple position in between the glass and the storage wall and a heat flow sensor and thermocouple on the inside wall surface. Figure 6.1 shows data for the Trombe wall instruments for two sunny days in February.

From this plot the lag factor of eight to nine hours for heat transfer into the room can be seen, as well as the reradiation loss at night and the floating surface temperatures of the thermal-mass wall.

The net thermal gain of the nonvented Trombe wall in JID is .24 kWh/m^2 for March. With an insulated cover for nighttime and cold cloudy days, this collection at maximum could be doubled.

A comfort study has been run behind the Trombe wall on one day to predict the level of comfort or discomfort resulting from the radiative surfaces in the room. Figure 12 is a plot produced by data from a thermal comfort meter, which is an instrument programmed with P. O. Fanger's Thermal Comfort Index.[5] The humidity conditions, activity level of the occupants, and the occupant's quantity of clothing (clo value) are dialed in. From there the instrument senses air temperature, mean radiant temperature, and relative air velocity and prints out the predicted mean vote or percentage of people likely to be thermally uncomfortable. The predicted mean vote is a subjective thermal reading taken from a large group of subjects. Readings from this instrument suggest that during a rather warm day the conditioned space behind the Trombe wall remains within the comfort zone of typical occupants engaged in sleeping or reading.

DIRECT SOLAR GAIN

The net direct solar gain estimated in the fourth week of February was 0.3 $kWh/m^2/day$. The building design calls for reflective insulating blinds which will provide an equivalent evening R-value of at least 7 $hr \cdot ft^2 \cdot °F/Btu$ (1.2 $hr \cdot m^2 \cdot °C/W$). If properly used, that is, if someone manually closes the blinds each winter evening and opens them in the morning, these blinds will increase net direct solar gain by a factor of two.

SUMMARY AND CONCLUSIONS

The major objective of this research project was to collect field-performance data on a number of innovative energy-conserving concepts and document their performance with respect to this potential effectiveness in future buildings. The energy-conserving concepts considered here are an earth-covered roof system, bermed walls, full perimeter insulation, direct passive solar gain, thermal mass, nonvented Trombe walls, and an economizer heat pump.

Detailed data acquisition began in February 1982, which was just in time to catch a glimpse of the building's performance in the heating season. In the second half of the heating season, energy-balance calculations based on field data suggest that because of the tight construction, massiveness, stable building operation, and the extensive data-acquisition system, the building's performance was extremely predictable. This statement is supported by the energy balance for a one-week period in February and a one-month period in March. In the one-week energy balance, the heat losses came within 7% of the heat gains, and in March the difference was less than 2%.

In most occupied buildings, the biggest unknowns are infiltration and ventilation, and this probably is also true in the JID. However, this building has features that minimize the daily variations in infiltration. First, the building is mostly covered with soil and constructed very tightly. The walls facing the outside air are covered with "dryvit," which provides the same tightness as stucco. The walls are also partly shielded from the wind by retaining walls. Secondly, the building operation is very stable. The circulating fan for the heat pump is always on and the ventilating fan's on/off status is monitored. Blower-door and tracer-gas tests have been run on the building to measure the air change rate. The two techniques yield measurements within 10% of each other.

The overall air change per hour in the building varies between .5 and .7, which, for a commercial structure, is quite low. A four-day continuous radon sampling test revealed that radon levels under worst-case conditions never rose above 25% of the maximum acceptable concentrations.

Based on what data was available on the JID a thermal integrity factor of .016 kWh/m^2 floor area per degree-day (2.8 $Btu/ft^2 \cdot °F$) was calculated. DOE-II predicts the electric energy consumption of the heat pump on a monthly basis to within 5% of that measured on site.

DOE-II was used to provide a reference for comparison. For instance, the base-case model was taken and modified into an above-grade structure with a roof that had a U-value of .22 $W/m^2 \cdot °C$ (0.04 $Btu/ft^2 \cdot °F$) and walls with a U-value of .41 $W/m^2 \cdot °C$ (0.072 $Btu/ft^2 \cdot °F$). Fifty percent of the total glass area was placed on the north and south face, and there were no extended overhangs on the south wall. The more conventional above-grade building model used 42% more energy for heating and 32% for cooling than the JID.

Instrumentation in the roof and floor is capable of measuring insitu insulation performance within 10% of the manufacturer's ratings. Measurements of the earth-covered roof system over a very limited period of the heating season showed an overall thermal transmittance of .18 $W/m^2/°C$ (0.03 $Btu \cdot ft^2 \cdot °F$).

Most detailed building-envelope studies conclude that the outside heat-flow sensor is the least reliable. In the JID, the inside heat-flow sensor appeared to be less reliable. Heat-flow sensors surrounded by soil and concrete appeared to be very accurate. Initial data examination suggests that both the heat-flow sensors on the ceiling and inside back wall gave high readings. Parallel heat paths within the wall and ceiling surface may account for some of the 30-40% higher readings of the inside heat-flow sensors.

The earth-covered thermocouples adjacent to the building in the berm suggest surprisingly cool temperatures compared to a similar thermocouple well in the undisturbed earth.

For one week in February the Trombe wall efficiency was approximately 17% compared to the south-facing glazing efficiency of about 11%. Efficiency is defined as solar energy transmitted through the glass as the input and the heat remaining in the building and not lost back through the glass surfaces as the output.

All of the conclusions on the thermal performance of the building and components are preliminary. Only part of the heating season was monitored, and the initial data does have some holes. Extrapolation and other techniques were needed to provide the complete analysis.

ACKNOWLEDGMENTS

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APPENDIX A

WEEKLY ENERGY BALANCE - FEBRUARY 22-28, 1982

A.1 Building Thermal Gains

$$G = IL + SW + TR + Q_H = 638 + 374 + 26 + 167 = 1205 \text{ kWh} \tag{1}$$

A.1.1 Internal Loads (IL)

$$IL = \sum_{i=2}^{5} M_i - H_L - L_O + F_L$$
$$+ P_E - B_F - K_F + A_E$$
$$M_i = 662$$
$$H_L = .95\ (M_2 - \Delta T_2 \times A_H \times U_H \times HR)$$

where

H_L = lost hot water energy
M_2 = water heater meter reading for week (96 kWh)
ΔT_2 = ΔT across water heater tank (22°C in winter)
A_H = water heater surface (3 m^2)
U_H = thermal transmittance of water heater wall (0.00081 kWh/m^2 · °C)
HR = hours (168)
L_O = $OL \times HR_D$ = 40 kWh

where

L_O = outside lights
OL = outside lights (.44 kW)
HR_D = hours of darkness (91 h)
F_L = $FP \times HR$ = 75.6

where

F_L = fan load
FP = fan power (.45 kW)
P_E = $SH(BD \times 14 + OF \times 6)$ = 27.7 kWh

where

P_E = sensible people load
SH = sensible heat per person per hour (0.73 kWh)
BD = number of beds occupied for study period
OF = number of offices occupied for period of study
B_F = $BP \times HR_O$ = 33.6 kWh

where

B_F = restroom fan load
BP = restroom fan power (.2 kW)
A_E = $M_0 - \sum_{1}^{5} M_i$ = 22.5 kWh
HR_O = operating hours

where

A_E = data acquisition and fire alarm load
M_0 = master meter
M_i = submeters
IL = 662 - 75.7 - 40 + 75.6 + 27.7 - 33.6 - 0 + 22.5 = 638 kWh

A.1.2 Direct Solar (SW)

$$SW = \sum_{i=1}^{3} A_i \times L_i \times SH_i \times SC_i = 374\text{kWh} \tag{2}$$

where

i = zone windows one through three
A = window area (30 m^2, 13 m^2, 16.5 m^2)
Li = pyromometer summation for period of study inside the glass
SH_i = average fraction of window are in direct light (in Feb. 1.0)
SC_i = shading coefficient (dormitory shades are down 50% of time)
SC_3 = .75 SC_1 = SC_j = 1.0

A.1.3 Trombe Wall (TR)

$$TR = Q_T \times A_T \times SH = 26\text{kWh} \tag{3}$$

where

Q_T = summation of hourly heat flow into building as measured by the inside heat flow sensor over study period (2.1 kWh/m^2)
A_T = total area of four Trombe walls (12.3 m^2)
SH = fraction of Trombe wall not shaded by overhang (1.0)

A.1.4 Heat Pump (Q_H)

$$Q_H = \sum_{L=1}^{168} (Q_L - FP) = 167 \text{ kWh} \tag{4}$$

where

Q_L = heat pump output recorded by data logger each hour

A.2 Building Thermal Losses

$$L = \left(\sum_{i=1}^{5} U_i \Delta T_i A_i + Q_{VI}\right) HR + Q_u \tag{5}$$

$$L = (154 + 52 + 24 + 65 + 290 + 538) + Q_u = 1123 \text{ kWh} + Q_u \tag{6}$$

Roof (i=1)

U_1	=	thermal transmittance for a 10 week period from February 22-April 30 (.18 W/m^2-°C)
ΔT_1	=	13.7°C
A_1	=	372 m^2
HR	=	168 hours
	=	.18 x 13.7 x 372 x 168 hours = 154 kWh

Bermed Walls (i=2)

U_2	=	thermal transmittance for bermed walls assumed design value of .355 W/m^2 -°C
ΔT_2	=	average temperature difference between inside and in the earth just beyond insulation for the week of February 22-February 28 (7.6°C)
A_2	=	114 m^2
$U_2 \Delta T_2 A_2$	=	.355 x 7.6 x 114 x 168 = 52 kW

Floor (i=3)

$U_3 \cdot \Delta T_3$	=	Q_i for the floor. It is difficult to characterize the floor by a thermal transittance value because the supply ducts are in the foundation so the actual average measure heat flows are used .39 W/m^2
A_3	=	372 m^2
$U_3 \Delta T_3 A_3$	=	.39 x 372 x 168 = 24 kWh

East, West, and South Walls (i=4)

U_4	=	for the wall itself with 7.6 cm (3 in.) of foam board insulation the thermal transmittance from ASHRAE design values suggest .4 W/m^2 -°C and the weighted east and west walls = .43 W/m^2 -°C
ΔT_4	=	using the ambient air temperature instead of the skin temperature results in average 14.2°C for south wall and 12.2 for the east and west walls for the week
A_4	=	46 m^2 of east and west walls and 22 m^2 of south wall
$U_L \Delta T_4 A_4$	=	(.4 x 12.2 x 22 + .43 x 14.2 x 46) 168 = 65 kWh

Windows (i=5)

U_5	=	2.03 W/m^2 -°C which is determined by observing the average wind speed across the south face and recommended values from ASHRAE[4]
Δt_5	=	14.5°C
A_5	=	59.5 m^2
$U_5 \Delta T_5 A_5$	=	2.0 x 14.5 x 59.5 x 168 = 290 kWh

Infiltration and Ventilation (Q_{IV})

$$Q_{IV} = \Delta t \times .343 \times V_o \; (.7HR_O + .5HR_F) = 538 \text{ kWh} \qquad (7)$$

where

Δt	=	average temperature difference between inside and outside air (14.5°C)
V_c	=	building volume (920 m^3)
HR_o	=	hours with restroom exhaust fan on (168)
HR_F	=	hours with restroom exhaust fan off (0)

Unknown Heat Loss (Q_V)

To close the energy balance equations, there is always either some unmeasured heat flow or experimental measurement, even over the analysis period.

APPENDIX B

MARCH ENERGY BALANCE

B.1 Building Thermal Gains

$$G = IL + SW + TR + Q_H \tag{8}$$

$$G = 1692 + 1281 + 93 + 1026 = 4092 \text{ kWh}$$

B.1.1 Internal Loads

$$IL = \sum_{i=2}^{5} M_i - H_L - L_0 + F_L + P_E - B_F - K_F + A_E \tag{9}$$

$$1692 \text{ kWh} = (1606 - 253 - 164 + 335 + 220 - 149 - 0 + 97) \text{ kWh}$$

where

M_2	=	339 kWh (H_2O)
M_3	=	655 kWh (lights)
M_4	=	498 kWh (receptacles)
M_5	=	114 kWh (kitchen)
A_E	=	97 kWh (data acquisition and fire alarm)
H_L	=	.95 (M_2 − SB x HR) = 253 kWh

where

SB	=	standby losses (.097 kWh)
L_0	=	OL x HR_D = 164 kWh

where

L_0	=	outside light load
OL	=	outside lights (.44 kWh)
HR_D	=	hours of darkness (372)
F_L	=	(circulating fan) = FP x HR = .45 x 744 = 335 kWh
P_E	=	(people sensible heat) = SH(BD x 14 + OF x 6) = 220 kWh

SH	=	sensible heat per person per hour (.073 kWh)
BD	=	beds occupied during balance period (166)
OF	=	offices occupied during balance period (115)
B_F	=	(restroom fan power) = BP x HR_0 = .2 x 744 = 149 kWh

B.1.2 Direct Solar

$$SW = \sum_{i=1}^{3} A_i \times L_i \times SH_i \times SC_i = 1281 \text{ kWh} \tag{10}$$

where

i	=	window zone
A	=	window area 30 m^2, 13 m^2, 16.5 m^2
L_i	=	insolation summation for balance period (W/m^2)
S_H	=	fraction or window area not shaded by overhang

SC_i shading coefficient $SC_1 = 1$; $SC_2 = 1$; $SC_3 = .75$

$$= 30 \times 38{,}952 \times .66 + 13 \times 38{,}952 \times .66$$

$$+ 16.5 \times 42{,}902 \times .66 \times .5 \times .75 = 1281 \text{ kWh}$$

B.1.3 Trombe Wall

$$TR = Q_T \times A_T \times SH = 93 \text{ kWh} \tag{11}$$

where

Q_T	=	summation of heat flow sensor on inside wall of the Trombe wall mass (7.56 kWh)
SH	=	fraction of Trombe not shaded by overhang (1.0)
A_T	=	Trombe area (12.3 m)

B.1.4 Heat Pump

$$Q_H = [\sum_{L=1}^{744} (O_L)] - F_L = (1361 - 335) = 1026 \text{ kWh} \tag{12}$$

B.2 Building Thermal Losses

$$L = (\sum_{i=1}^{6} U_i \, \Delta Ti \; Ai + Q_{VI}) \, HR + Q_u = 4100 \text{ kWh} + Q_u \tag{13}$$

B.2.1 Roof

$$U_1 \, \Delta T_1 \; A_1 \times HR = 508 \text{kWh} \tag{14}$$

where

U_1	=	thermal transittance for a 10 week period (.18 W/m^2 -°C)
ΔT_1	=	average temperature difference between inside and outside temperature for March (10.2°C)
A_1	=	372 m^2
HR	=	744

B.2.2 Bermed Walls

$$U_2\ \Delta T_2\ A_2 \times HR = 202\ kWh \tag{15}$$

U_2	=	design thermal transmittance (.355 W/m^2 -°C)
ΔT_2	=	average temperature difference between inside wall surface and in the earth next to the insulation (6.7°C)
A_2	=	114 m^2

B.2.3 Floor

$$U_3\ \Delta T_3\ A_3 \times HR = 263\ kWh \tag{16}$$

where

$U_3 \times \Delta T_3 = Q_3$	=	average heat flow through the floor to the earth (.95 W/m^2) in March
A_3	=	372 m^2

B.2.4 East and West Walls

$$U_4\ \Delta T_4\ A_4 \times HR = 150\ kWh \tag{17}$$

where

U_4	=	design thermal transmittance (.43 W/m^2 -°C)
ΔT_4	=	ambient air temperature - inside surface temperature (10.2°C)
A_4	=	46 m^2

B.2.5 South Wall

$$U_5\ \Delta T_5\ A_5 \times HR = 75\ kWh \tag{18}$$

where

U_5	=	thermal transmittance (.4 W/m^2 -°C)
ΔT_5	=	ambient air temperature - inside surface temperature (11.4°C)
A_T	=	wall area (22 m^2)

B.2.6 Window

$$U_6 \, \Delta T_6 \, A_6 \times HR = 1045 \text{ kWh} \tag{19}$$

where

U_6 = $(2.03 \text{ W/m}^2 \text{-°C})$
Δt_6 = 11.8°C
A_6 = 59.5 m^2

B.2.7 Ventilation and Infiltration

$$\Delta T \times H_c \times V_c \, (.7HR_O + .5HR_F) = 1857 \text{ kWh} \tag{20}$$

Δt = inside/outside temperature difference (11.3°C)
H_c = specific heat x density $(.343 \text{ W/m}^3 \text{-°C})$
V_c = building air volume = 920 m^3

ORNL-DWG 80-7757R2

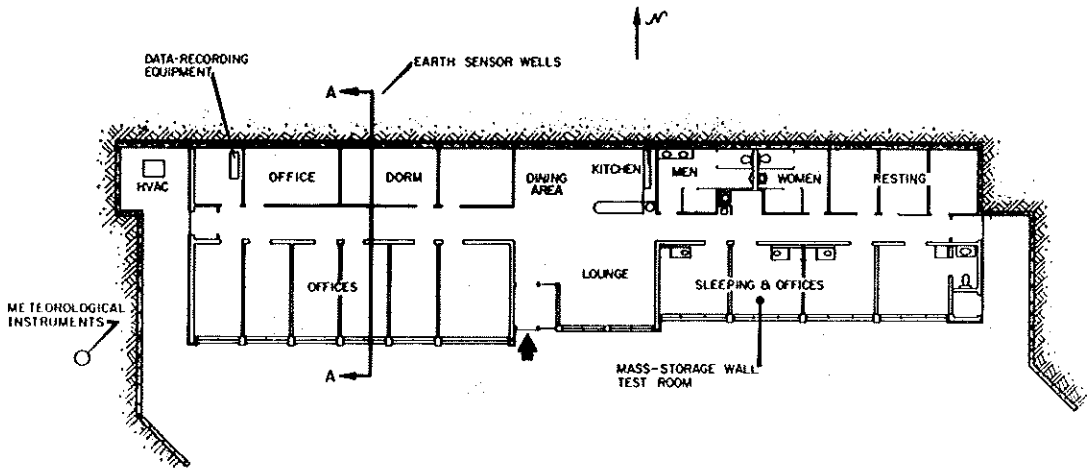

Figure 1. Joint Institute office/dormitory floor plan

ORNL-DWG 82-5469

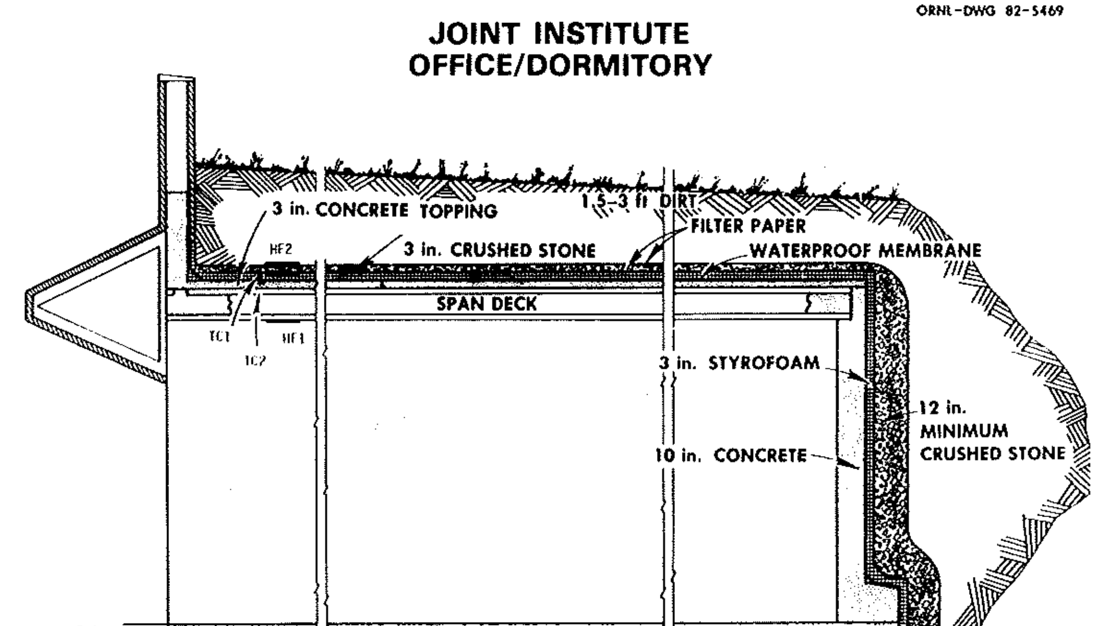

Figure 2. Joint Institute office/dormitory cross section

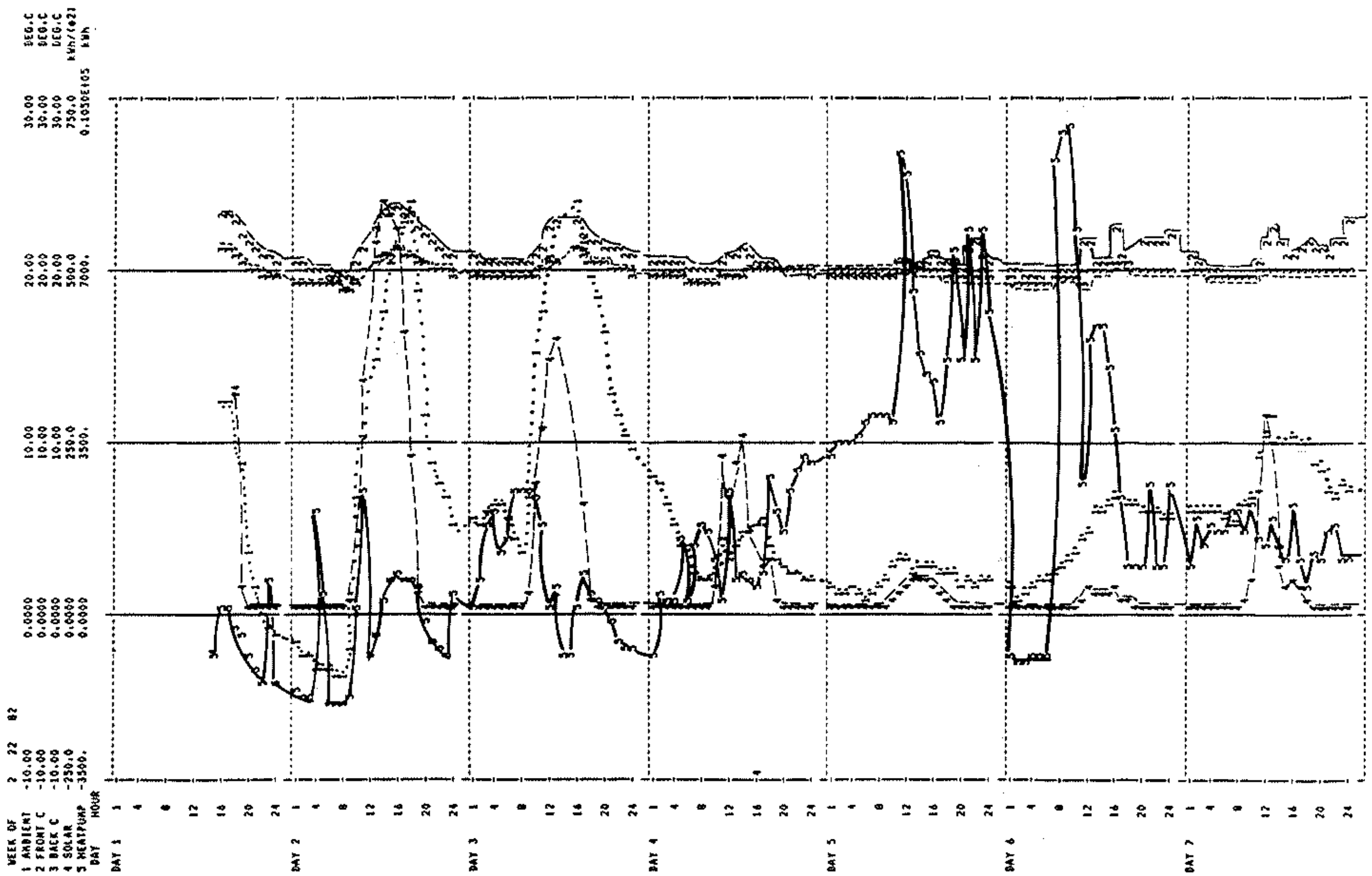

Figure 3. Plot of hourly data from Feb. 22-28, 1982; inside and outside temperature, solar energy and heat pump outlet

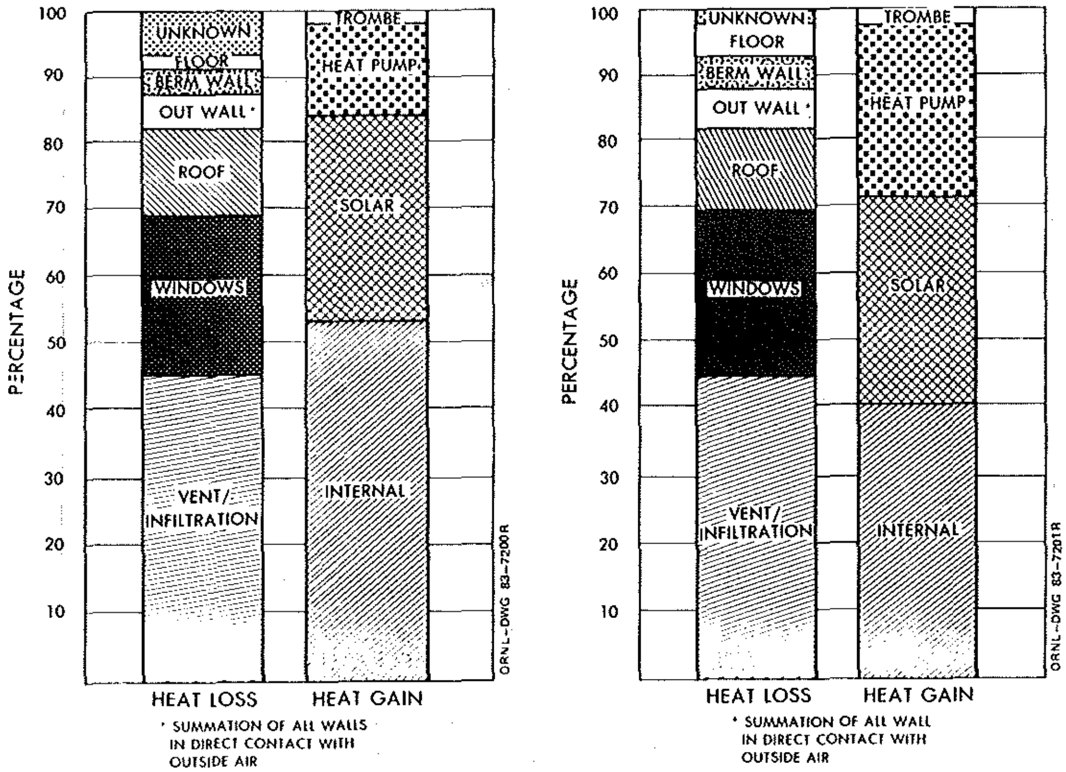

Figure 4. One week and one month energy balance showing fractional heat losses and heat gains of the Joint Institute dormitory

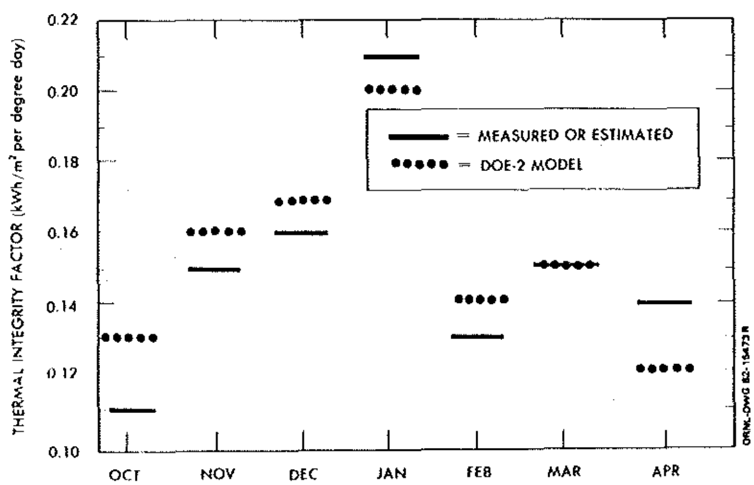

Figure 5. Monthly field data derived thermal integrity factor (TIF) versus DOE-II simulation results

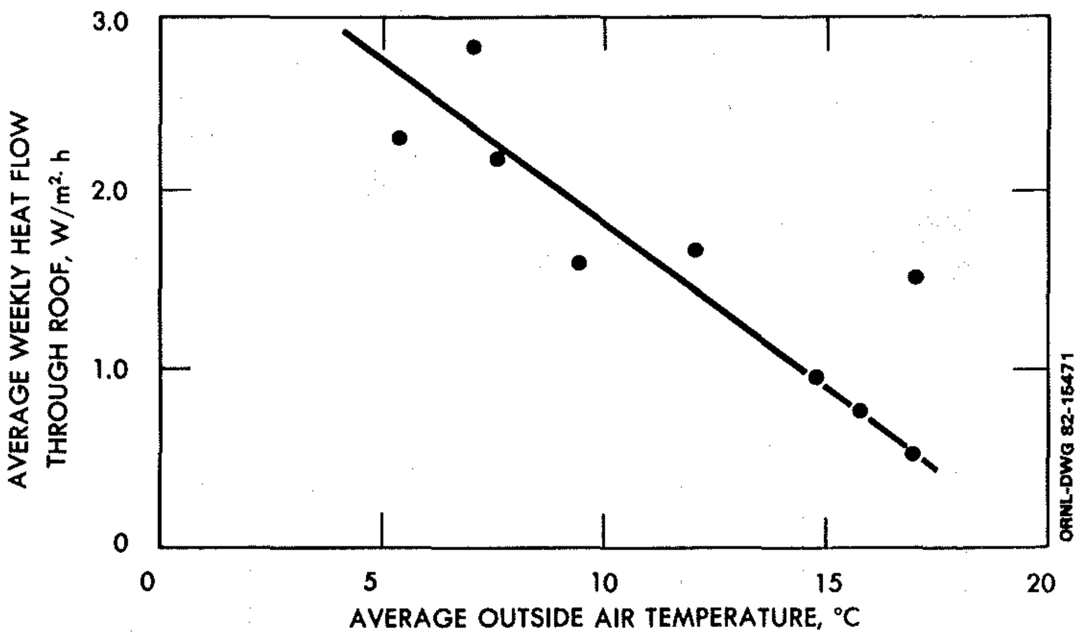

Figure 6. Average weekly heat flow through the roof at different average outside air temperatures compared with steady state heat flow

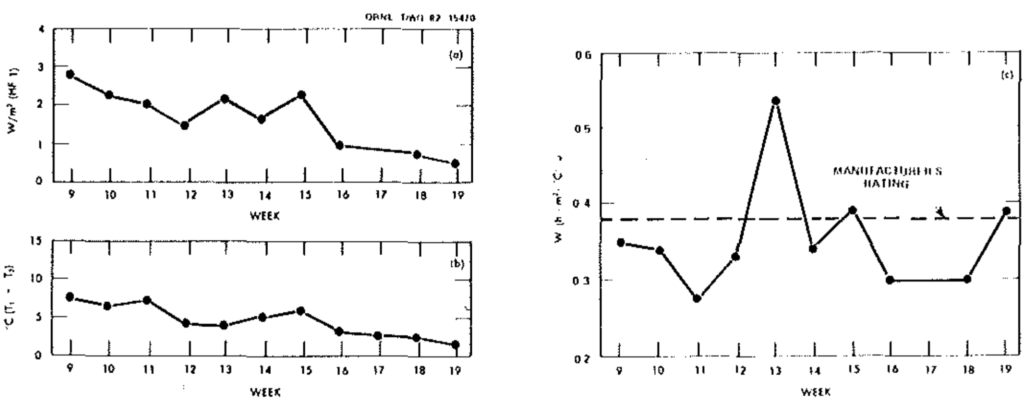

Figure 7. Roof thermal measurements

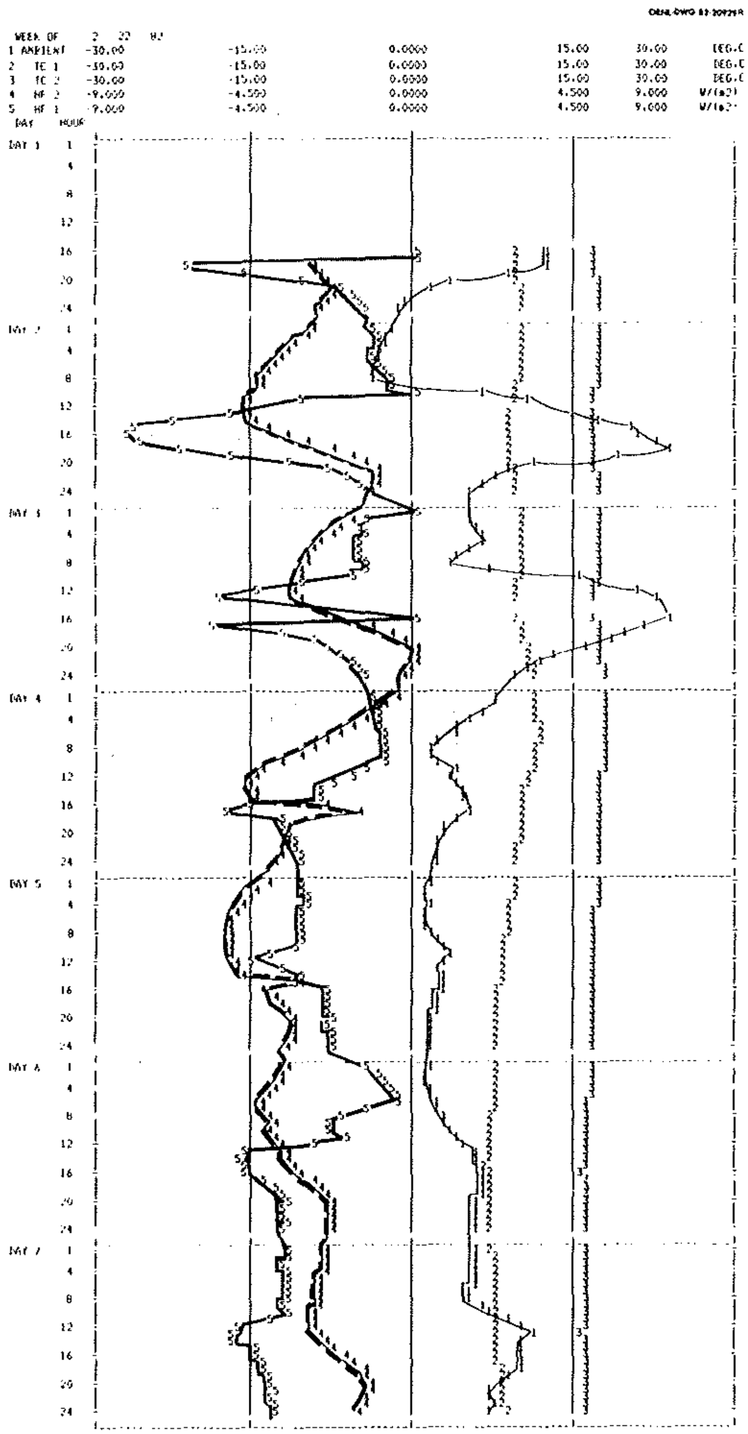

Figure 8. Plot of hourly roof heat flows and temperatures

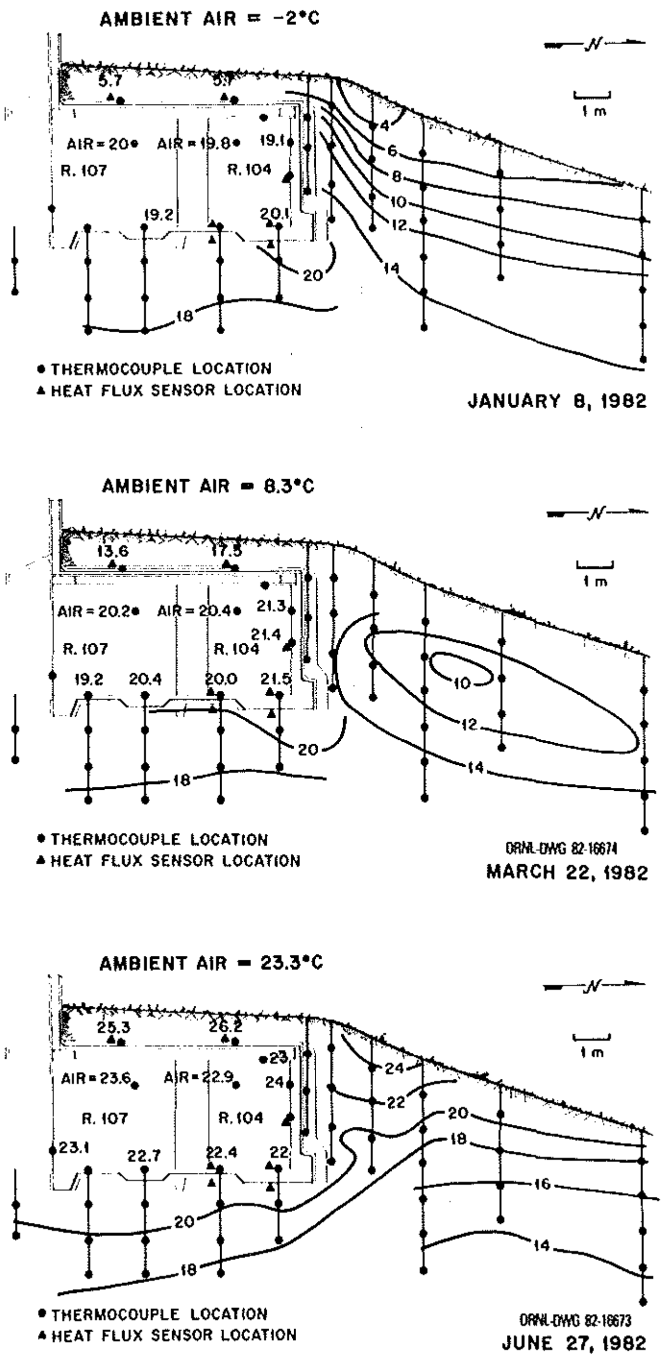

Figure 9. Soil isotherms surrounding the Joint Institute dormitory

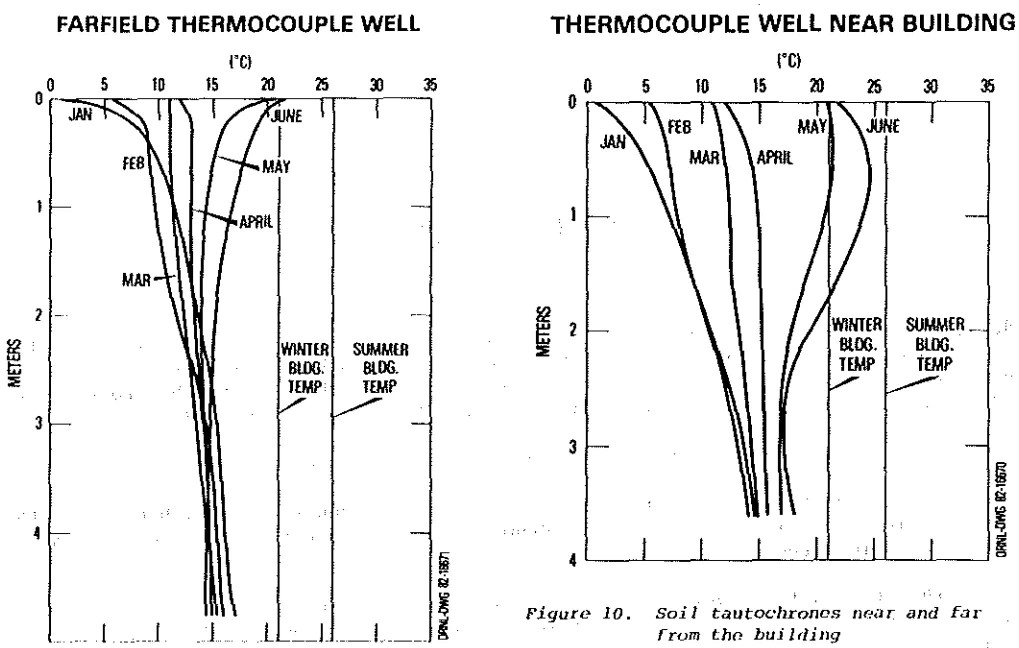

Figure 10. Soil tautochrones near and far from the building

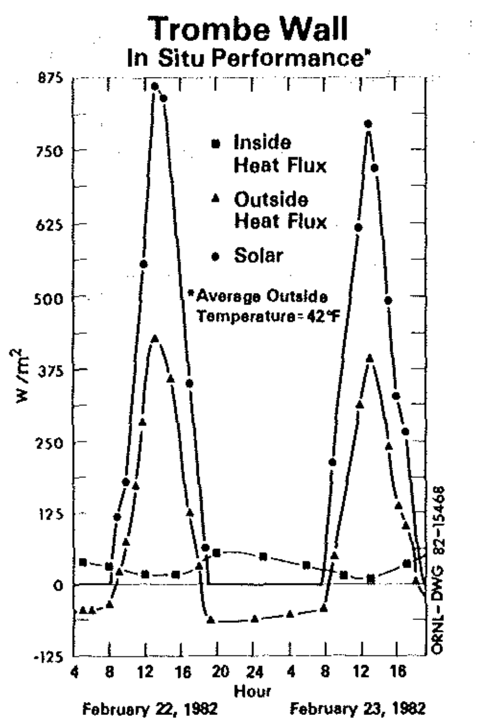

Figure 11. Plot of Trombe wall performance

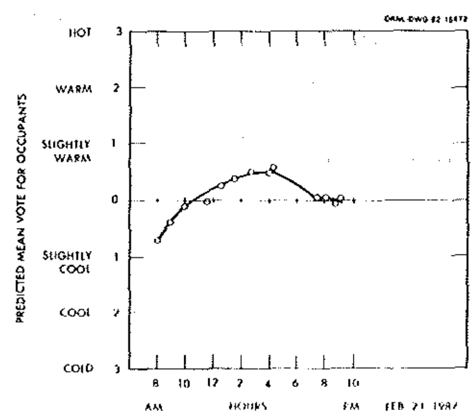

Figure 12. Thermal comfort measurements

Discussion

S.M. Flanders, U.S. Army CRREL, Hanover, NJ: Would you agree that the roof system is the least justifiable component in the structure, from the standpoint of both practicality and economics, to achieve the desired thermal performance at construction and to have a reliable roof later? Also, could you rank the economic justifiability of other building components?

J. Christian: At this time, a life cycle analysis has not been conducted.

J.S. England, Washington State University, Pullman; You have given the energy benefit of the conservation practices used in the building as about 40% saving, overall. What cost penalty on an overall basis was incurred?

Christian: At this time a life cycle analysis has not been conducted on the additional joist cost of the energy-saving features in the building. A final report on this building will include this analysis.

L.J. Daughtry, Mississippi Power Co., Fulfport: What is the Btu/ft^2 of sensible heat gain/loss for the experimental building -- 2.8 Btu/ft as compared to 15 Btu/ft^2 or higher for normal construction. What type of soil, clay or sand? In only on clay, you might want to study sand.

Christian: The TIF measured for the building is 2.8 Btu/ft^2. The soil surrounding the building is clay and the building is an occupied building with limitations on the extent of modification for experimental purposes.

R.H. McEntire, DAE Engineering, Logan, UT: Can you give more detail on soil R-values?

Christian: Based on observation of the earth thermocouple readings over time in the wet clay soil surrounding the building, the conductivity value of the soil averaged around 15 Btu/ft^2·°F for the heating season.