THE FINAL THERMAL INSPECTION OF BUILDINGS BY MEANS OF SHORT-PERIOD PERFORMANCE MONITORING: TWO CASE STUDIES

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ABSTRACT

Thermal performance monitoring of buildings and heating systems has been used in Italy since 1979. The main purposes were to assess both the typical energy consumption of the different construction technologies used and the amount of saving obtained by energy conservation measures or solar energy applications.

For the purposes of research, the data acquisition systems used were quite sophisticated, and the monitoring period very long (up to three years). In this paper the author discusses the possibility of using shortperiod performance monitoring as a basis for the final thermal evaluation of a building; this is done by presenting two relevant case studies. The first case concerns a school building (17,750 m^3) where the heating system is solar assisted by 800 m^2 of air collectors. The operation of the systems were specially designed to take into account the complex utilization pattern of the building. The second case concerns a convertible mobile home (140 m^3) designed for emergency assistance in case of earthquake: in this case the heating system is electric. After outlining the construction and physical parameters of these buildings, the author describes the testing procedure adopted. The results obtained are then presented, comparing the measured behavior of the buildings and systems with the expected one. Starting from these first experiences, some aspects regarding the possibility of performing a final thermal evaluation of buildings based on this technique are discussed, such as:

- the shortest significant performance monitoring period;
- types and minimum significant number of parameters to be measured;
- physical parameters qualifying the energy consumption of buildings;
- complementary measurements (useful or necessary).

Finally, the author gives a short account of future work on the possibility of using low-cost instrumentation.

INTRODUCTION

Monitoring of the physical parameters typical of a system during operational model was made possible by the development of more intelligent and miniaturized data acquisition and data processing systems. This technique, used in most fields of engineering, started with the production of high-technology goods. It was first applied on a large scale, as concerns buildings and their thermal behaviors, within the framework of the specific energy projects of the Italian National Council of Research.

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Among the objectives pursued in this context, particular mention should be made of the goal to obtain data concerning the energy balance and thermal behavior of a significant sample (about 1000 buildings) and of assessing improvements introduced by various remedial actions on heating systems and outer walls. A further objective was to evaluate the contribution of active or passive systems for the use of solar energy. These monitoring projects were characterized mainly by the high number of measuring points and periods of time varying from a minimum of thirty days to a maximum of two to three heating seasons.

Experience has shown, as in similar European projects - that setting up an efficient monitoring system on such a large scale involves long realization times and remarkable difficulties. The work, which is now being completed, has allowed for identifying and overcoming the many problems involved by perfecting the procedures and instruments available. The Institute for Building Technology, working in the context of the Energy Program, collected data relative to buildings equipped with solar heating from 1977 to 1981 and participated in the exchange of information in this field within a group organized by the EEC.

At present, monitoring of the thermal behavior of components and systems in testing conditions is performed at ICITE for various research and certification programs. The experiments carried out are, in turn, organized so as to explore the possibility that the monitoring technique - simplified as regards both the number of measuring points and the duration of the measuring period - may become a fundamental part of "building energy testing" together with thermography. The possibility of using this type of testing has three fundamental implications:

- testing compliance with definite contract requirements, which is beneficial both to those who build and those who purchase or use a building;
- evaluating the technical choices made by means of feedback information;
- identifying the correlation function relating the building's components and subsystems that are specifically designed for energy conservation purposes (e.g., heating system and outer walls).

THE CASE STUDIES

In order to clarify the present state of knowledge as regards the possibility of applying this technique for testing purposes, we present the case study of a solar-assisted school building in the Ascoli province. This building (17,000 m^3) was designed with optimum morphological and technological characteristics for maximum energy conservation. High thermal insulation and the use of conservative spaces (enclosed patio, glasshouses facing south) were combined with a complex air-heating system. This was based on a conventional heating plant feeding several air-heating batteries placed on the building's roof, which could make use of the pre-heating supplied by the air from the many air solar batteries (a total of about 800 m^2).

The working modes of the building, designed with regard for the various climatic conditions and school activities, were many and complex. It should be pointed out that the main objective of this first experiment was identifying the dynamics of the building's thermal behavior, because in several instances the inside thermal level had proved insufficient to guarantee comfort.

The analysis was conducted over a period of four days , including the fitting and removal of instruments. The use of radio data transmission systems helped reduce the time of analysis. Thirty measuring points accounted for the complete monitoring of a few sample rooms and batteries and spot monitoring of other components and rooms for comparison. The type of data acquisition system utilized is shown in Figure 1. The configuration of this type of system was designed especially for use during monitoring of buildings. During this time, a thermographic analysis of the building's outer walls also was performed, along with an accurate visual inspection. The purpose was to assess other factors impacting on energy consumption.

All the data gathered presented a very complex picture which is now being evaluated by those concerned with the project. In order to provide examples of the type of information obtained and of the analysis this allows, two diagrams are shown in Figure 2 and Figure 3. They show the data relative to a 24-hour period from 1 p.m. one day to 1 p.m. the next day. Figure 2 reports the data relative to solar radiation (W/m^2), outside temperature and air temperature of the outlets from the collectors. Figure 3 reports the curve of the temperature in a classroom of the school measured at two points, i.e., near the warm air outlet and in the middle of the room. The analysis of these two diagrams points to behaviors typical of the system, which can be summarized as follows:

- Figure 2 shows the sharp rise in the temperature of the air coming from the solar collectors starting at 7 a.m., even though in poor radiation conditions; the action of the regulation system on the collectors is visualized by three peaks (on-off) starting at 9.30 a.m.
- Figure 3 shows the trends of temperatures from 9.30 a.m. (particularly at the warm air outlet), as a consequence of switching the collectors on and off. The contribution is clearly significant on the temperature level inside the classroom. It rises by almost two and a half degrees Celsius as compared with the level maintained at 7 a.m.
- The time of 7 a.m. coincides with a change in the school's working mode. As part of the regulation system, from 5 p.m. to 7 a.m. the heating air is not taken from outside - as in the period when the school is used - but recycled from inside the school. This procedure is clearly shown in the diagram of Figure 3. It is noted, however, that in the recycling period, the inside temperature rises, to decrease sharply at the moment when recycling is suspended and the intake of outside air starts.

By analyzing the data of the assessed thermal balance, this trend can be explained; the fact is that the conventional heating system never made full use of its installed capacity, despite the insufficient inside temperature level. A maximum of 280,000 kcal/h was supplied, as compared with the 350,000 the heat generator could supply. An analysis of the thermal difference between the exchangers fed by the boiler and placed in the air-heating batteries showed that it corresponded to the maximum expected level. It was thus clear that such exchange batteries resulted to be underdimensioned. In fact they were not able to exchange more heat when the outside temperature level lowered under +4°C in spite of the school building heating demand.

A complete analysis of the recorded data, which - as has already been mentioned - is now being evaluated and discussed, also pointed to redundancy problems in regulation systems under particular operation conditions. The following regulation systems operated together:

- temperature of the boiler;
- temperature of the air-heating battery exchangers;
- air temperature in the batteries (from collectors, from outside, or mixed);
- temperature in the school rooms.

There is no doubt that a traditional thermal test consisting of air temperature measurements in the classrooms during the morning of the same day, or on a day when the outside temperature was 4 to 5°C higher than it was in our case (i.e., - 0.5°C at 7 a.m.), may not have detected the trends or problems that emerged. The thermographic analysis allowed identification of situations showing poor thermal insulation of the load-bearing structures (Figure 4), of the heat distribution system (Figure 4), and anomalous heat distribution inside the building (Figure 5).

The second case study concerned the monitoring of the energy balance and temperature conditions in a convertible mobile home (140 m^3) designed for emergency use in case of earthquake. When it is folded up, the mobile home has a volume equivalent to that which may be transported on a road without the need for special vehicles or permits. Once open, it turns into a small home of about 50 m^2, suitably equipped and ready for use for up to four people. Figure 6 shows the sequence of operations for opening the mobile home. The construction technology is based on fiberglass-reinforced plastic "sandwich" panels, containing polyurethane foam. The heating system is by distribution of air heated by electric resistance elements. The main objectives of the study were as follows:

- Identification of inside temperature levels maintained by the heating system with reference to outside temperature;
- Visualization of the heating system's working dynamics with particular reference to the regulation and distribution systems;
- Assessment of the mobile home's energy balance and of the total heat loss coefficient per unit of volume.

The unit installed at ICITE was complete with all relevant electric connections for normal operation. The unit was then equipped with a number of sensors for measuring the values relevant to the above-mentioned objectives. In order to monitor inside and outside temperature and humidity conditions, a data acquisition system was used that controlled a set of 21 temperature sensors and 5 humidity sensors according to the plan presented in Figure 7.
Air temperature sensors were located in the various rooms relative to:

- distribution outlets;
- temperatures in the upper sections of the rooms;
- temperatures in the middle sections of the rooms;
- temperatures in the lower sections of the rooms;
- outside temperature screened from radiation.

The electric power supplied by the system was measured by an energy meter. These values were assessed and recorded for the whole test period at four minute intervals. Two measuring sessions were performed, the first on a prototype, which allowed detection of some problems, and the second on a preproduction unit, which had been improved after the analysis of the first test. Results of the first set of experiments are reported below:

- outside temperature, daily average;
- inside room temperature, daily average;
- thermal difference;
- power supplied to the heating system.

No. of days	Outside temperature	Average room temperature	Thermal difference	Power
1	12.11	21.68	9.57	33.1
1	9.47	21.11	11.64	44.4
1	9.28	21.13	11.85	44.5
6	12.87	22	9.13	203.7

The total heat loss coefficient per unit of volume was the calculated ($W/m^3 \cdot °C$), which , in Italy, is the parameter that characterizes the energy performance of the whole building. Calculating the total heat loss coefficient per unit of volume for the periods mentioned in Table 1 by means of the following formula:

$$C_G = \frac{Q \times 1000}{\Delta T \times 24 \times V} \quad (W/m^3 \cdot °C)$$

where

Q = electric power absorbed for heating (kWh)
ΔT = inside-outside thermal difference (°C)
V = volume of the unit 139.5 m^3 (m^3)

the following results were obtained:

No. of days	Coefficient per unit of volume
1	1.03
1	1.14
1	1.12
6	1.1

As can be seen, the mean total coefficient is 1.1 $W/m^3 \cdot °C$.

Also note the limited dispersion of the data, probably due to variations in the action of the sun. This performance was evaluated with reference to the surface/volume ratio, in keeping with Italian law on energy conservation in building. It was found to be acceptable in climatic areas where the number of heating degrees/day does not exceed 1900.

Even though the mobilehome is considered as emergency use, it is clear the performance could not be considered ideal; in Italy, in fact, about 30% of the national territory has a number of degrees/day ranging between 2100 and 3000. Further experimental analyses and studies of the project attributed this performance to a number of unexpected thermal bridges and to the poor air-tightness of the joints. As far as the performance of the thermal plant concerned in Figure 8 the curves show:

- room temperature
- warm air outlet temperature
- external temperature

It is worth observing that the system switches on with a very low frequency at rather high peak temperature. The consequence of this inside the rooms is clearly shown by temperature trends at the various points. In particular, considering the temperature in the middle of room four, an oscillation of almost 4°C can be noted. This can influence the level of comfort negatively and is probably due to the type of thermostat regulation used, which mobilizes the full load when the room thermostat allows, so that air is supplied up to 48°C.

Results of the second set of experiments are listed in Table 1, which reports the following daily values:

- Outside temperature daily average
- Inside room temperature daily average
- Thermal difference
- Power supplied to the heating system
- Total heat loss coefficient per unit of volume.

As can be seen, the resulting values were definitely more satisfactory than in the first session, so that the mobile home could be better classified for the purposes of law requirements.

As far as the performance of the heating system is concerned, the analysis of the data - an example of which is reported in Figure 9 - shows that the temperature level of the inside air is kept constant by the system independently of the variations in outside temperature. The curve of temperature (see the values of temperatures in the middle of the rooms in the various tables) is such that differences from the mean value do not exceed a few tenths of a degree. Temperature oscillations near the air outlets are within the limit of 6°C. It should be mentioned that the temperature value to be maintained was directly preset at the factory.

The results presented should be considered in view of the possibility of performing a comprehensive thermal evaluation of buildings in the near future, fulfilling the following requirements:

- provide reliable though simplified information about the energy balance of the building and its characteristic behavior;
- be manageable on a short-period basis and by simplified interventions on buildings;
- involve low instrumentation and personnel costs.

In both case studies, it was possible to collect useful information on the energy balance by adopting a simplified monitoring system (from 20 to 30 measuring points). In particular, in the case of the one-family mobile home, it was possibile to improve the characteristics of the external walls, and to verify the results obtained.

In both cases, the measuring of the energy used for heating was relatively simple; electricity was, in fact, used for the mobile home and methane gas for the school. The general rule was in any case established for the future to avoid heat measuring based on both temperature and hot water flow rate, which involves problems of accuracy as well as difficult and sometimes even unfeasible installations, in existing buildings. The results obtained show that is already possible to identify the characteristic behavior of a system with sufficient clarity. In particular, in the case of a complex system such as that of the school, it was possible to detect deficiencies and operational defects that impaired the system's performance. The measuring period necessary to obtain this type of information is quite short; one or two days are considered to be sufficient.

As far as the energy balance is concerned, on the contrary, it seems to require a longer measuring period, in order to take into account the influence of heat storage in the building structure. This, however, depends on the period chosen within the heating season, which, in turn, is dependent on local climate. We are now discussing which criterion to adopt, even though both the data gathered and the results of calculations suggest that deep winter months (from December through February in northern Italy) allow for measuring periods ranging from three to five days, depending on the thermal mass of the building structure.

As has been said, a decisive element is the cost of the equipment and experimentation. As for the instrumentation, the cost of the equipment used of the type described, including the sensors, was approximately US$ 8300 (32 measuring points). A simplified type of equipment is already being tested, which is capable of achieving the same results at a cost that should not exceed US$ 2000.

It was not possible in the course of the two case studies to correctly calculate the actual number of man-days employed; it should be considered in the context of a research project. The research activity will be continued next winter in the framework of the Finalized Energy Project of the CNR. The work plan includes the study of a larger number of cases, selected on the basis of their significance with reference to the types of buildings and heating systems and by the use of some types of simplified instrumentations. A further objective will be that of establishing whether it is possible to use a thermal consumption parameter measured experimentally as a basis for calculating the yearly thermal requirement of a building, utilizing as case studies for this purpose some buildings that have been monitored for a few heating seasons.

CONCLUSION

This experience showed it is possible to utilize the information derived from extensive monitoring programs to evaluate buildings by checking their performance. In particular, short-period monitoring utilizing a fairly simple measuring pattern (20-30 measuring points) effectively highlights the characteristic performance of the building/heating system interface. It also allows the choice of improvements to be introduced. Complementary techniques, such as infrared thermography, combined with visual inspection of the external walls, held assess the existence of any possible problems affecting the performance and energy balance.

The measurements performed also suggest the possibility of evaluating energy consumption by means of short-period monitoring. The duration of the monitoring period must be established by further experimentation, as a function of the ratio: period of winter selected/thermal mass of building. The experiments presented were, in fact, conducted in midwinter and in conditions that minimized the thermal mass effect (constant temperature, limited radiation). The applicability of the procedure from the point of view of the cost of instrumentation and of the difficulties of operation and labor involved are promising. Further activities will verify the aspects still to be clarified and the cost of labor required by the test procedure.

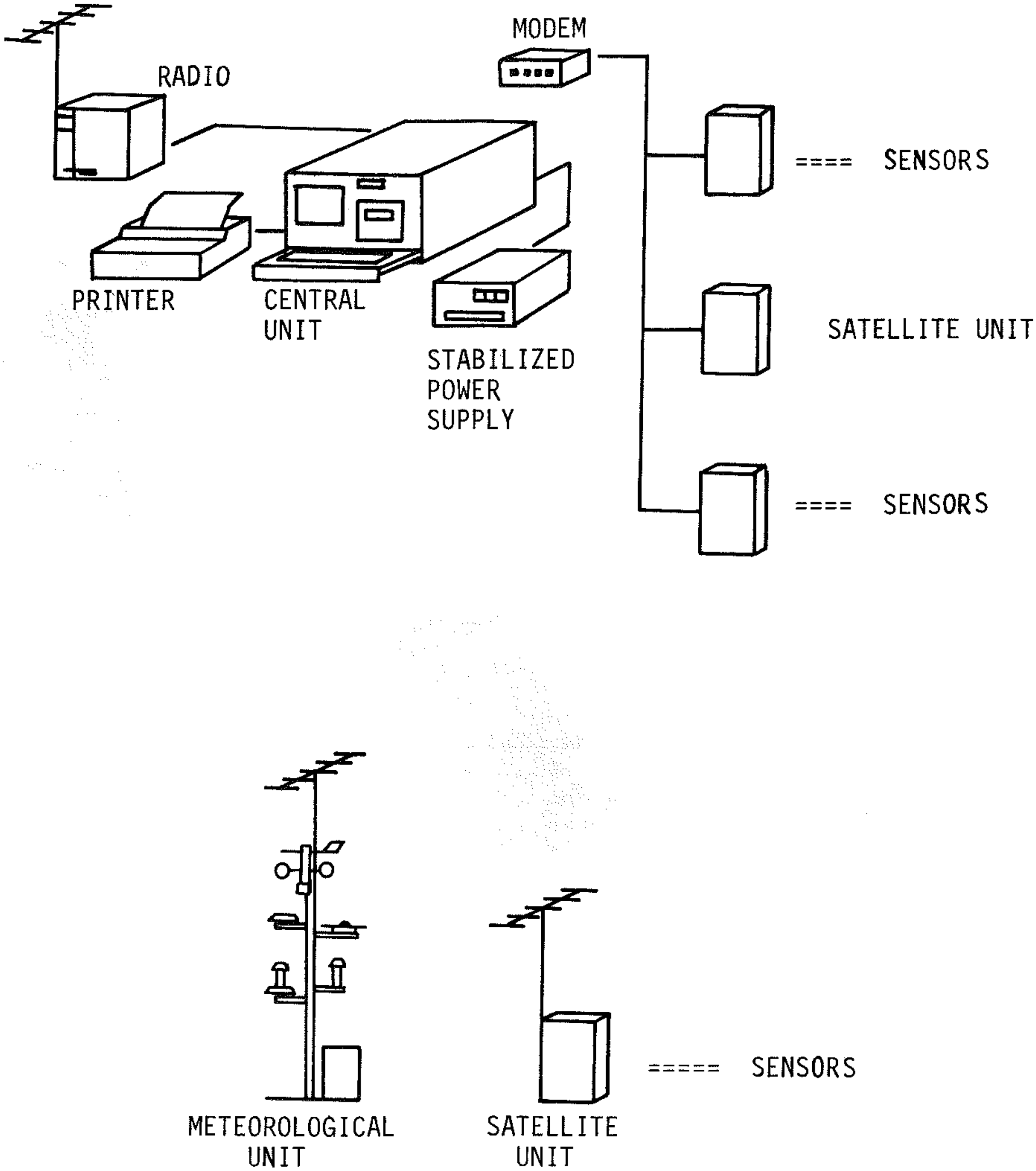

Figure 1. Schema of monitoring system used

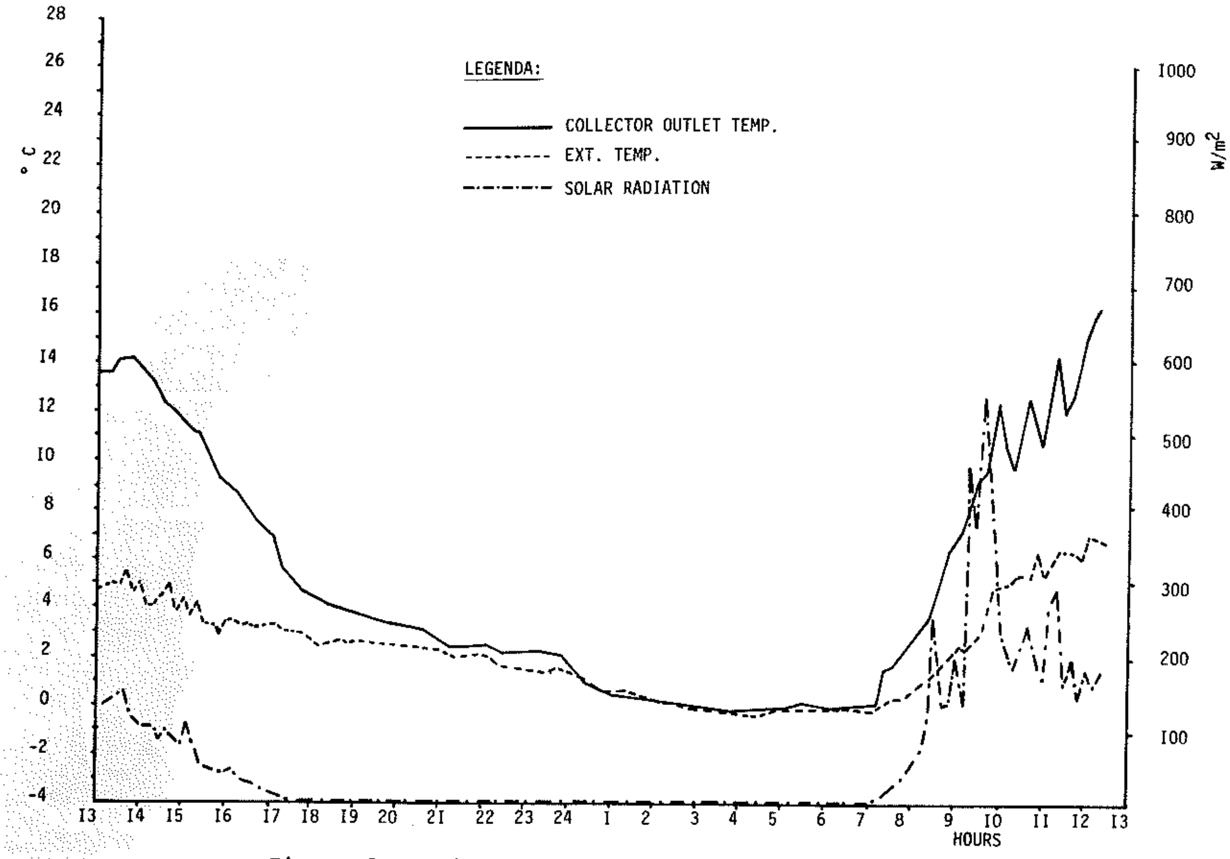

Figure 2. Daily profile of parameters recorded in solar school building

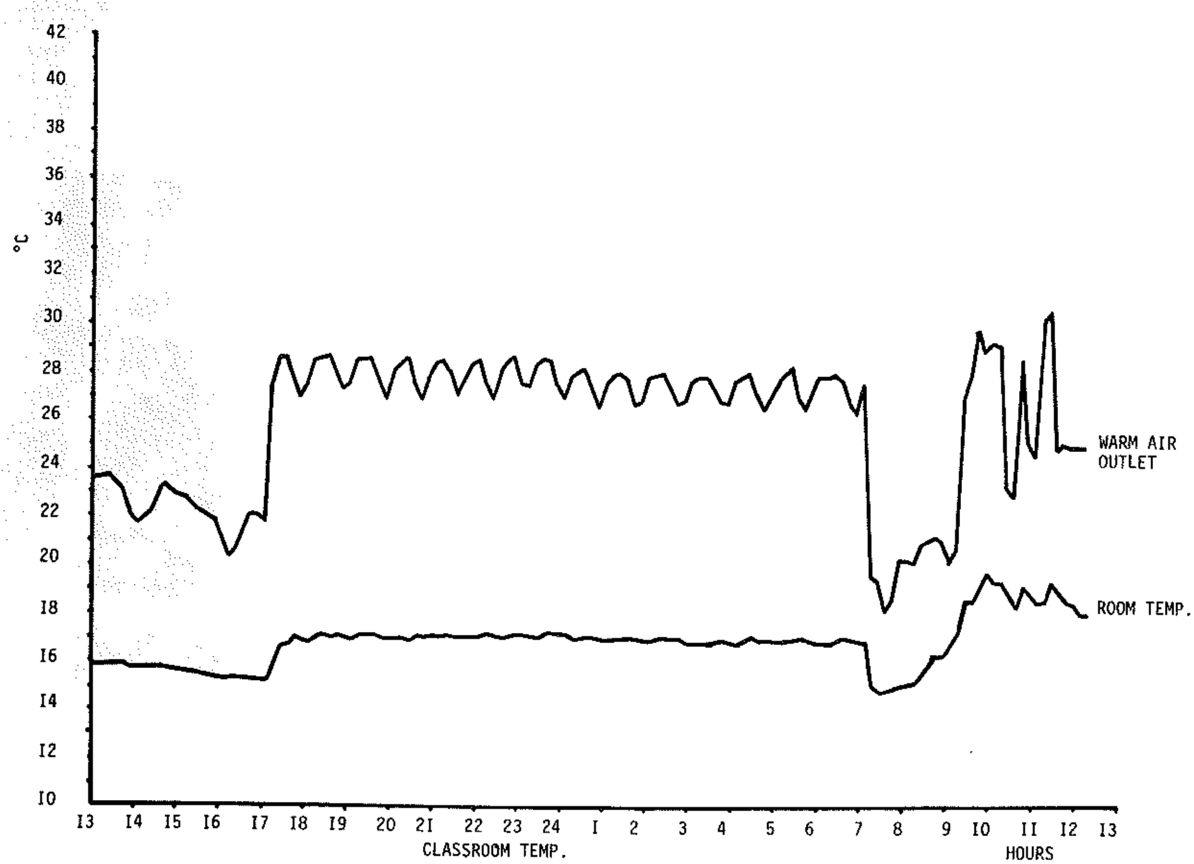

Figure 3. Daily profile of parameters recorded inside classroom

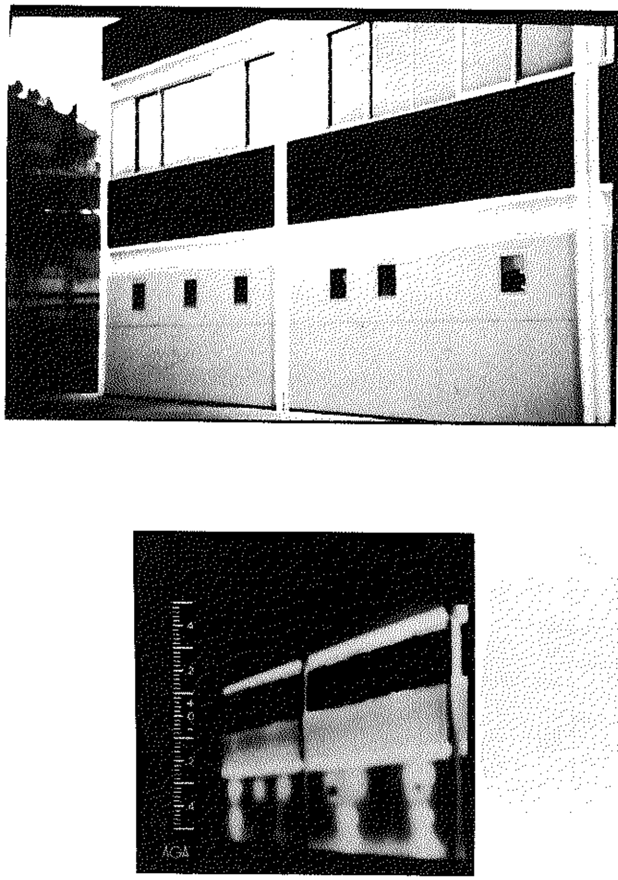

Figure 4. *Images in (a) visible and (b) infrared field of western wall of school. White points correspond to warmer zones of wall and black points correspond to colder ones. Note thermal bridges due to uninsulated beams and thermal trace of radiators and heating system pipes*

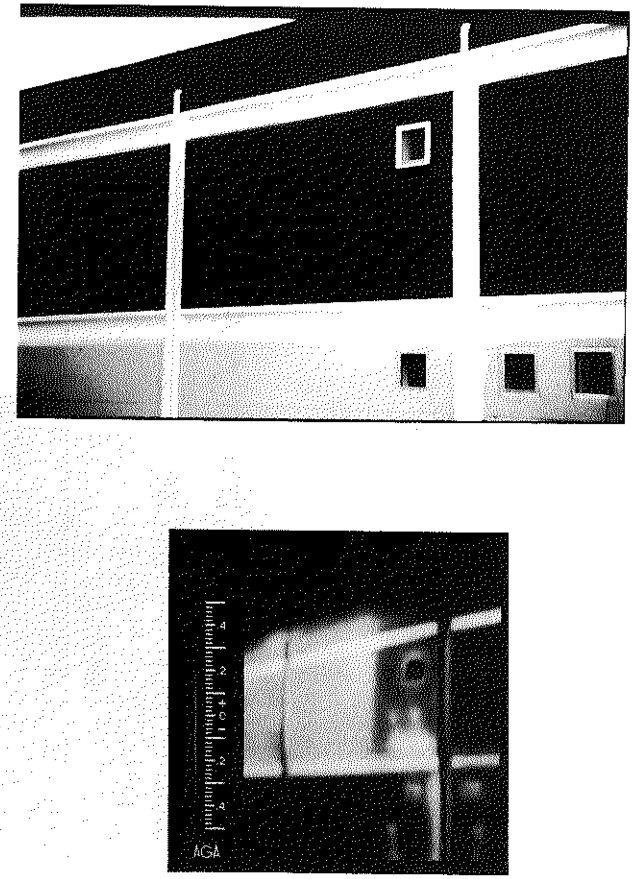

Figure 5. *Images in (a) visible and (b) infrared field of the northern wall of school. Note presence of thermal bridges and radiators and a warmer zone corresponding to gymnasium where ambient temperature was about 2.5°C warmer than other zones*

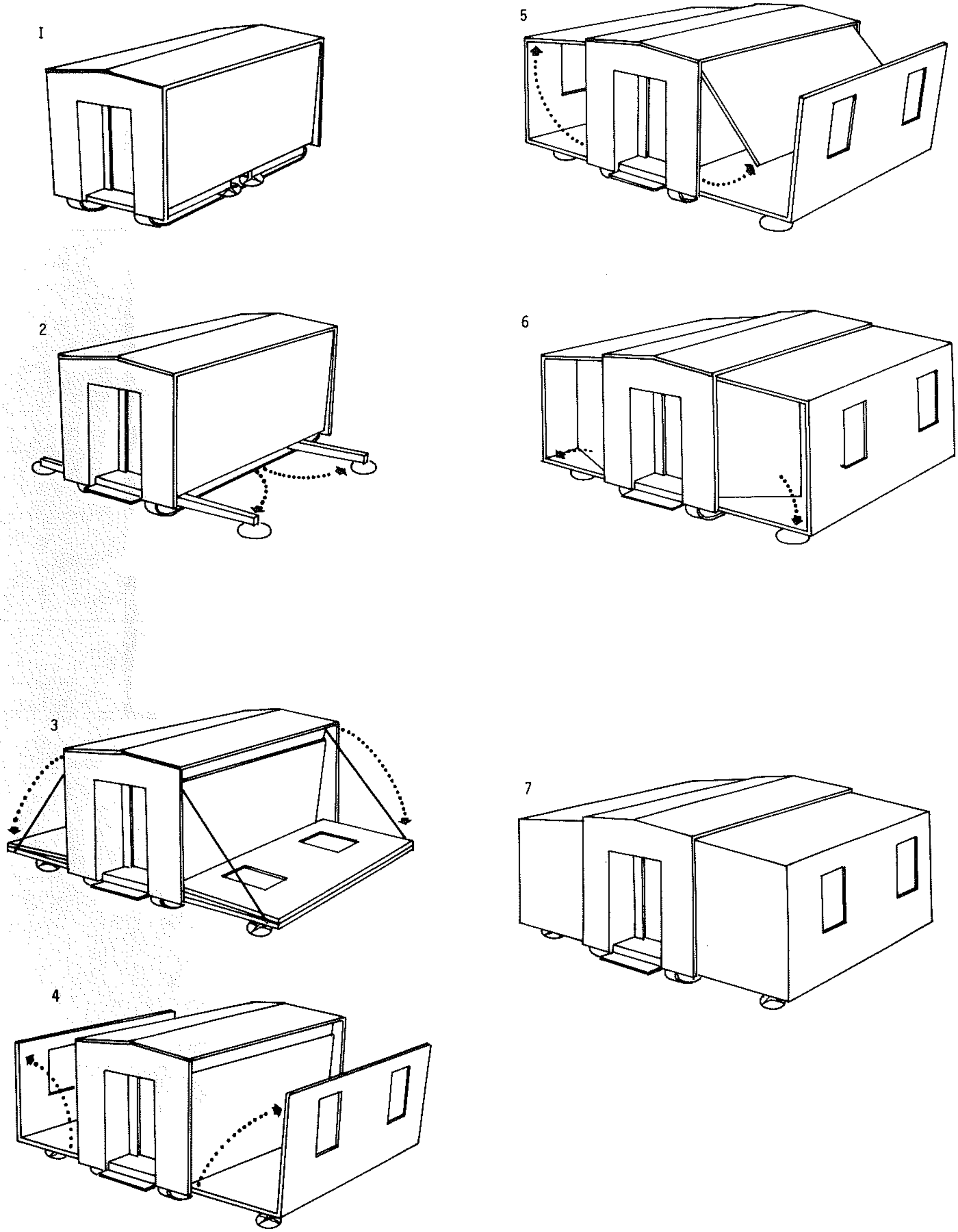

Figure 6. Sequence of operations for opening mobile home

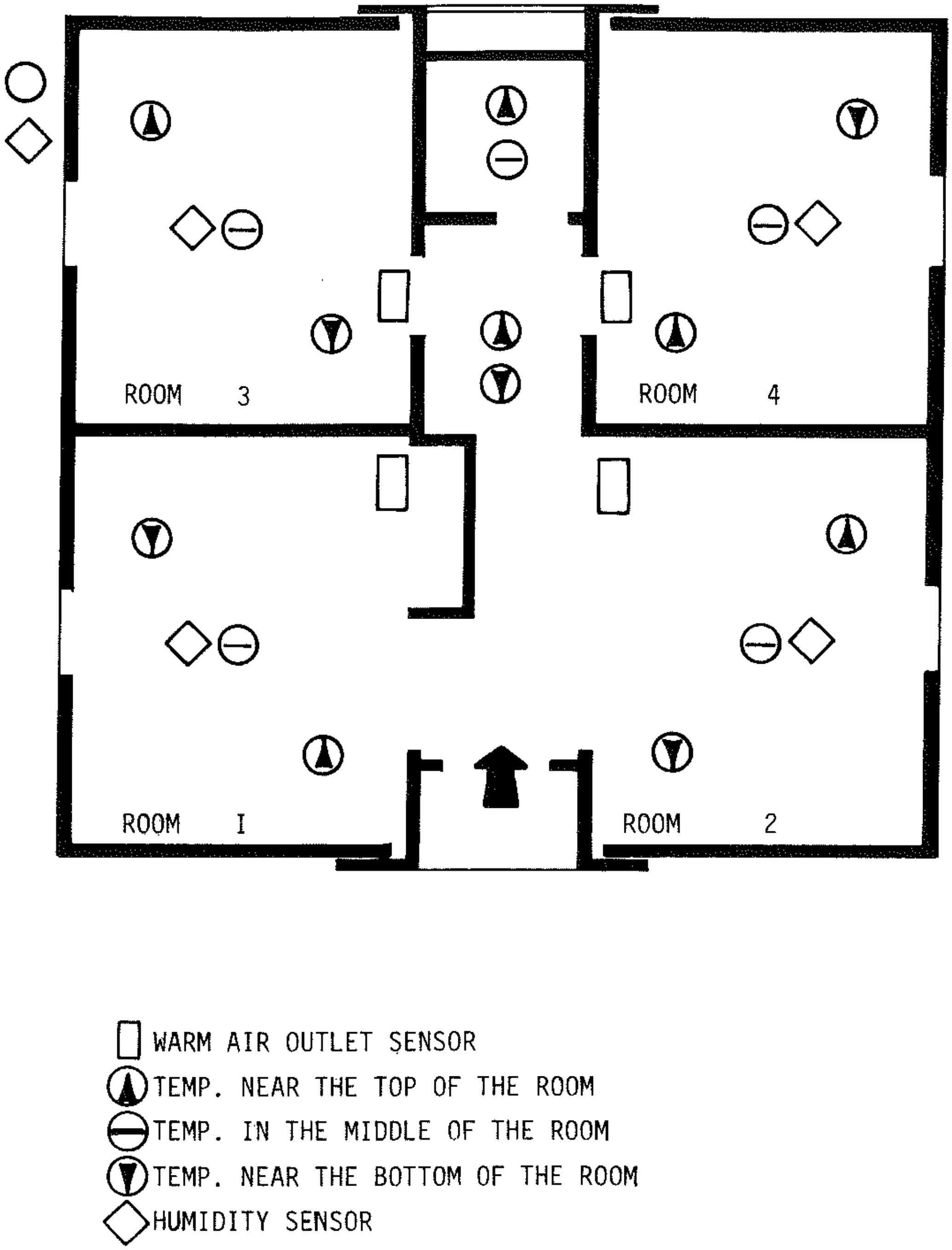

Figure 7. Sensors distribution in mobile home

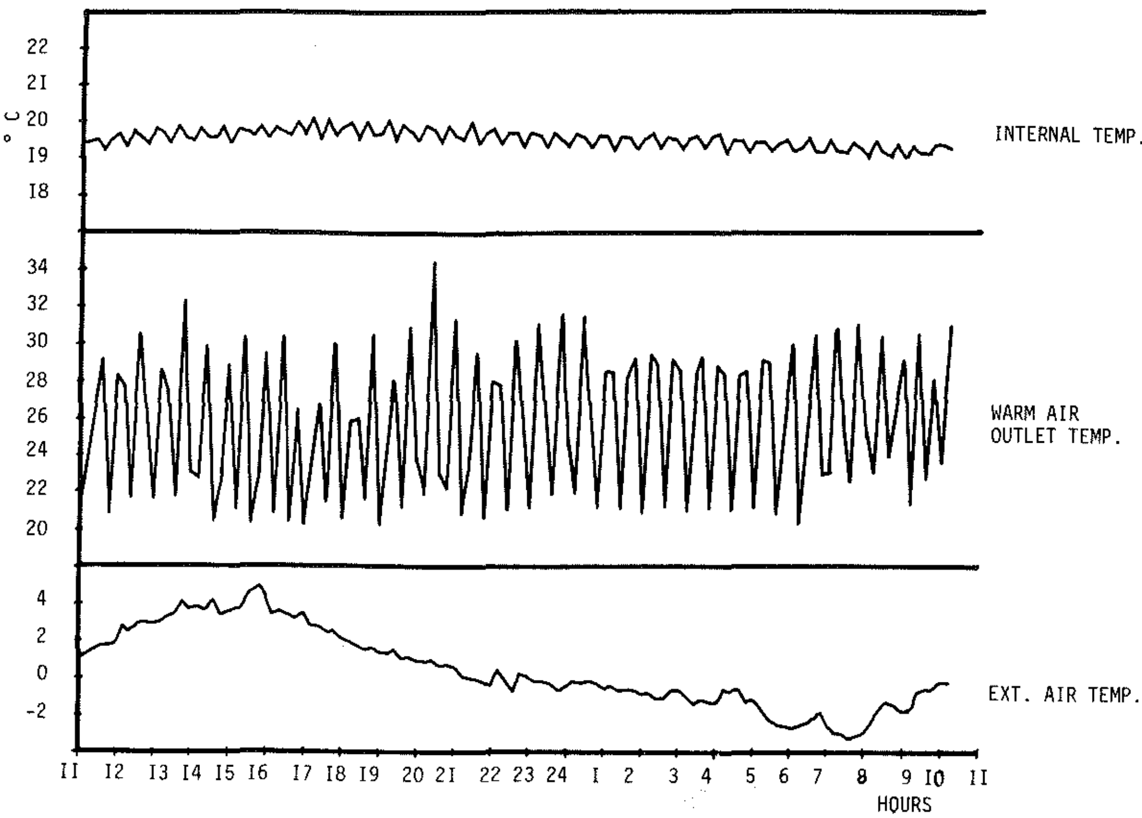

Figure 8. Daily profile of parameters recorded during first set of measurements on mobile home

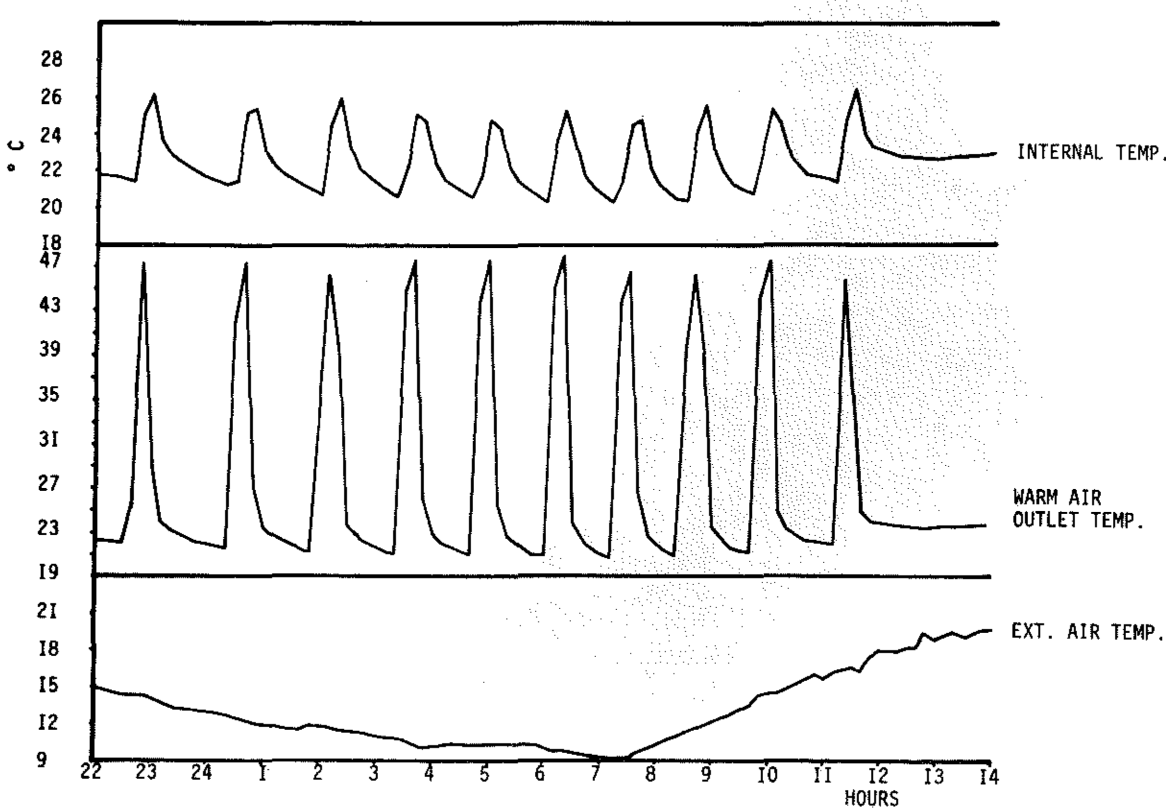

Figure 9. Daily profile of parameters recorded during second set of measurements on mobile home