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THERMAL BEHAVIOR OF MIXTURES OF PERLITE AND PHASE CHANGE MATERIALS IN A SIMULATED CLIMATE

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in association with
Phase Change Technologies, Inc.

Prepared by the
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Introduction

The benefits of phase change materials (PCMs) in building envelopes have been recognized for a long time. In the 1970s and 1980s, activity focused on development of suitable materials and configurations to absorb solar energy during periods of peak solar insolation and release it gradually during off-peak periods or during nighttime to the conditioned space or to heat exchange equipment serving it. Materials were developed with properties tailored to building heating and cooling requirements (Lane, 1983). For example, in heating, phase change temperatures could be fixed to occur a few degrees above room temperature. Latent energies of melting and freezing exceeded 100 BTU/lb (233 kJ/kg) so that reasonable weights of materials could serve an entire building without severe changes in the design of structural supports. Architectural design changes were needed, of course, to allow sunlight to strike the phase change materials.

Interest in phase change materials for building envelopes waned with interest in active solar heating and cooling. We have renewed interest in this technology in response to the desire of our CRADA partner to develop a configuration involving phase change materials for passive thermal control during building cooling by conventional means rather than for active thermal storage as part of direct heating or cooling. The phase change materials are used in series with conventional insulation to absorb thermal energy directed toward the conditioned space and release it to the ambient environment during nighttime hours.

The tests described here were performed in the Large Scale Climate Simulator (LSCS) in the Buildings Technology Center (BTC), an Oak Ridge National Laboratory User Facility. The LSCS allows conditions of temperature and humidity to be imposed above horizontal test sections to simulate outdoor conditions ranging from extreme winter to extreme summer climates. Corresponding indoor conditions can be set below the test sections. For this work, the outdoor conditions were varied to simulate diurnal variations as well as constant temperatures. The latter forced the phase change materials to progressively melt or freeze completely so we could see their total potential for thermal control.

Apparatus and Procedures

The primary objective of the tests in the LSCS was to understand the behavior of candidate configurations of foam insulation and phase change materials in perlite well enough to do engineering design of thermal control systems for whole buildings. We sought prediction of heat fluxes into and out of the candidate configurations with the computer program HEATING (Childs 1993) to compare to our measurements of these heat fluxes. Boundary conditions were the temperatures imposed in the tests.

Our past experience with phase change materials in a vertical wall of an outdoor test facility in the BTC taught us that carefully controlled and well documented experiments are needed to model the heat transfer phenomena during phase change. Accordingly, two test cells were constructed to contain different mixtures of phase change materials and perlite. Perlite is a granular conventional insulation material that provided a convenient means to control and disperse the amount of PCM in the test cells. The PCM was a hydrated calcium chloride and was very hygroscopic so vapor-tight sealing of the test cells was imperative.

One test cell contained a ratio of 2:1 PCM to perlite on a weight basis; the other had a 6:1 ratio. The 2:1 mixture was easy to handle. It formed some soft lumps, but they were easily crushed by hand. The 6:1 mixture, on the other hand, was difficult to handle. It formed hard lumps that had to be pulverized with a hammer to get a pourable mixture for its test cell.

Figure 1 shows the construction details of the test cells. The construction material was methylmethacrylate because it could be formed into a transparent and water impermeable box. The sides and bottoms were joined to each other by applying solvent along the seams. Pieces of methylmethacrylate also formed the tops of the cells. They were cut to loosely fit inside the sides and were sealed and held against the top of the PCM/perlite mixture in each box by wide plastic tape stretched tightly.

The precise pattern of holes enlarged in Fig. 1 was drilled into the sides before joining and was used to locate wires which held the thermocouples. Three thermocouples were attached to each support wire, at the center and 1 in. (2.54 cm) either side of center. The support wires were 0.2 in.

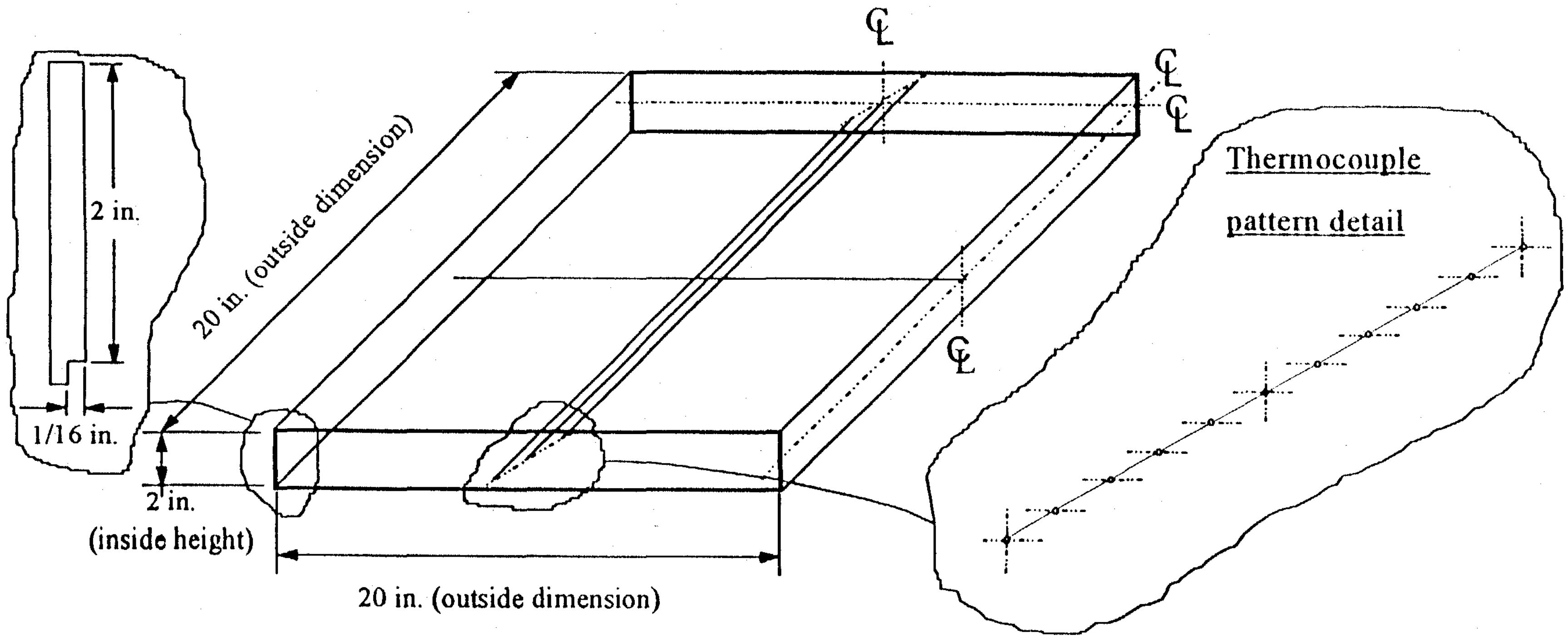

Fig. 1. Construction details of the test cells for PCM/perlite.

(0.51 cm) apart vertically. The 45° slope of the pattern kept thermocouples at least 0.4 in. (1.02 cm) apart physically. In each box, three more thermocouples were attached to the center and 1 in. (2.54 cm) either side of it on the insides of the bottom and the top, respectively. Averages of the temperatures at each level gave the temperature profile through the PCM/perlite mixtures. Two thermocouples were also placed along the center of the box 0.5 in. (1.27 cm) and 1 in. (2.54 cm), respectively, in from each of the four sides to see how much the temperature changed from the centerline to the edge in each direction.

Squares for thin 2 in.×2 in. (5.08 cm×5.08 cm) heat-flux transducers (HFTs) were routed out of the centers of the outsides of the bottom and top of each box. Only a paper-thin layer of methyl-methacrylate was left between the HFTs and the PCM/perlite mixtures. Thus the HFTs measured the heat fluxes virtually on the surfaces of the mixtures.

The test cells were each placed on two squares of nominal 0.5-in. (1.3-cm) thick pieces of extruded polystyrene (XPS) and covered by a single piece of the same thickness. This resulted in a 2:1 ratio of thermal resistance below compared to above the cells. A 2:1 ratio was suggested by our CRADA partner from their insight to thermal control. The 2:1 ratio was to allow heat to escape from the top of the cells during the nighttimes of diurnal cycles while preventing much from flowing into the space under the cells.

The cells with XPS insulation above and below them fit between the 24 in. (0.61 m) OC ceiling joists of our manufactured home test section for the LSCS. Slots were cut in the two layers of fiberglass batt insulation in the space between the joists either side of the center space. The instrumentation in the center space was left in place. It consisted of two HFTs on the bottom of the fiberglass batts and two pairs of thermocouples next to the HFTs and above them on top of the fiberglass batts. With it we could follow the thermal behavior of the fiberglass batts for comparison purposes while the test cells were being put through the series of tests to characterize the PCM/perlite mixtures and understand the behavior of the candidate configurations for thermal control.

Figure 2 is a photograph of the attic space of the manufactured home test section before the metal roof was rolled down and fastened to the trusses. The test cells with the XPS layers below and

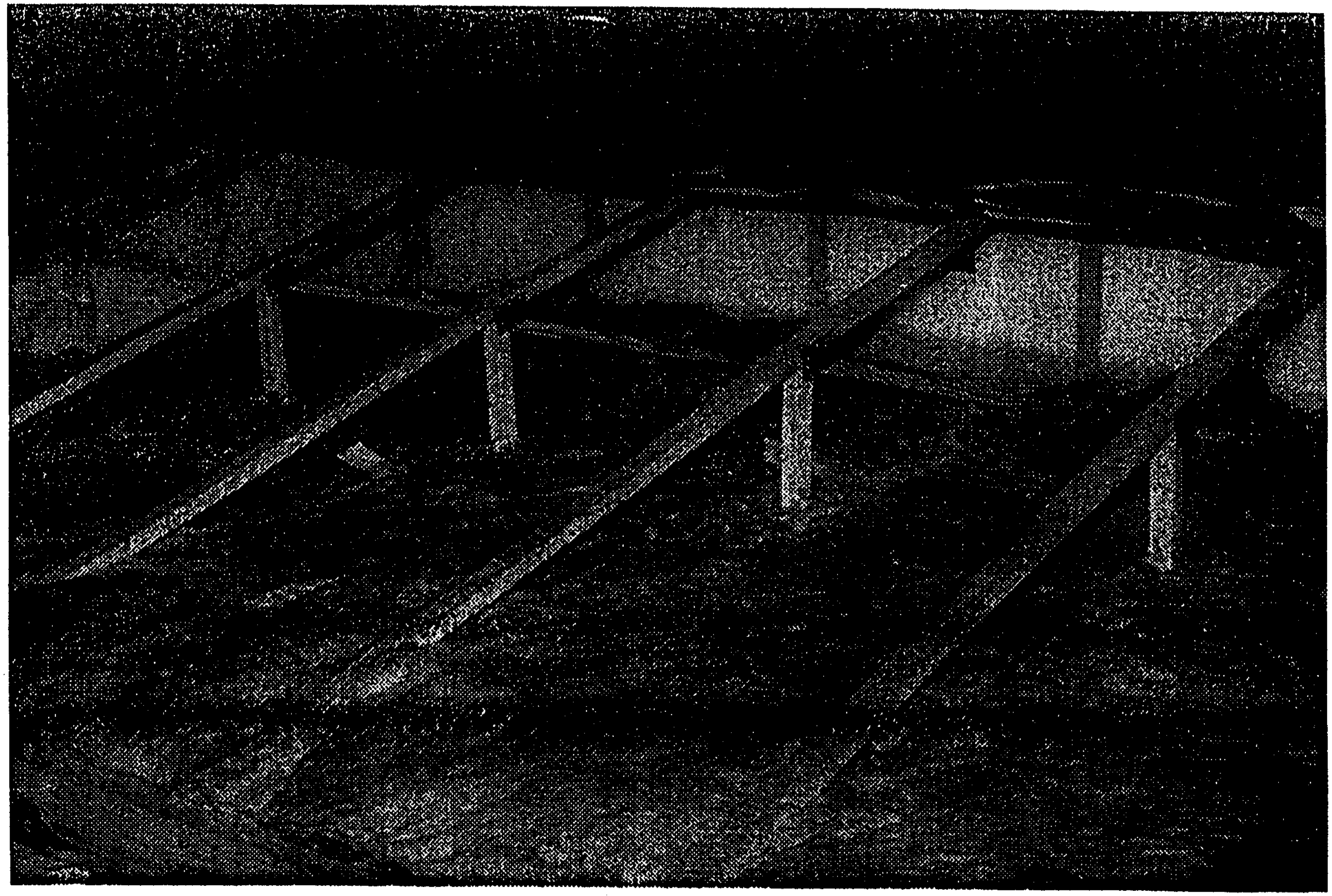

Fig. 2. Attic space of manufactured home test section with test cells in place between XPS insulation.

above them are barely visible in the photograph except for the thermocouple wires that emerge from the test cells. The configurations are physically as thick as the fiberglass batt insulation and turned out to have about the same steady-state R-value. The test cells behave very differently from conventional fiberglass batts, however, while phase change is occurring in them. Nonetheless, the energy balance for the whole metering chamber under the test cells, with its 8 ft×8 ft (2.44 m× 2.44 m) opening, was done for base case runs before the test cells were inserted and for all tests afterwards. These balances allowed us to see the total effect of the relatively small 20 in. (50.8 cm) square test cells rather than just the picture from top to bottom down the center of each cell.

Melt and Freeze Results

After the test cells were installed in the manufactured home test section and their instrumentation was connected to the LSCS data acquisition system, several days were spent with all chambers at 75°F (24°C) to achieve complete freezing of all PCM in the test cells. The upper (climate) chamber temperature was then rapidly brought to 125°F (52°C) and held constant. The lower (metering) chamber temperature was held constant at 75°F (24°C) throughout all tests. Figure 3 shows temperatures and heat fluxes for the test cell containing the 2:1 PCM/perlite mixture over the next 70 hours as the PCM in it proceeded from completely frozen to completely melted. The climate chamber temperature history is included proving that the step change from 75°F (24°C) to 125°F (52°C) was rapid and smooth. Figure 4 is a similar plot over a longer time period to show the same data for the 6:1 mixture.

Positive heat fluxes mean that heat is flowing into the top or out the bottom of each cell. The HFTs were deliberately oriented for this effect. The top and bottom heat fluxes for the 2:1 mixture are equal at by 70 h into the test and the phase change is essentially complete by 42 h when the bottom heat flux begins to rise rapidly. The top and bottom heat fluxes are not yet equal for the 6:1 mixture by 135 h into the test. A check 30 h later showed about the same difference. There must still be a small amount of PCM undergoing phase change in the 6:1 mixture for a long time after the bulk of the material has melted by 90 h and the bottom heat flux begins to rise rapidly. In both cells, the heat flux out the bottom is small and essentially constant while phase change is occurring because

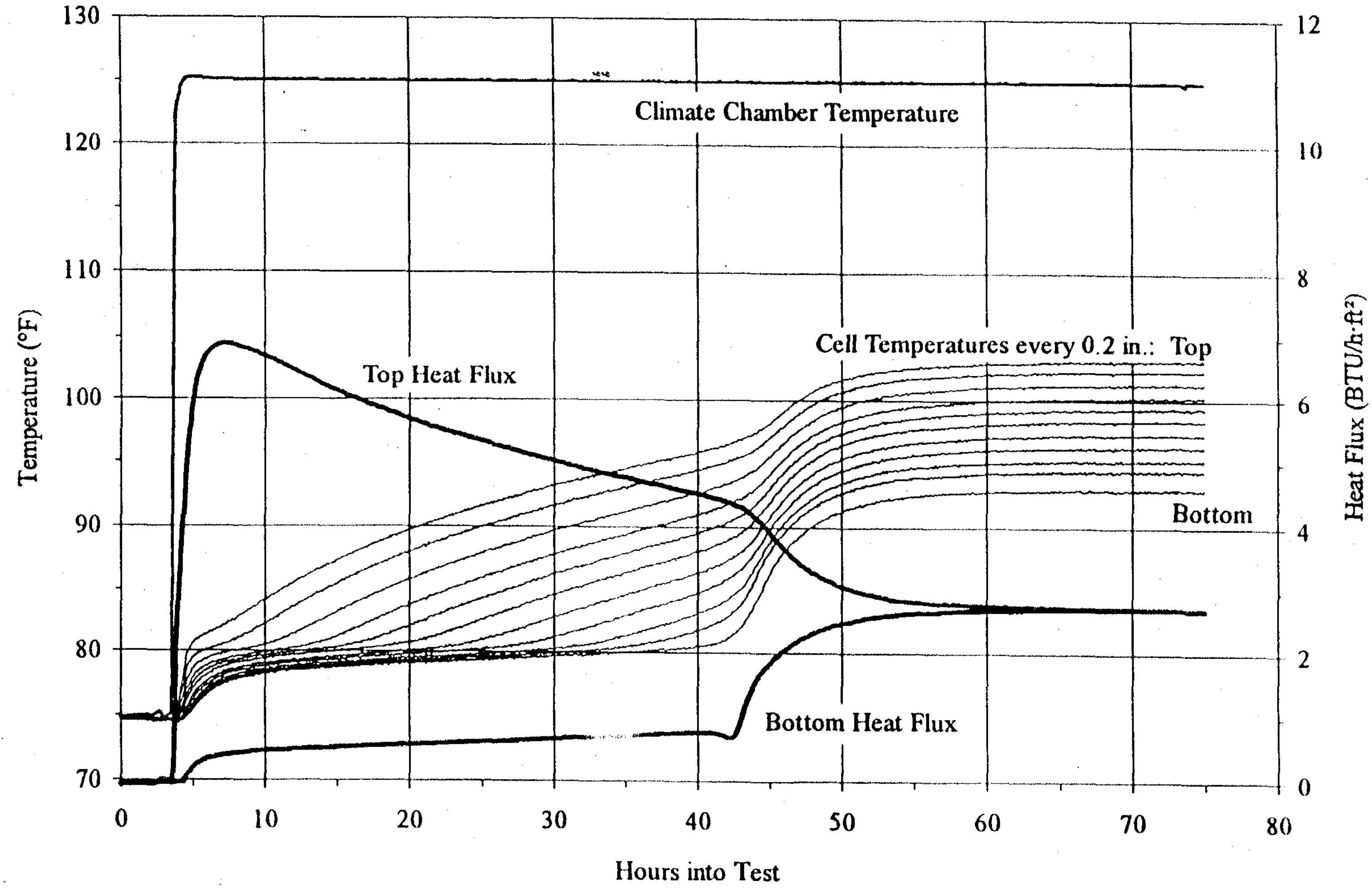

Fig. 3. Results for melting of the 2:1 mixture of PCM/perlite.

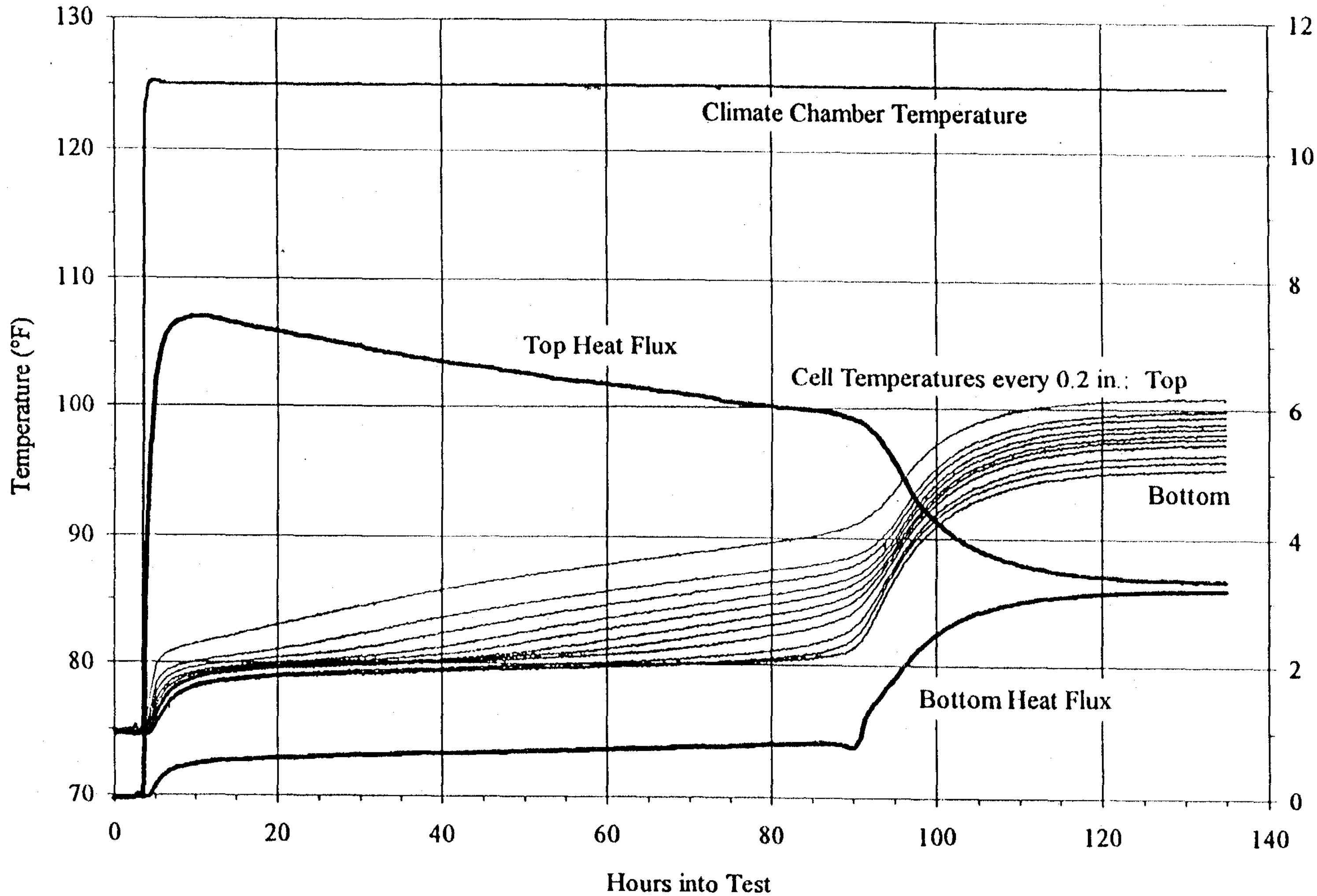

Fig. 4. Results for melting of the 6:1 mixture of PCM/perlite.

the unmelted material is shielding the bottom heat flux transducer, presenting a very small difference in temperatures between it and the chamber below at 75°F (24°C).

The top heat flux and the temperature profiles in both cells show the complicated nature of the phase change for this PCM. As the phase change front proceeds into the material, the upper layers melt and their temperatures rise. Thus, the top heat flux decreases because of the smaller temperature difference between the chamber above at 125°F (52°C) and the upper PCM layers. The phase change does not occur isothermally, however. Very important information obtained from the temperature profiles is that melting occurs from about 80 to 82°F (27 to 28°C) for this PCM. The temperature at each level rises rapidly before phase change starts, especially for the upper layers. The smallest rates of increase of temperature occur during phase change in each layer, but they are not zero. When phase change in a layer is finished, temperatures rise a bit more rapidly. Only when all phase change is complete in the whole cell do the temperatures again rise rapidly, especially in the lower layers, to achieve the nearly uniform gradient shown at steady state when there is no more transient energy storage taking place due to phase change. Any slight discrepancy from equally spaced temperature profiles at steady state is attributed to variations from even spacing of thermocouples from top to bottom at the center of the support wires.

To illustrate the concept of thermal control, which is the application sought by the present work, consider Fig. 5. Shown are heat fluxes through the ceiling under the center of each cell as well as under the fiberglass batts in the joist space between the spaces housing the test cells. When steady heat fluxes are obtained for each system, an R-value can be assigned to the system by dividing the temperature difference across it by the heat flux through it. The results are shown in the figure and the steady R-values are 13.6 $ft^2 \cdot h \cdot °F/BTU$ (2.4 $m^2 \cdot K/W$) for the fiberglass batt system, 13.1 $ft^2 \cdot h \cdot °F/BTU$ (2.3 $m^2 \cdot K/W$) for the 2:1 PCM/perlite system and 11.1 $ft^2 \cdot h \cdot °F/BTU$ (2.0 $m^2 \cdot K/W$) for the 6:1 PCM/perlite system. Thermal protection, as measured by these R-values, is not much different from system to system, but is largest for the fiberglass batt system. Yet, while the PCMs are changing phase, the 6:1 system and, for a shorter time, the 2:1 system control the heat flow through the ceiling much better than the fiberglass batt system.

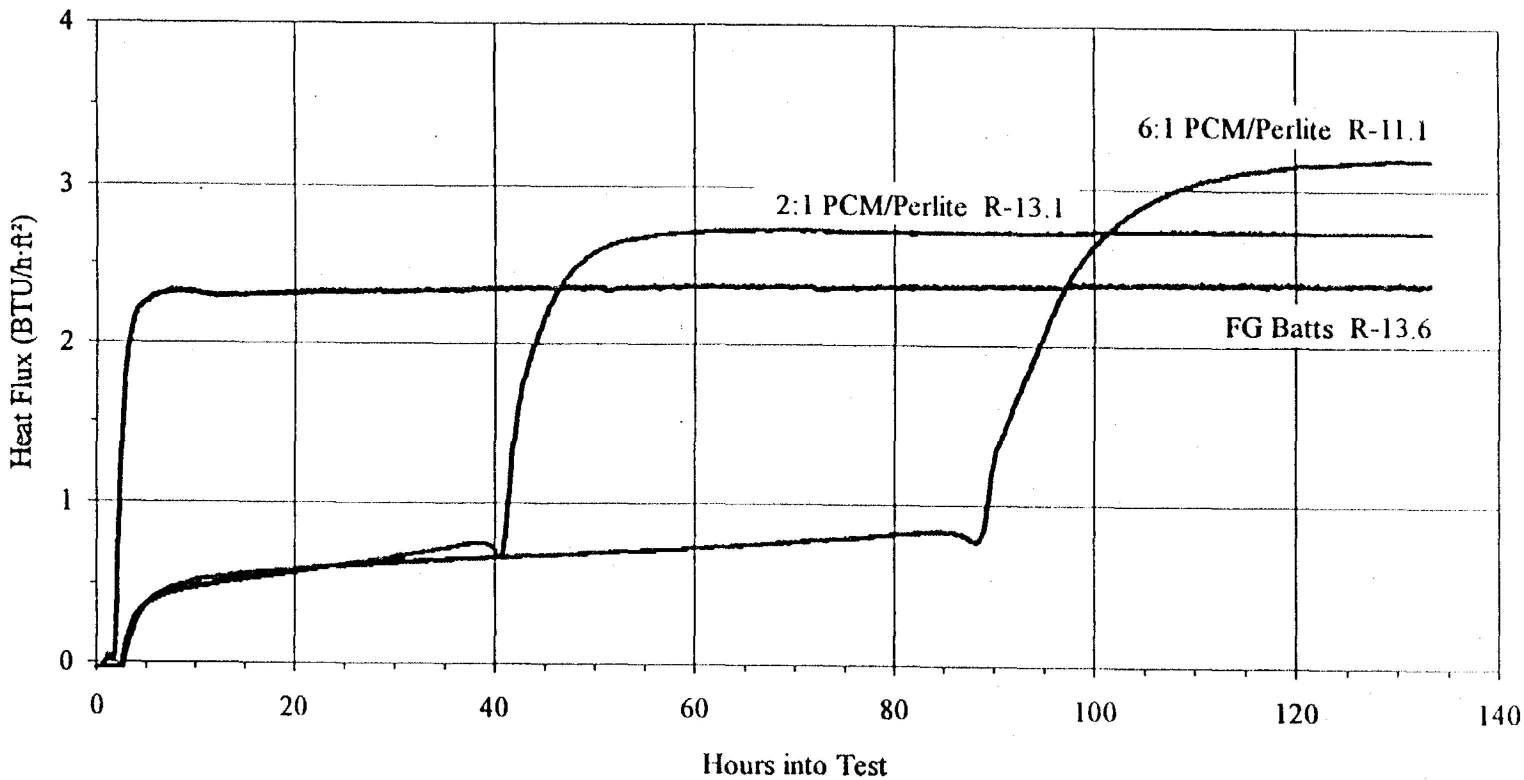

Fig. 5. Bottom heat fluxes for the PCM/perlite systems and the fiberglass batt system with steady-state R-values for each.

When the PCM in both cells had melted and the steady-state temperature profiles had been established for the 125°F to 75°F (52°C to 24°C) difference between the climate and metering chamber temperatures, freezing was initiated. Climate chamber temperature was brought to a steady 50°F (10°F) as rapidly as possible. Figures 6 and 7 show temperatures and heat fluxes for the ensuing freeze, like Figs. 3 and 4 did for the melt. The climate chamber temperature does not undergo as perfect a step change for the freeze. Cooling is required to effect the change. We use direct expansion coils in the climate chamber and have a large compressor for rapid cooling and a small compressor to hold steady state against small loads. The large compressor overcooled the climate chamber slightly and there were a few hours of small climate chamber temperature fluctuations near 20 h into the test when the switch was made from the large to the small compressor.

The overcooling and fluctuations during switchover are seen in the test cell temperatures and heat fluxes, especially near the tops. There is also evidence of supersaturation in the heat fluxes and temperatures. The top heat flux goes through a maximum and the bottom a minimum not related to the fluctuations in the climate chamber temperature. At the same time, the PCM seems to be subcooled below its equilibrium phase change temperature for a few hours just after 10 h into the test but returns to the equilibrium curves by 15 h..

A very important piece of information from the freezing curves is the temperature at which freezing occurs. It is significantly below the melt range; in other words, this PCM exhibits hysteresis. For the 2:1 mixture, freezing occurs below 75°F (24°C) and, for the 6:1 mixture, below 78°F (26°C). Since the temperature difference between the climate chamber and the PCM during freezing is smaller that it was for melting, freezing takes longer: over 70 h for the 2:1 mixture vs. around 42 h to melt. For the 6:1 mixture, freezing took too long to wait for it to be completed although by 95 h into the test, the heat fluxes indicate that most of the freezing has occurred..

Diurnal Cycle Results

A truer test of the potential for thermal control with the candidate configurations is shown by their response to diurnal cycles. A diurnal cycle was programmed into the controller for the climate chamber temperature. Maximum daytime temperature was chosen as 150°F (66°F) at each

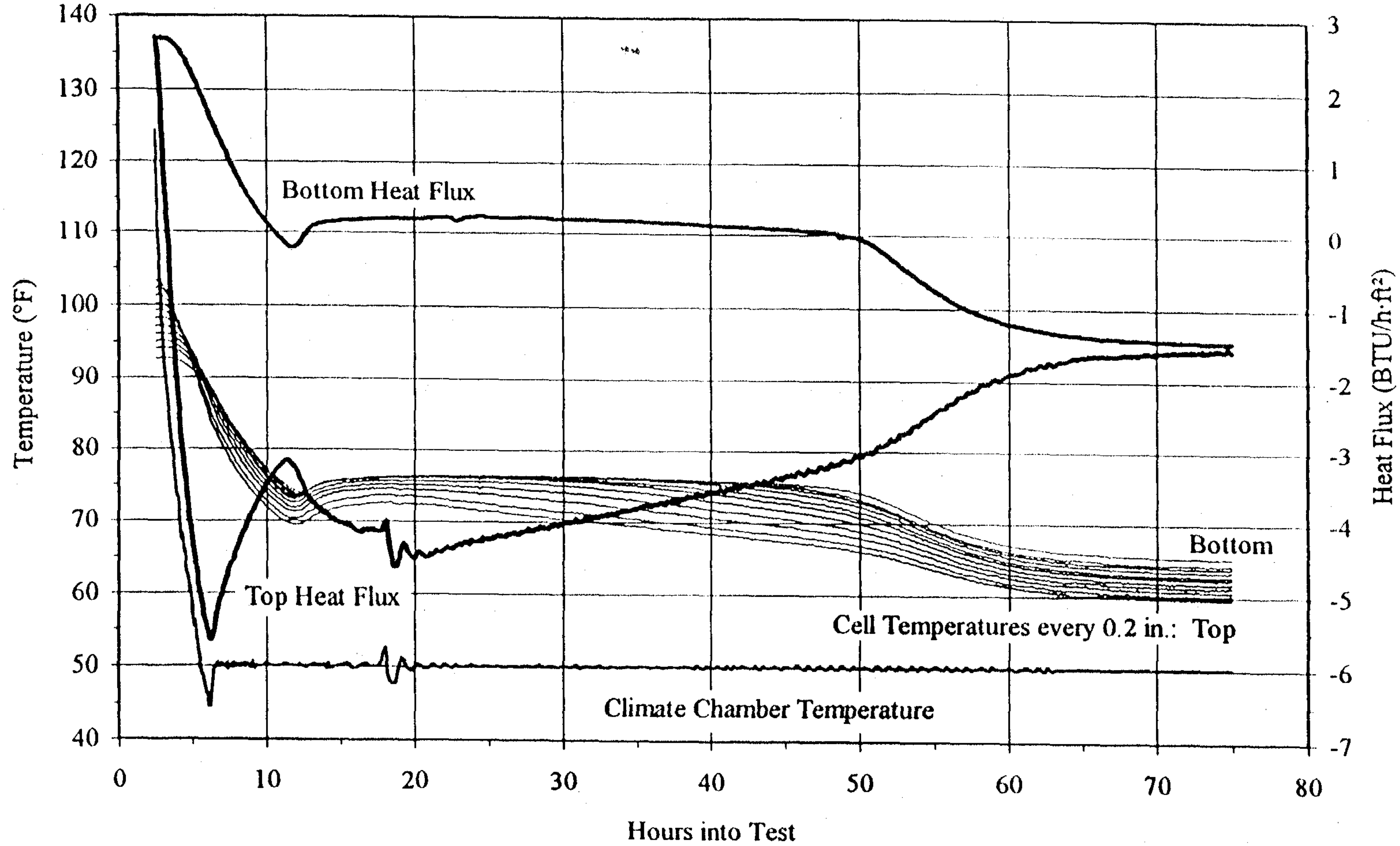

Fig. 6. Results for freezing of the 2:1 mixture of PCM/perlite.

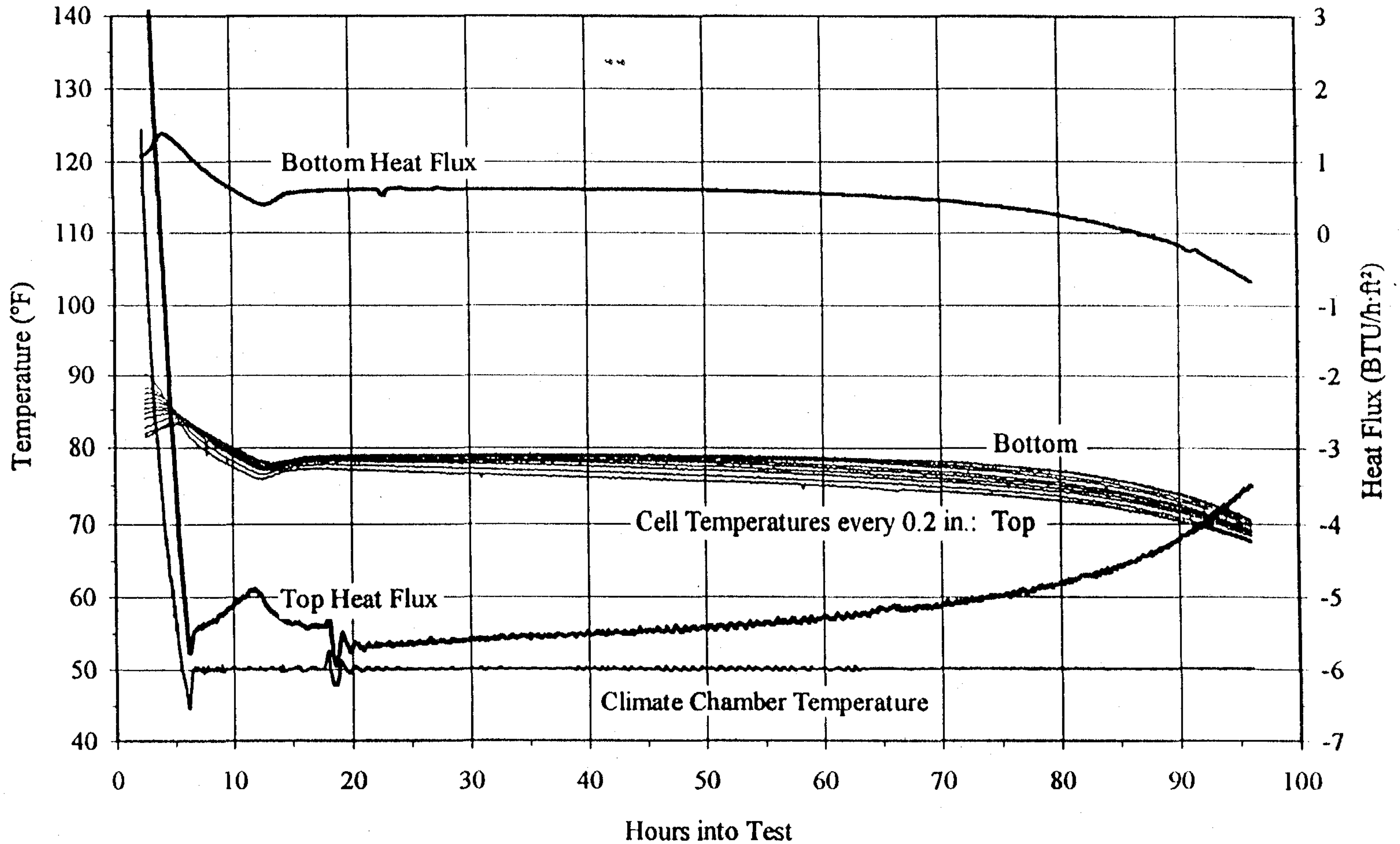

Fig. 7. Results for freezing of the 6:1 mixture of PCM/perlite.

noon and minimum nighttime temperature as 50°F (10°F) at each 4 a.m, respectively, with the first noon at 0 test hours. This simulates the extremes of a desert climate. Variation between minimum and maximum temperatures was nearly sinusoidal but with less variation at night in agreement with our observations of diurnal temperature variations above our outdoor test facilities.

Figures 8 and 9 show how the 2:1 and 6:1 mixtures in the candidate configurations (one layer of XPS underneath and two layers above each test cell) responded to the cycles. The cells settle to periodic stationary behavior by the second cycle shown, starting at 24 h into the test. For both cells, the top heat flux is in phase with the imposed temperature in the climate chamber. This is reasonable because only the attic space and a single 0.5-in. (1.3-cm) thick layer of XPS intervene and neither provides significant thermal mass.

The 2:1 configuration undergoes considerable phase change during each cycle and shows well the ability for thermal control. The bottom layer gets hotter than 85°F (29°F) during daytime and cooler than 75°F (24°C) at night so PCM in the cell can melt and freeze. The peak bottom heat flux is over 75% less than the peak top heat flux and is delayed nearly 6 hours. Hardly any heat flows into the space under the cell at night whereas the top heat flux goes negative, allowing energy stored in phase change to flow to the upper chamber as desired.

The 6:1 configuration seems to have its phase change confined to material in the top of the cell. The temperatures for the lower layers stay around 80°F (27°C) day and night. The top temperature (from a thermocouple with no PCM above it) separates from the temperature 0.2 in. (0.51 cm) down, indicating that phase change is happening in the top layer. The thermal control is nearly perfect: the bottom heat flux has been levelled out at less than 10% of the peak heat flux and presents a small and constant heat load on the space below the PCM/perlite mixture (here the metering chamber) despite the severe conditions imposed in the climate chamber. What little peak there is in the bottom flux occurs 10 h later than the peak in the top flux. The 6:1 mixture's top heat flux is slightly larger during the day than the 2:1 mixture's because the top temperatures of the 6:1 mixture are cooler. Conversely, its top heat flux becomes slightly more negative at night than the 2:1 mixture's because the 6:1 mixture's top temperatures are warmer.

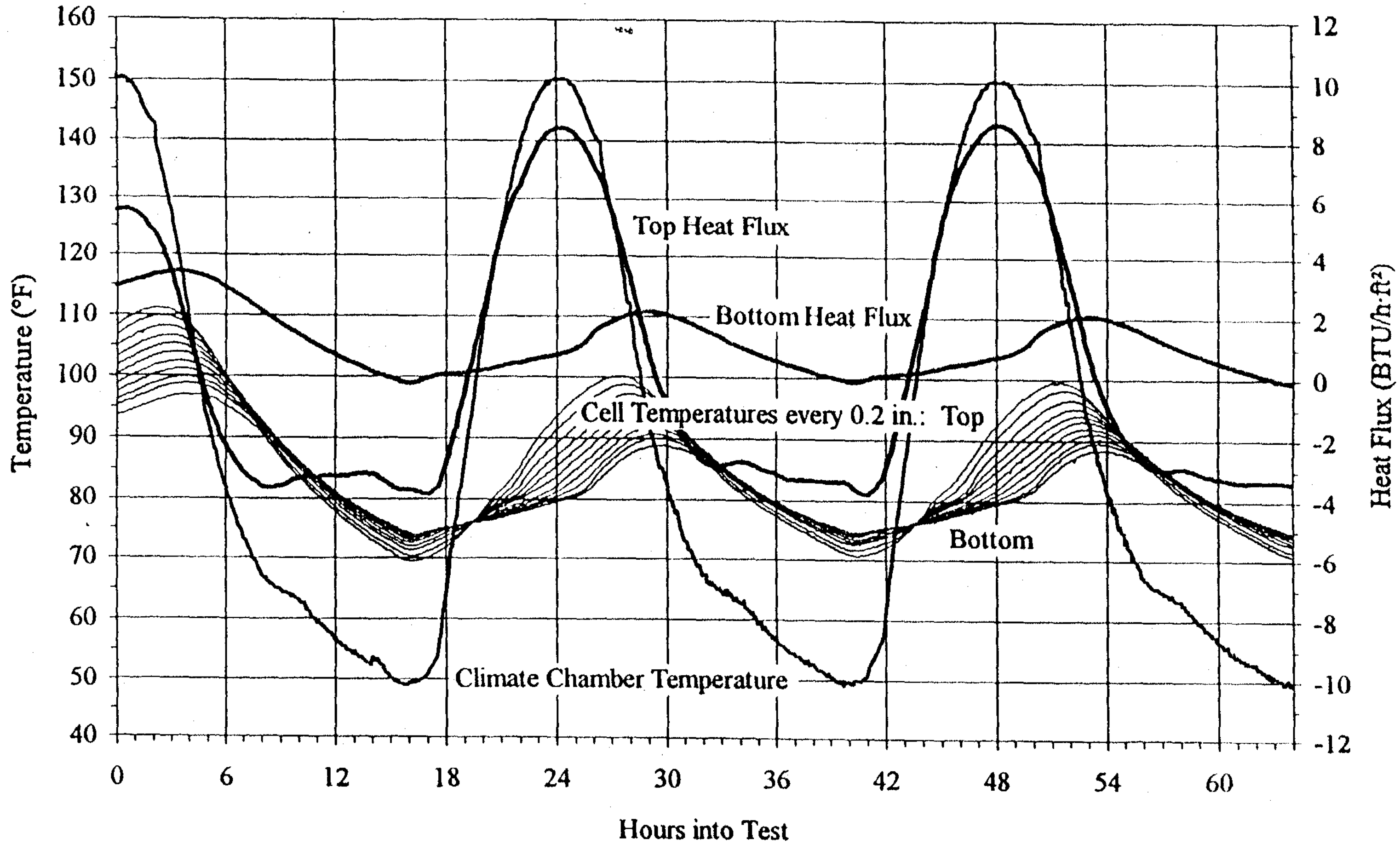

Fig. 8. Results for diurnal cycles with the 2:1 mixture of PCM/perlite.

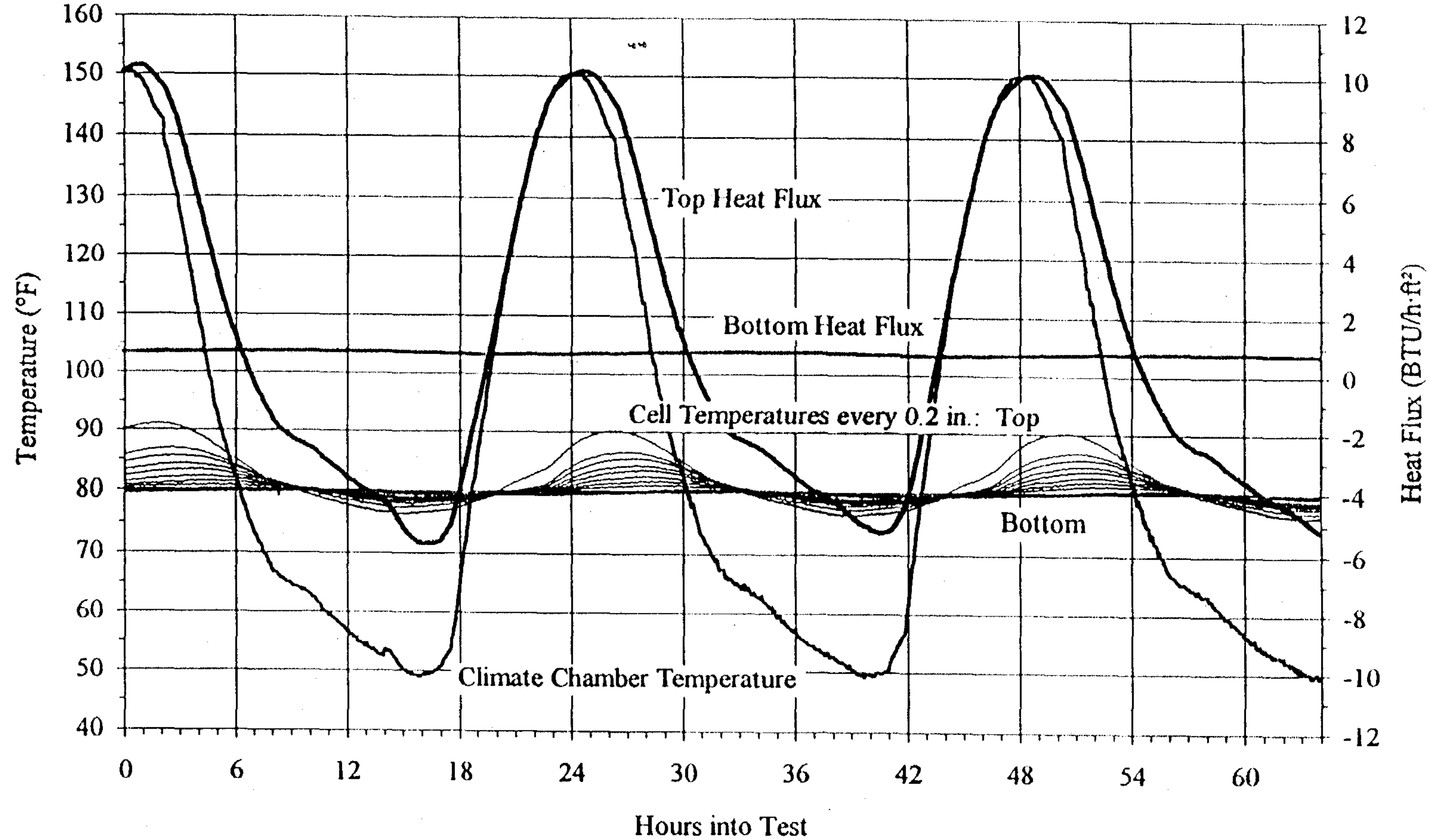

Fig. 9. Results for diurnal cycles with the 6:1 mixture of PCM/perlite.

To compare the thermal control capabilities of the two candidate configurations of PCM/perlite with the performance of fiberglass batts, only the bottom heat fluxes are of interest. They are shown in Fig. 10 along with the diurnal climate chamber temperature cycles. The latter are useful to establish a reference for phase shifts. Notice that the fiberglass batts, despite having the highest steady-state R-value of the three systems, hardly shift the peak heat flux into the metering chamber at all relative to the imposed temperatures. Compared to the nearly 6 h delay for the 2:1 PCM/perlite system and, as much as there is any peak left for the 6:1 system, its 10 h delay, the fiberglass batt system offers no peak load shift.

A quantitative measure of thermal control is obtained from the total heat flows into the metering chamber. On a daily basis, the fiberglass batt system allows 25.8 BTU/ft² (263 kJ/m²) of heat to flow downward, which is removed by the metering chamber cooling system in order to maintain the constant temperature of 75°F (24°C) there. To maintain this constant temperature at night, 8.3 BTU/ft² (85 kJ/m²) needs to be supplied. These daily heat flows per unit area are obtained by integrating the area above the highlighted 0 heat flux level for the heat flow into the metering chamber. The area below the 0 level is the heat flow out of the metering chamber.

For the 2:1 PCM/perlite system, heat flow downward is only 20.2 BTU/ft² (206 kJ/m²), 22% less than with the fiberglass batt system. No significant amount of heat flows out of the conditioned space at night. For the 6:1 PCM/perlite system, the total heat flow is 17.6 BTU/ft² (180 kJ/m²), 32% less than for the fiberglass; as noted above, it is virtually constant with time.

Predictions with HEATING

From the results with diurnal cycles, the 2:1 PCM/perlite mixture seems to contain enough phase change material to thermally protect the space below the test cells, but not so much that the actual amount of PCM in the system is underutilized, like happens for the 6:1 mixture. In order to do engineering design to specify the configuration of PCM/perlite and conventional insulation that achieves optimum thermal control, a model is needed to do parametric variations. The focus in this section is on results obtained for the 2:1 PCM/perlite system with HEATING, a finite difference three-dimensional transient thermal conduction program. The purpose of this modeling was to

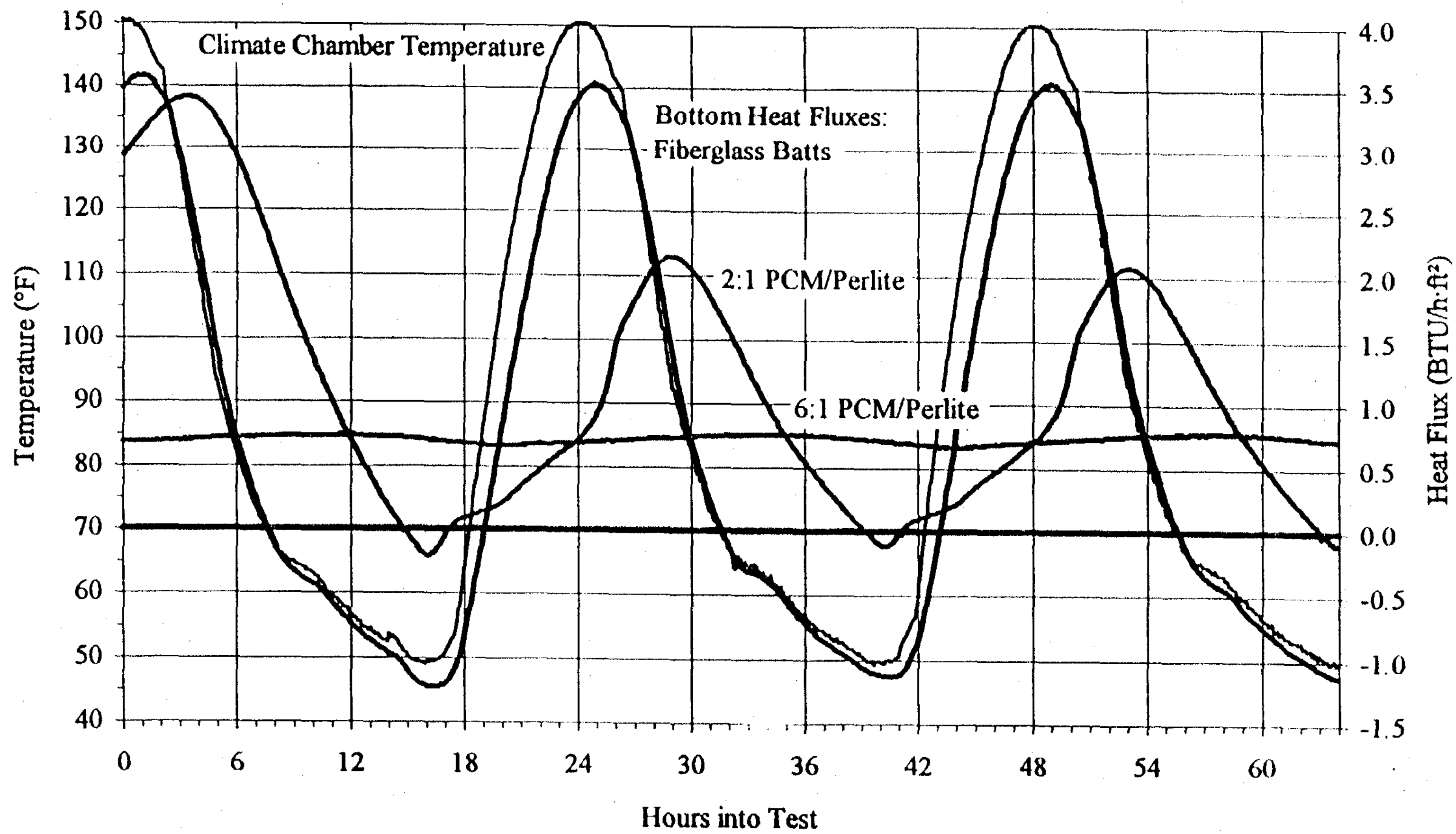

Fig. 10. Comparison of bottom heat fluxes during diurnal cycles for fiberglass batt and 2:1 and 6:1 PCM/perlite systems.

reproduce the temperatures in the 2:1 test cell and its top and bottom heat fluxes, thereby verifying our understanding of the heat transfer and phase change phenomena occurring in it.

This verification is the first step in the more ambitious modeling effort needed to get a design tool. To optimize the amount of PCM in a thermal control system and the amount of conventional insulation and its placement relative to the PCM, a whole building model is required. Typical whole building modeling programs, such as DOE-2 (LBL 1981, LBL 1993), use one-hour time steps for the response of the building to applied conditions. To interface with such programs, subroutines to handle the effects of phase change would need to be written. Our results with diurnal cycles show that significant effects are occurring over one-minute rather than one-hour time steps. The size of the finite time and spatial steps used by HEATING can be adjusted to suit the application. Whole building modeling with phase change algorithms is beyond the scope of the present study.

For the present, the objective is to model the specific configuration of the 2:1 PCM/perlite system under the conditions that were imposed in its melting, freezing and diurnal cycle experiments. HEATING was provided with a description of the geometry, reduced to a one-dimensional series of material layers: a 0.5-in. (1.3-cm) thick layer of XPS; a 0.125-in. (0.3175-cm) thick layer of methylmethacrylate; the 2-in. (5.08-cm) deep PCM/perlite; another 0.125-in. (0.3175-cm) thick layer of methylmethacrylate; two 0.5-in. (1.3-cm) thick layers of XPS; and a 0.375-in. (0.9525-cm) thick gypsum board. Temperatures measured on the top of the top layer of XPS and on the bottom surface of the gypsum board were the boundary conditions for the model.

Thermophysical properties were assumed to be constant with temperature. Density was 16.65 lb/ft^3 (266.7 kg/m^3) by weighing a known volume on an electronic balance. Other values were estimated from the measurements for the melt and freeze experiments and averaged. The apparent thermal conductivity was 0.5287 BTU·in./h·ft^2·°F (0.0763 W/m·K) from the steady-state heat fluxes and temperature differences across the test cell. Sensible heat capacity was 0.5604 BTU/lb·°F (2.346 kJ/kg·K) from the steady-state change in stored energy vs. temperature. The total energy absorbed for the complete phase changes less a correction for sensible heat stored yielded a latent heat capacity of 59.48 BTU/lb (138.3 kJ/kg). As noted previously, the temperature range over which the melting occurred was observed from the measurements to be 80 to 82°F (27 to 28°C). The freezing range was more difficult to estimate: 74 to 76°F (23 to 24°C) was established by trial-and-error. For the diurnal cycles, the average of these ranges, 77 to 79°F (25 to 26°C), was used. HEATING has a subroutine for isothermal phase change that handles latent energy storage separately from sensible storage. Temperature changes in an element are suspended until phase change is complete. Here, where phase change occurred over a range of temperatures, the latent storage subroutine was not used; sensible heat capacity was augmented in the desired range of temperatures by a triangular function with a total area equal to the desired latent heat capacity.

Figure 11 shows the predictions of HEATING for melting of the 2:1 mixture of PCM/perlite. The XPS and gypsum temperatures used as boundary conditions are shown for reference in addition to the climate chamber temperature repeated from Fig. 3. The predictions of HEATING are labelled in bold characters. Compared to the measured temperatures in Fig. 3, the predicted temperatures go more abruptly to the slowest rate of increase associated with phase change and to the higher rate of increase at the end of phase change. This is likely due to the triangular profile used for the latent heat capacity; a bell-shaped profile would allow more gradual changes in slope. The predicted bottom heat flux has a slight spike at the end of phase change because it is computed from the bottom and next to bottom temperature difference. It is difficult to produce an accurate and smooth curve from the difference of two quantities almost equal in value but changing at different rates. For the same reason, the predicted top heat flux has a slightly higher peak value than the measured value in Fig. 3, even though the variation is smooth. The melting experiment is the simplest of the three conducted and HEATING does an excellent reproduction.

Figure 12 shows the predictions for the freezing of the 2:1 mixture. No attempt was made to model the apparent supersaturation phenomena affecting the measurements presented in Fig. 6. Therefore, the predicted temperatures show the same relatively abrupt changes in slope at the start and end of phase change as in Fig. 11 for melting. The minimum in the measured temperatures is, therefore, definitely attributable to supersaturation. The temperatures, and the heat fluxes, too, take a bit longer to show the end of phase change. The same average value for total heat capacity was used in both the melting and freezing models. Without the effects of supersaturation, the freezing model seems more sensitive to this total heat capacity. The top and, although only slightly, the bottom heat fluxes are affected by the temperature fluctuation when the small compressor took over

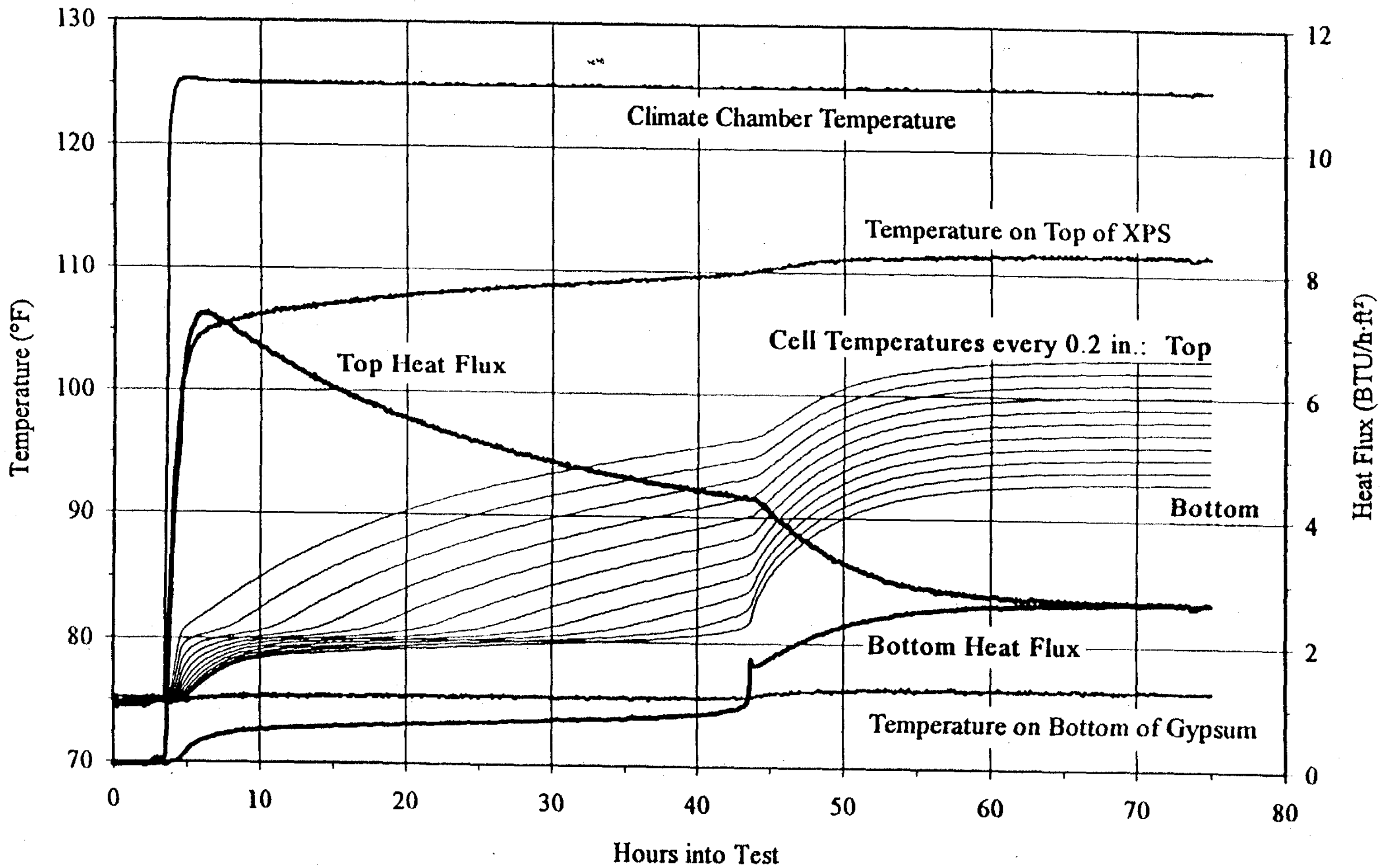

Fig. 11. Predictions of HEATING for melting of the 2:1 mixture of PCM/perlite. Compare to Fig. 3.

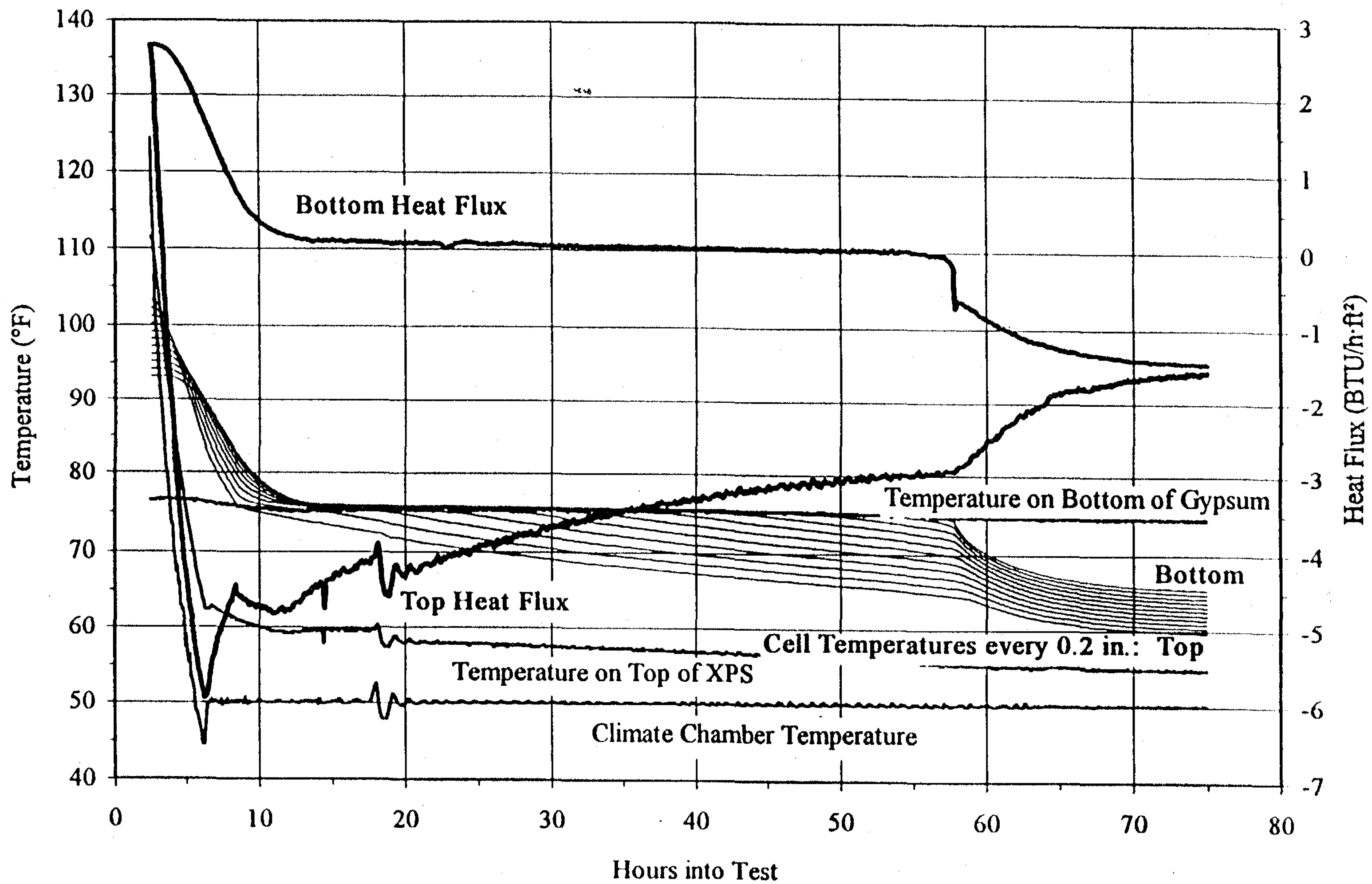

Fig. 12. **Predictions of HEATING for freezing of the 2:1 mixture of PCM/perlite. Compare to Fig. 6.**

the load. The top heat flux responded to overcooling when the large compressor was in service, but the bottom heat flux did not. The measurements in Fig. 6 showed a subsequent maximum in the top heat flux and a minimum in the bottom heat flux. The lack of these extrema in the predictions is further proof of the presence of supersaturation. The ragged profile of the top heat flux predictions between the small compressor takeover effect and the large compressor overcooling effect is due to subtle variations in the temperatures used to generate it. The spike in the bottom heat flux at the end of phase change is due to the same reason. Except for the absence of effects from supersaturation, the predictions for the freezing of the PCM agree well with the measurements. Moreover, they show sensitivity to the less than perfect variation in climate chamber temperature that was imposed by using the measured XPS and gypsum temperatures as boundary conditions.

Figure 13 shows the results of the predictions for the diurnal cycles of climate chamber temperature. Besides ignoring supersaturation effects observed during freezing, the model uses a range of phase change temperatures that is the average of the melting and freezing ranges. This effectively ignores the hysteresis exhibited by this PCM. Hence, more significant differences between the measured and predicted temperatures and heat fluxes are expected. After the half cycle needed for the measurements to settle into periodic stationary conditions, the temperatures during the melting part of the cycles do not get as warm as the measured values in Fig. 8. Nor do they get as cool as the measured temperatures during the freezing part. Since the phase change temperature was moved down from the actual melting range and up from the actual freezing range, the predictions are consistent. Without supersaturation during freezing, less PCM seems to be changing phase in the predictions compared to the measurements. Hence, the predicted temperatures near the bottom of the test cell are bunched together, especially at night. This explains the irregular behavior of the bottom heat flux although its magnitude and range of variation are remarkably close to the measurements. Moreover, since the top temperatures are a bit lower than the measured ones, the top heat flux peaks a bit higher and bottoms out a bit lower than the measurements. Even though the top and next to top temperatures in the cell peak slightly after the imposed temperature on top of the XPS, the top heat flux, which is computed from their difference, peaks slightly before. This is again due to the difficulty of predicting a rate from the difference of two approximately equal numbers with slightly different time variations.

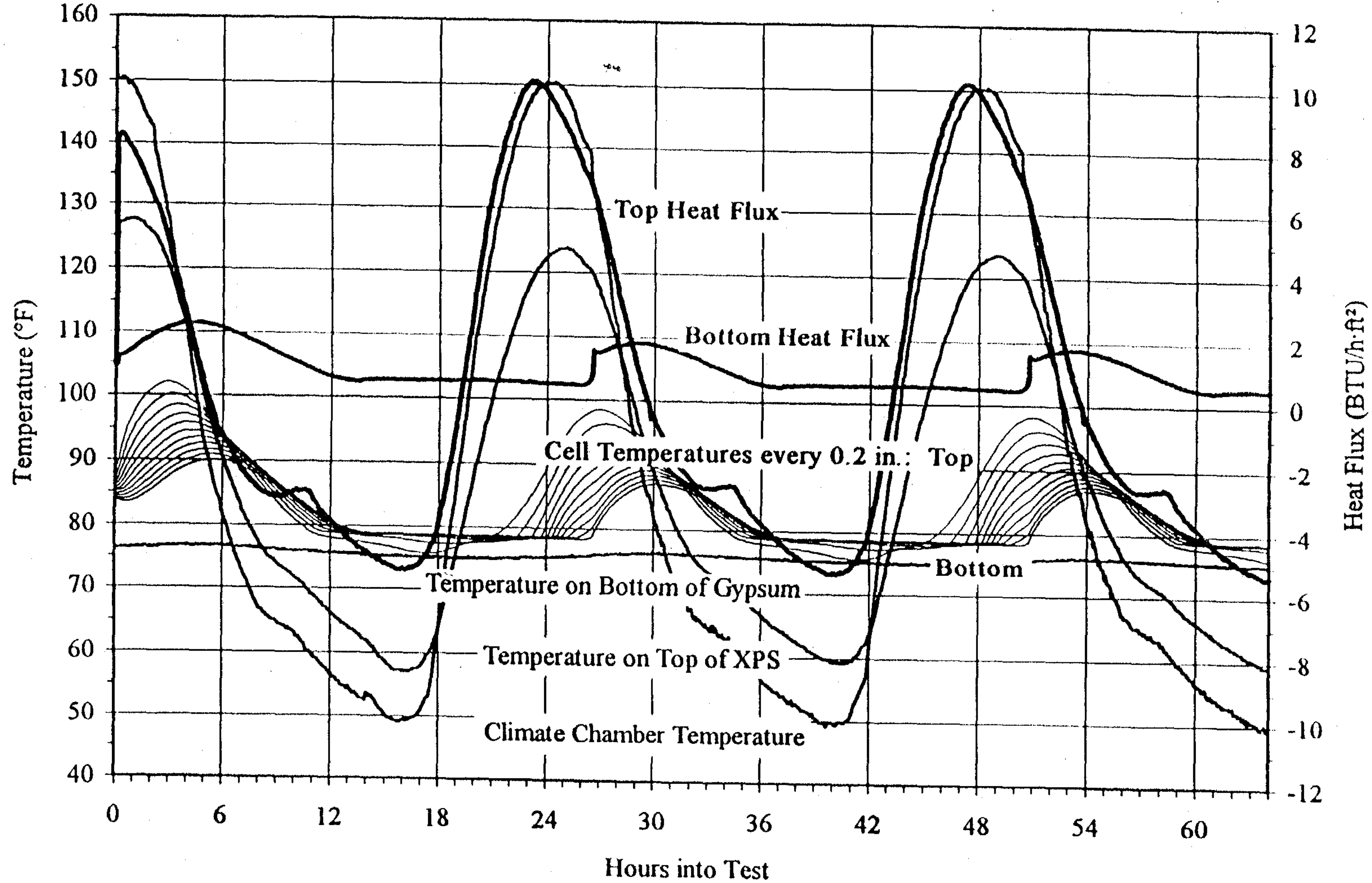

Fig. 13. Predictions of HEATING for diurnal cycles with the 2:1 mixture of PCM/perlite. Compare to Fig. 8.

The objective of the modeling with HEATING was to prove that we understand the phenomena involved in using the PCM available for the experiments as part of a thermal control system. To summarize how well we have met this objective, Fig. 14 compares directly the bottom heat fluxes predicted and measured for the melting, freezing and diurnal cycles with the 2:1 system. As stated above, HEATING does not include a model for supersaturation during freezing (i.e., a delay in the onset of freezing until temperatures are lower than equilibrium values) and hysteresis (i.e., a difference between the melting and freezing temperatures). Even so, the magnitude and variation of the predicted bottom heat fluxes are similar enough to the measurements to allow the scheme used by HEATING to form the basis of a subroutine for thermal control in a whole house model.

Implications for Whole Building Performance

Figure 8 showed the diurnal cycle behavior of a good candidate configuration for thermal control: the test cell with a 2:1 mixture of PCM/perlite, two layers of 0.5-in. (1.27-cm) thick XPS underneath and a single layer of this XPS on top. To explore the implications of this system's behavior for whole building performance, the thermal loads generated by a simple ranch house in Las Vegas NV were determined with DOE-2.1E. An hourly report of building component loads was produced for the peak cooling day (July 29 for the Las Vegas TMY weather data that were used). Monthly total loads due to each component were also extracted in a report.

The building chosen is a one-story house with nominal R-19 h·ft^2·°F/BTU (R-3.3 m^2·°C/W) ceiling insulation and frame walls with R_{US}-11 (R_{SI}-1.9) insulation. The exterior of the walls is covered with stucco. The house is built on a slab over a sand base. Floor area is 1540 ft^2 (143 m^2). Net wall area, after allowing for 10% of the gross area for windows and doors, is 1174 ft^2 (109 m^2). In the modeling literature, it is referred to as the California house.

For comparison to the heat fluxes measured during the diurnal cycle experiment at the bottoms of the fiberglass batts and the 2:1 PCM/perlite system, hourly cooling loads due to the roof and the walls on the peak cooling day were divided by their respective areas. The resulting average cooling loads are labelled as DOE-2 roof and wall loads and plotted in Fig. 15 along with the heat fluxes measured directly in the experiment. The thermal mass of the roof insulation is very similar

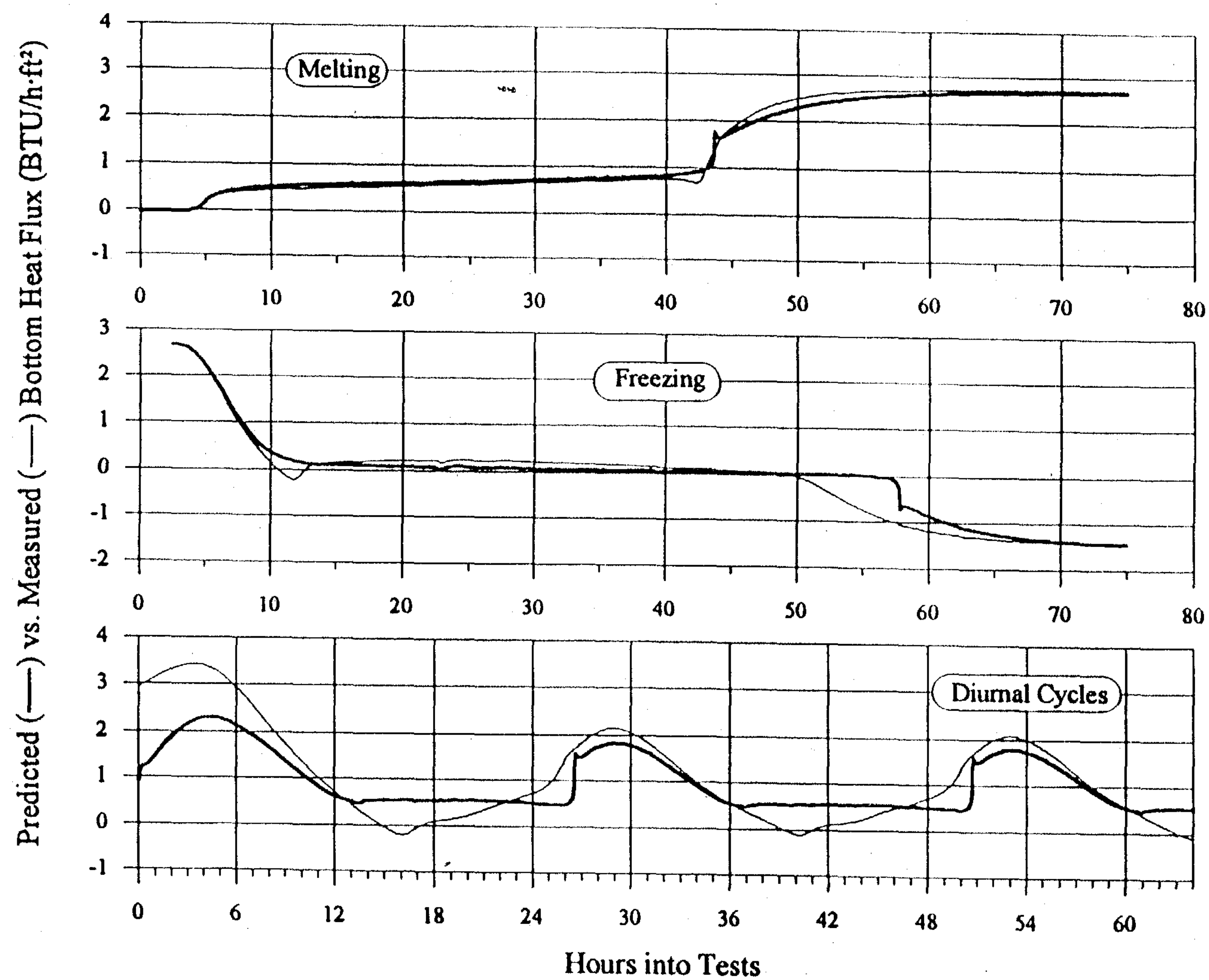

Fig. 14. Comparisons of predicted vs. measured bottom heat fluxes for the 2:1 mixture of PCM/perlite.

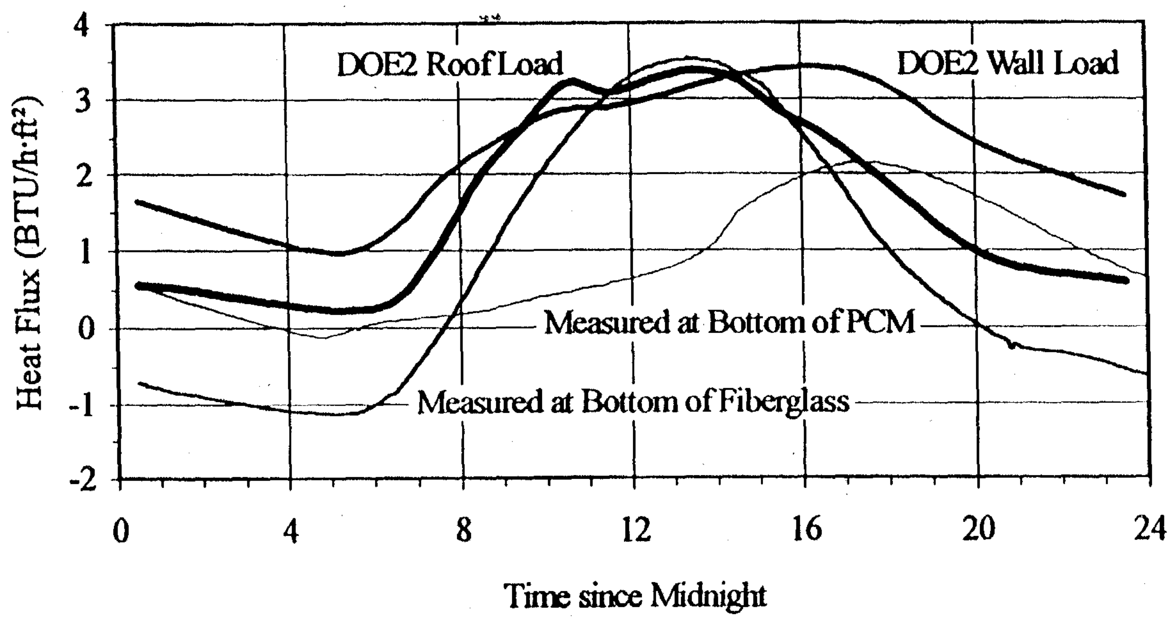

Fig. 15. Comparisons of heat fluxes for estimate of savings with whole building thermal control.

to that of the fiberglass in the experiments so the profiles are similar except for a slight variation just before noon due to the weather conditions used in the DOE-2 run. The stucco coated walls have more thermal mass so the delay in their peak heat flux is reasonable. Although the maximum heat fluxes through the roof and walls are about the same as that of the fiberglass, the minimum heat fluxes are significantly greater than that of the fiberglass and are positive. The TMY weather is not as cool at night as the programmed diurnal cycle. The latter needed to be low enough to allow the PCM to refreeze at night.

If a PCM were available with a higher freezing temperature than that of the one used, it could regenerate at night with warmer temperatures. A material without the hysteresis exhibited by the one used would be a significant improvement. For purposes of the present estimate of potential savings due to thermal control, it is assumed that the DOE-2 roof and wall load profiles are the same as was measured at the bottom of the PCM. Over the daily cycles that are shown, the roof load is 37.8 BTU/ft^2 (429 kJ/m^2)and the wall load is 54.7 BTU/ft^2 (621 kJ/m^2). The PCM load is 20.2 BTU/ft^2 (229 kJ/m^2), 47% less than the roof load and 63% less than the wall load.

The cooling season for this house in the Las Vegas NV climate, taken to be the months when the cooling load significantly exceeds the heating load, extends from May through October. Total roof cooling load over this period for the TMY weather data is 6.44 MBTU (6.80 MJ). Total wall cooling load is 6.85 MBTU (7.23 MJ). These are 17% and 18%, respectively, of the total cooling load of 38.9 MBTU (41.0 MJ). If use of PCM reduced the monthly roof and wall cooling loads by the percentages assumed for the peak cooling day, the roof and walls would only contribute 3.44 MBTU (3.63 MJ) and 2.53 MBTU (2.67 MJ), respectively. The new total cooling load, assuming all other component loads remain unchanged, would be 31.6 MBTU (33.3 MJ), 19% less; 8% of the reduction is due to the roof and the other 11% is due to the walls..

The cost savings could potentially be much greater than 19%. If the cooling equipment ran 19% less at the same operating efficiency, cost savings would be 19%. But, a building that is thermally controlled by PCM in the roof and walls would have its peak load delayed until early evening. Outdoor conditions then might permit more natural cooling. The peak load delay would also provide cost savings for buildings served by time-of-day rates.

Conclusions and Recommendations

Carefully controlled and well documented experiments have been done for two candidate configurations to control the heat load on a conditioned space. The 2:1 PCM/perlite mixture and the 6:1 PCM/perlite mixture, both on a weight basis, accomplished thermal control. The 2:1 system seemed to have enough PCM to be effective and involve a much larger fraction of its PCM in diurnal freezing and melting than the 6:1 system. It is a good starting point for engineering design of an optimum thermal control system.

The results from the 2:1 system were reproduced with the computer program HEATING to prove that we know the relevant mechanisms and thermophysical properties of the PCM used in the experiments. Even without a model for the supersaturation and hysteresis that this material exhibited, HEATING reproduced the heat fluxes to the conditioned space in the experiments accurately enough to mirror the good thermal control performance of the system. The modified sensible heat capacity that was used in HEATING is a handy way to account for phase change effects and could be used in a subroutine to compute hourly phase change effects for whole building models like DOE-2.

The experiments were done with PCM/perlite mixtures sealed in small methylmethacrylate boxes and covered top and bottom by XPS. The boxes allowed precise placement of the instrumentation used to follow the phase change effects. The XPS gave high R-value per unit thickness. A more practical prototype configuration, such as PCM/perlite hermetically sealed in plastic pouches between layers of batts or blown-in insulation, should be tested over a larger cross section. A good candidate is the whole attic cavity of the manufactured home test section used in the present work. Use of a PCM that does not exhibit supersaturation and hysteresis would make interpretation of the results easier.

If the results of the larger scale test are as encouraging as the test cell results, a whole house model with a phase change algorithm should be constructed to optimize the configuration for the climate in which it will perform.

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