EXPERIENCES DURING THE FIRST YEAR OF OPERATION OF THREE LOW-ENERGY APARTMENT BUILDINGS, A PART OF THE STOCKHOLM PROJECT

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ABSTRACT

One of the aims of the Stockholm project is to construct comfortable apartment buildings which consume less than 100 kWh/m2-year of bought energy during a normal year, almost half the consumption of a normal new building. Three of the Stockholm project buildings, namely Konsolen, Kejsaren and Sjuksköterskan, were ready for occupancy in 1984. Their first year of operation was planned as a shakedown period during which both the buildings and their computerized monitoring systems could be brought up to the best possible running order.

An overview of experiences during this first year is presented for each building. The shakedown has proceeded differently in the various buildings, since Konsolen has high mass and an exhaust air heat pump, Kejsaren has a solar collector and a warm air heating system, and Sjuksköterskan is almost conventional except for unusually thick insulation and a balanced mechanical ventilation system with an air-to-air heat exchanger.

In all of the buildings it was found that the apartments were being kept at approximately 22 C, rather than the 20 C which was assumed when computer simulations of the energy consumption of the buildings´ were made. The attempts that have been made in Konsolen to correct this discrepancy are described.

The energy balance for the Konsolen building is examined in detail. An estimate is made of how the energy balance will look next year, now that the faults found during the shakedown have been corrected.

It is suggested that all buildings with complex heating and ventilation systems should undergo a short, intensive shakedown period during which all systems are adjusted to their optimal settings. According to our experience, such a commissioning process could be extremely helpful.

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INTRODUCTION

The Stockholm Project includes five rental apartment buildings, Konsolen, Kejsaren, Sjuksköterskan, Bodbetjänten, and Höstvetet, as outlined in Table I. One aim of the project is to construct buildings which consume in a normal year less than 100 kWh/m2-year of bought energy (district heating and electricity) for space heating, domestic hot water and all other purposes. The means of achieving this goal is the use of the best conventional techniques coupled with either the improvement of well-tried existing techniques or the use of advanced new techniques. These techniques can concern either the building shell or the HVAC system. The evaluation of the Stockholm project is being carried out by the Energy Conservation in Buildings Group at the Royal Institute of Technology, Stockholm, Sweden. An overview of the project is given in the Swedish Council for Building Research (1984) and more detail is given in Elmroth et al. (1985)

TABLE I: Stockholm Project Buildings.

Name	# of apts.	Occupancy	Features
Kejsaren	10	Summer 1984	Solar Collector Air heating
Konsolen	57	Summer 1984	Solar walls High mass Exhaust heat pump
Sjuksköterskan	40	Summer 1984	Extra insulation Quality control
Bodbetjänten	35	Summer 1985	Combi Effect Glazed atrium
Höstvetet	71	Spring 1986	Bedrock storage Glazed atrium Air heating

The Combi effect: use of waste heat from a commercial building to heat a residential building by means of the Thermodeck floor system.

BUILDINGS´ FEATURES

This paper deals with the first year of operation of the first three buildings. This period was planned as a shakedown year for the buildings, and has - as expected - revealed a number of construction and heating- and ventilation-system problems. The energy consumption of the buildings has therefore been higher than the design value. However, it is lower than than the energy consumption of conventional new buildings.

The measured total bought energy use for the buildings during their first year should be interpreted with caution for several reasons. The winter was unusually cold, which increased energy use somewhat. Also, the use of household electricity and hot water differs considerably from building to building. To adjust the energy use to a standard year would have been difficult, since that would have required the detailed simulation of malfunctioning systems. Once the buildings are operating normally, adjustments are easier to make and more justifiable.

It is expected that energy use will be reduced during the next year, now that a number of teething troubles have been solved. To understand the difficulties which have occured in each individual building, it is necessary to know a little about their designs. Their main features are as follows:

Kejsaren is a ten-apartment row house close to the city centre, with a heated garage and a little gazebo that turns out to be the laundry. The main feature of the building is the striking solar collector which forms the roof; it supplies energy both for space-heating and domestic hot water (DHW). Excess heat is stored in a water tank and in the concrete floor slabs. The solar collector uses air to transport heat.

A second feature is the use of air as the transport medium for combined space heat and ventilation. Although common in the USA, this is quite unusual in existing buildings in Sweden. Two different methods of air supply are being tested. In half of the apartments, air is delivered from registers placed underneath each window to counteract downdrafts in winter. In the other half, air is supplied from ceiling registers far from the windows. Heat is recovered from the exhaust air by an air-to-air heat exchanger and used to pre-heat air supplied to the solar collector.

Konsolen has 57 apartments in two free-standing four-story buildings in a more suburban location still inside the City of Stockholm but close to the city limits. It has two unique energy saving features: solar walls and a very high thermal mass. A third feature is a heat pump which takes heat from the exhaust air and dumps it in either the radiator system or the DHW system.

The exterior wall elements on the south and southwest have solar walls. These are narrow vertical air passages constructed just under the outer skin of the concrete element. The building is kept at below atmospheric pressure by exhaust fan ventilation, and supply air is forced through these passages and then via ducts through the wall into the apartments. The air is warmed up by heat delivered to the element´s skin by solar radiation. Heat loss from transmission from the inside also contributes to warming the air. These solar walls do not give much energy to the building, but they are relatively cheap to build and so may be worthwhile. All elements are prefabricated, and to put air passages in them is not a large extra cost.

The solar wall is an interesting use of the facade of a building as a vertical solar collector to pre-heat ventilation air. Once inside the building, the air is further heated as it rises up behind a hydronic radiator which supplies the space heating.

Sjukskoeterskan is, like Konsolen, in an almost suburban setting. It is a wide U-shaped snake of a building. It has two energy saving features: extremely thick insulation, and quality control. Many of the walls have 220 mm of mineralwool insulation behind 190 mm of lightweight concrete cinder blocks. This technique is regarded as experimental because it is unknown whether convection and radiation will degrade the performance below the specifications. Some of the curtain walls have special lightweight wood studs. These both reduce the amount of wood needed and decrease heat loss by reducing the size of the thermal bridges caused by the wood. The insulation is divided into layers. Roof insulation is 50 cm of blown-in glassfibre.

The other feature of this building is quality control. The idea is that there are vast numbers of minor construction flaws that contribute to excessive air leakage and unwanted heat loss. If only these flaws could be prevented, then the building could use less heat than an identical building constructed with normal levels of watchfulness. Another aspect of quality control was extra education of the construction workers and extra inspections by thermography and pressurization tests.

The heating system uses hydronic radiators, and ventilation is from a balanced supply-exhaust system with an air-to-air heat exchanger.

EXPERIENCES DURING THE FIRST YEAR

Kejsaren: The building techniques employed - standard cellular concrete wall blocks - are relatively well-known and uncomplicated. There have been few problems in this area. With hindsight it is possible to identify avoidable thermal bridges where the balconies are attached to the walls. The solar collector is an integrated part of the roof, an interesting solution. The solar collector forms the weather shield, so that the extra costs of the collector are somewhat offset by reduced costs for the roof. The attic is ventilated, so that the underside of the collector should have been insulated; this insulation was accidentally omitted, and was installed later. Pressure testing of the apartments at 50 Pa revealed no systematic air leakage; the building is quite airtight. Most of the apartments tested were below 0.5 ach at 50 Pa.

In contrast to the shell construction, the solar hot water and ventilation system is extremely complicated and has suffered from a number of problems. Many of the components have not been able to meet the designer's specifications: dampers tend to leak, the airflow is difficult to regulate, the control system program contained fatal errors, the fan-coil units have proved to be intolerably noisy. There were also a number of design flaws in the solar system; an extra fan had to be added to overcome the collector pressure drop, and water was found to flow in the wrong direction in some of the pipes in the hot water storage system.

Both air distribution systems - ceiling or floor registers - seem to give comfortable conditions in the apartments. However, the ceiling ducts and their associated registers are much easier and cheaper to install than the floor systems.

Except for periods when the main ventilation fan failed, the HVAC (heating ventilation and air-conditioning) system has maintained comfortable conditions in the building. This has been possible, despite faults in the system, because there is a back-up system which provides heat from the district heating main when the solar system fails. Unfortunately, this tends to conceal any failures from the building maintenance personnel.

One important conclusion from this experimental building is that such a complicated system requires careful operation and a well-designed control system. It also needs well-trained personnel for operation and maintenance. It may not be economic to provide such personnel in a small building.

<u>Konsolen</u>: Except for the solar walls described above, the construction techniques used in Konsolen are conventional. The walls consist of pre-cast heavy concrete elements. To ensure good airtightness and to avoid thermal bridges, it was found to be important that the edges of the elements had been cleaned off and that there was a good seal wherever pipes and ducts ran between apartments. The only other construction detail that could be improved is the foundation insulation at the corners of the building.

There have been a number of problems with the exhaust air heat pump: the freeze protection set point was too high, so the heat pump was often turned off; the evaporator heat exchanger was too small and had to be replaced; and a time-clock was wired wrongly, and turned off the heat pump at night. Even after these problems were corrected, the daily average coefficient of performance (COP) has been as low as 2.1, whereas a value of 2.9 was used in design calculations. The electrical input has been close to the design value, but the output has been nearer 46 kW than the expected 56 kW. One other difficulty is that there have been continual complaints about noise from the heat pump. Further attempts will be made to improve the COP.

The flap valves which control airflow from the solar walls have caused some problems. They are not well designed, difficult to operate, and do not seal tightly. Another minor difficultly with the solar walls is that in extremely cold weather, cold air tends to spill down onto the floor instead of being warmed and rising behind the radiators. However, in general this method of pre-heating ventilation supply air seems to be effective, though some development of the ducts and vent openings is clearly necessary to avoid draughts.

The high thermal mass has not caused any difficulties. However, we have not yet carried out any analysis to determine whether it reduced peak power demand or stored energy during the swing periods. The building control system is a standard off-the-shelf unit, and the building temperature is not deliberately varied to make use of free heat. The average temperature of the building is very stable at about 22 C in the winter. However, there has been a wide spread of measured apartment air temperatures, and a large variation of temperature with time. This phenomenon is described in more detail below.

Sjuksköterskan: This building has a very simple design strategy: very thick insulation in walls and ceiling, and triple-glazed windows with selective coatings (design U-values 0.17, 0.12 and 1.6 W/m^2-C respectively). However, there have been a number of problems with construction details, and the performance of the thermal insulation is well below expectations. The reasons for this are not known, although a number of minor construction flaws have been detected.

Thermography revealed a number of areas where the air barrier was discontinuous. Typical sites were window and door frames. As far as possible, these leakage sites have been fixed.

The thermal resistance of the ceiling and external walls has been measured by hot-box techniques and by heat-flow meters, and the ceiling value appears to be much lower than expected. However, it is extremely difficult to make in-situ measurements of such high thermal resistances and so there is still uncertainty about the magnitude of the discrepancy between theory and practice. It is not known whether or not the measured low value is real, and if so whether it is caused by convection or radiation within the insulation, or by moisture escaping from the concrete, or by something else. The lightweight walls seem to work well.

City planning requirements demanded that the roof pitch be very low. As a consequence, there is no access within the attic to ventilation ducts and mixing boxes. Therefore there are about 45 roof hatches to permit access for adjustment of the ventilation system components. These hatches present potential sites for water leakage, and there is a risk that they will be left open after attic inspections. Indeed, this has already occured.

EXPERIENCES IN ENERGY USE

The Stockholm project buildings all include unique features, many of which are difficult to model analytically. However, two independent simulations (BRIS and DEROB) (Isfält et al., 1986) of the energy use in the Stockholm Project buildings were made. These simulations give a good idea of the expected energy use of the buildings in 1971 Stockholm weather. The simulations are also used to estimate some of the difficult-to-measure energy inputs (such as metabolic gains) and losses (such as transmission).

The energy balance for Konsolen will be examined in detail below. It follows a general model for the whole Stockholm Project (Hambraeus and Werner, 1985). The values of the input parameters are known to various degrees of assurance since they come from several different sources. Some parameters are based on direct measurements, and some are either based on the BRIS and DEROB simulations or use the same assumptions as those simulations did. Some of the values based on the simulations have been corrected for the outdoor temperture for 1985, but most of them have been used direct. The energy is given per square meter of heated floor area. This area includes the basement, laundry, hobby room and stairways, since these are all heated to 20 C or higher. Heated area is 5336 m^2, apartment area is 4143 m^2 and gross area is 5831 m^2.

Energy Inputs

The bought energy, perhaps the most interesting part of the balance, is measured as follows. District Heating is measured as the total energy suplied by the utility with a possible error of 5%. Electrical Energy is measured with normal electric meters, with a possible error of less than 2 % . Electricity losses are fictitious losses added to make the simulations balance in summer. Since we neither calculate solar gains nor deliberate ventilation losses in summer, this entry is useful only as a comparison with the simulations.

On the input side of the energy balance there are some energies we do not have to pay for. Heat Recovered from ventilation by the heat-pump, is measured as the energy delivered by the heat-pump minus the electric energy to the heat-pump. The error in this measurements is estimated to be less than 5 % . Solar gain from both the solar walls and through windows is estimated on basis of the two simulations. The percentage error in these two items can be thus very large. However, that contributes very little to overall error since the solar gain in the heating season is so small as a percentage of total energy input to the building. Metabolic heat is also estimated on basis of the two simulations, which used estimated occupancy figures.

Energy Outputs (Losses).

Grey Water Losses are calculated from the measured total cold water usage and the difference between the temperature of incoming cold water and the temperature of the outgoing grey water. We assume that all water entering the building leaves as grey water. The error is estimated as less than 15 %. Ventilation losses are measured before the recovery unit (to avoid double counting), and the error (primarily from air flow measurement) is estimated as less than 10 %. Air leakage out from the Konsolen building is assumed not to occur during the heating season, because the building is kept at about 10 to 20 Pa below atmospheric pressure by the exhaust air system. There may be leakage out of the building if people have their windows wide open. Transmission losses are the values from the simulations, adjusted for the actual indoor-outdoor temperature difference.

Figure 1 shows the energy balance for January 1 to December 31, 1985. The left-hand columns show inputs, the right-hand columns outputs. It can be seen that the input is usually greater than the output. We think one reason for this is that transmission losses are underestimated. In the simulations, little attention was paid to the influence of thermal bridges, which can contribute quite a significant proportion to the losses in such a well insulated building. Note that the first three sections of the input column are the bought energy: district heating, electricity for the heat pump and electricity for all other uses. The measured annual totals were 68, 29, and 44 kWh/m^2 respectively.

Table II shows some of the reasons why total bought energy use, 141 kWh/m2-year, was greater than predicted by the simulations. BRIS and DEROB gave 98 and 86 kWh/m2-year respectively.

TABLE II

Causes of unexpectedly high energy bills in Konsolen, 1985.

Cause	Estimated Effect %	Reparable	Repaired March 86
Outdoor temperature: 1985 colder than 1971	5	No	No
Indoor temperature: 22 C instead of 20 C	5	Possibly	No
Heat pump run-time: Intermittent operation Jan-Mar	1.5	Yes	Yes
Heat Pump COP 2.1 instead of 2.9	5	Possibly	No

If adjustments shown in Table II are made, then the difference between actual and predicted energy use is acceptably small. Even if energy use is a little higher than expected, the results still illustrate that it is possible to produce buildings whose energy demand is much lower than that of conventional modern buildings. There must be a shakedown period during which the HVAC system and its controls can be carefully adjusted. However, there still may be problems maintaining comfort at low air temperatures, as detailed in the next section.

TEMPERATURE DISTRIBUTIONS

It can be seen from Table 2 that one of the most important factors for the discrepancy between the simulation and the measurement is the indoor temperature, approximately 2 C higher than assumed. When the simulations were made it was assumed that it would be possible it maintain the buildings uniformly at 20 C. (In Sjukskötertskan it was hoped that the expected high mean radiant temperature might make it possible to lower the temperature below 20 C while maintaining comfort.) However, experience has shown that all three buildings tend to be kept at between 21.5 and 22.5 C on average, with a spread of about 3 C or more between the hottest and the coldest apartments. This has clearly increased heating energy use. Once again, no precise simulation of the effect can be made; the temperature distribution is rather non-uniform, and varies considerably with time. This is a matter of some concern, since one of the aims of the project was to build comfortable apartments (Jägbeck 1985). A separate study is being carried out by the City of Stockholm to elucidate the occupants´ opinions on all aspects of the buildings.

The variation is much the same in all three buildings, but since all apartments had temperature sensors in Konsolen, it was decided to attack the problem there. Figure 2(a) shows the distribution of average apartment temperatures for the period October 1 to 14, 1985. The hotest apartment had an average temperature of over 24 C, while the coldest had almost 21 C. The building is heated by a hydronic radiator system, and all radiators have thermostatic valves factory-set for a maximum of 21C.

It should be kept in mind that the temperature is an average value of air temperature from a shielded sensor 1.7 m above floor level. The temperature varies by about 1 C each day because of occupant activities and solar gain, and over a period of days there may also be a slow variation of up to 2 C above and below the mean value.

Figure 2(b) shows average temperatures for the period November 1 to 14, 1985. This is not very different from Figure 2(a), despite the fact that the pressures in the radiator piping system had never been set to their design values, and were first adjusted in late October. This is a common retrofit for existing buildings, and is supposed to reduce the spread of temperatures.

The next experiment was to reduce the temperature of the water supplied to the radiators by lowering the curve which defined the supply temperature as a function of outdoor temperature. Over a period of four months this curve was lowered by over 5 C. Figure 3 shows the cumulative temperature distribution for all hourly apartment temperatures for December 1985 and January 1986. As can be seen, the curve for January is shifted down a little, and there has also been some movement of points from the coldest end of the curve. We assume this latter effect occured either because occupants turned on radiators that had previously been turned off or by a change in their ventilation habits. Finally, the temperature distribution of Figure 2(c) resulted. There is one cold apartment; the radiator valves there will be checked. There are five hot apartments. One is above the equipment room, and will always be hot. In another we suspect the temperature sensor. That leaves three outliers; if that state continues, it will probably be acceptable.

The effect of this efforts on the energy consumption is shown in Figure 4, which shows the power to the radiators as a function of outdoor temperature for two 2-week periods in November, 1985 and March, 1986. As can be seen, there has been a noticable reduction in heat demand.

It should be noted that there is still a large daily and monthly variation in temperature. It should also be noted that we have not been able to reduce the air temperature down to 20 C. It may be that it is not acceptable to reduce the air temperature of rental apartments to 20 C in Sweden. A discussion of temperatures in various types of Swedish residential buildings may be found in Widegren-Dafgård (undated).

CONCLUSION

Data has been presented which shows how three of the Stockholm project buildings performed in their shakedown year. Their performance has been much as expected: those with complicated systems have shown system problems, while those with innovative construction practices have shown problems caused by construction details. Many of these problems have been solved, and it is hoped that energy consumption in the forthcoming year will be significantly lower. Also, now that many systems problems have been dealt with, it is reasonable to expect to be able to adjust energy consumption for a standard year and for domestic electricity and hot water use.

The heating, ventilation, and domestic hot water systems in these three buildings are complex, but quite typical of modern construction which aims for low energy consumption. Our experience has shown that these systems did not at first function as designed, and that it took some time and effort to get them running optimally. This suggests that modern buildings need a well-defined commissioning procedure during which all systems can be thoroughly checked. If such a procedure had been followed in the Konsolen building, it appears likely that energy consumption would have been about 10% lower.

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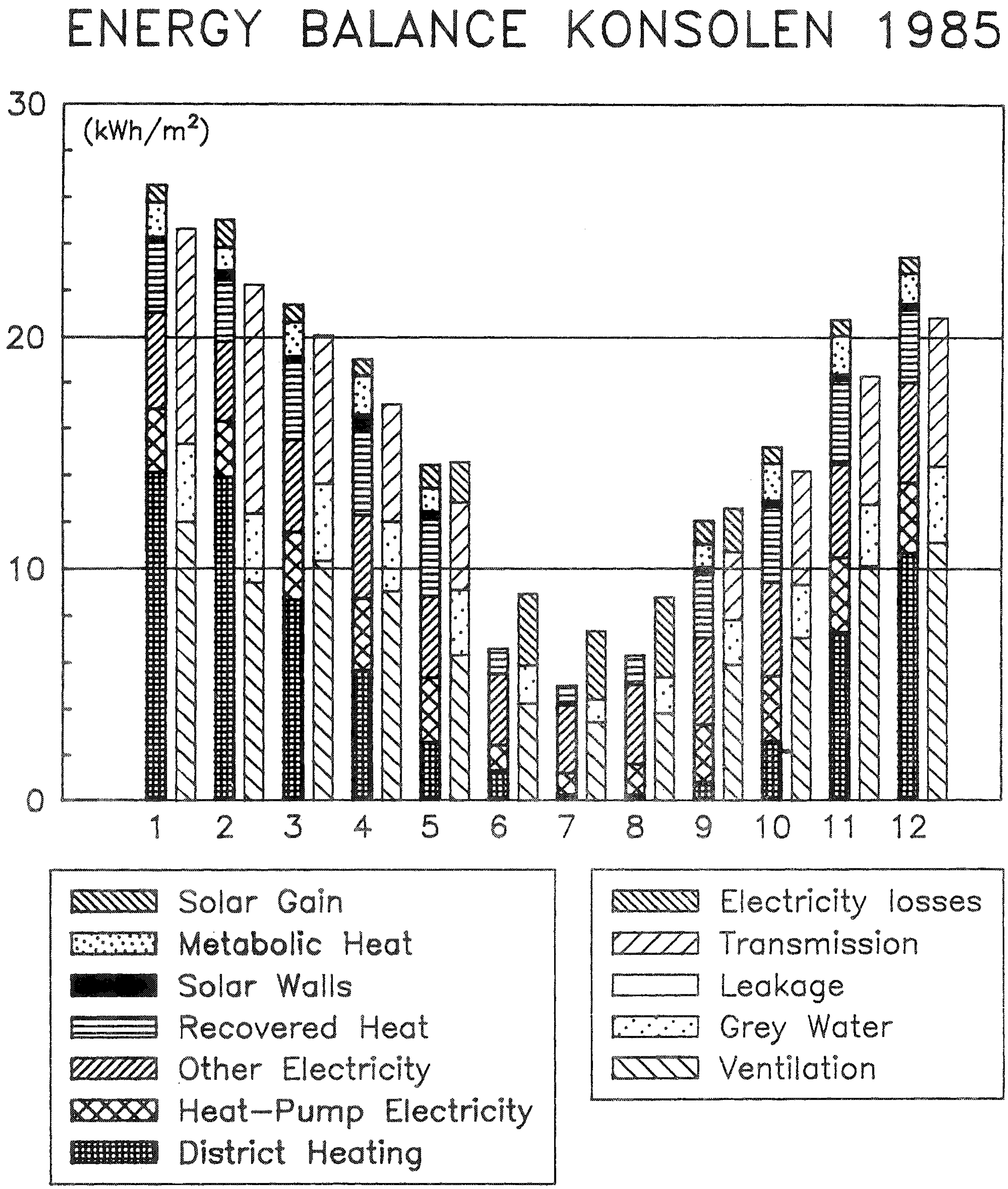

Figure 1. Energy balance for the Konsolen building for 1985. The left-hand column shows energy inputs, the right-hand column energy outputs.

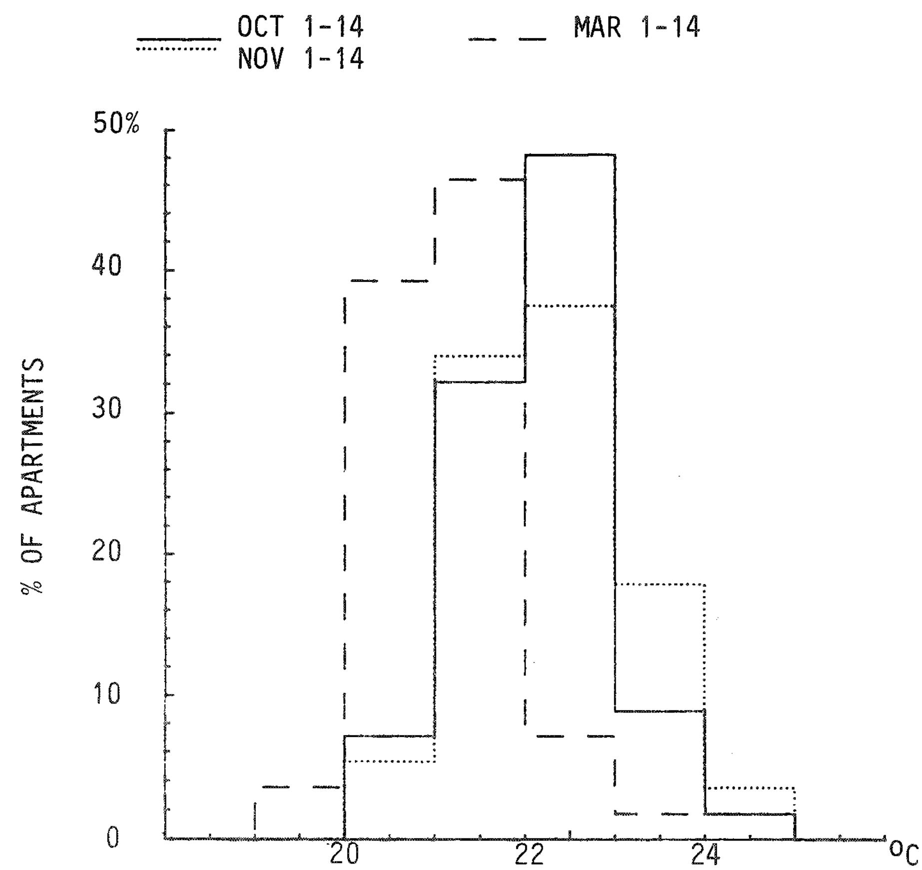

Figure 2. Frequency distributions for the average monthly apartment air temperatures for the Konsolen building for three periods. The solid curve, 2(a), is for October 1-14, 1985. The dotted curve, 2(b), is for November 1-14, 1985. Between these two periods the radiator system was "adjusted". The final curve, 2(c), is for March 1-14, 1986. Between November and March the curve which defines radiator feedwater temperature as a function of outdoor temperature was steadily lowered.

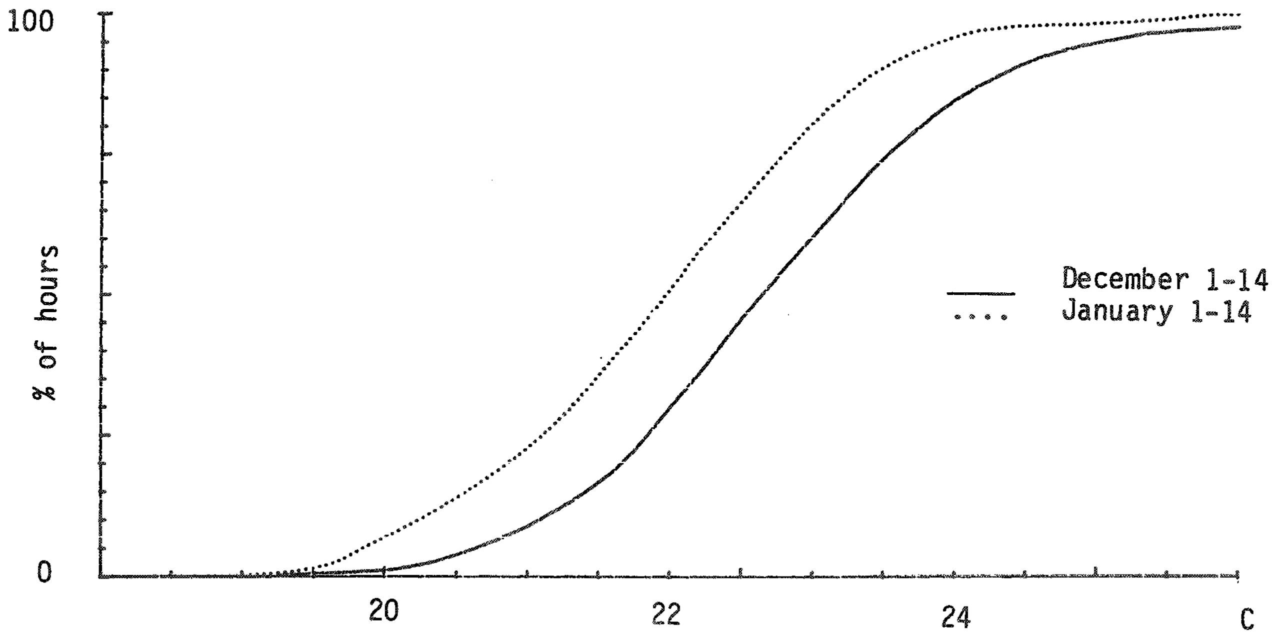

Figure 3. Distribution of hourly temperatures of all apartments in the Konsolen building for the period December 1-14, 1985, and January 1-14, 1986. In the interim, the curve which defines radiator feedwater temperature as a function of outdoor temperature was steadily lowered.

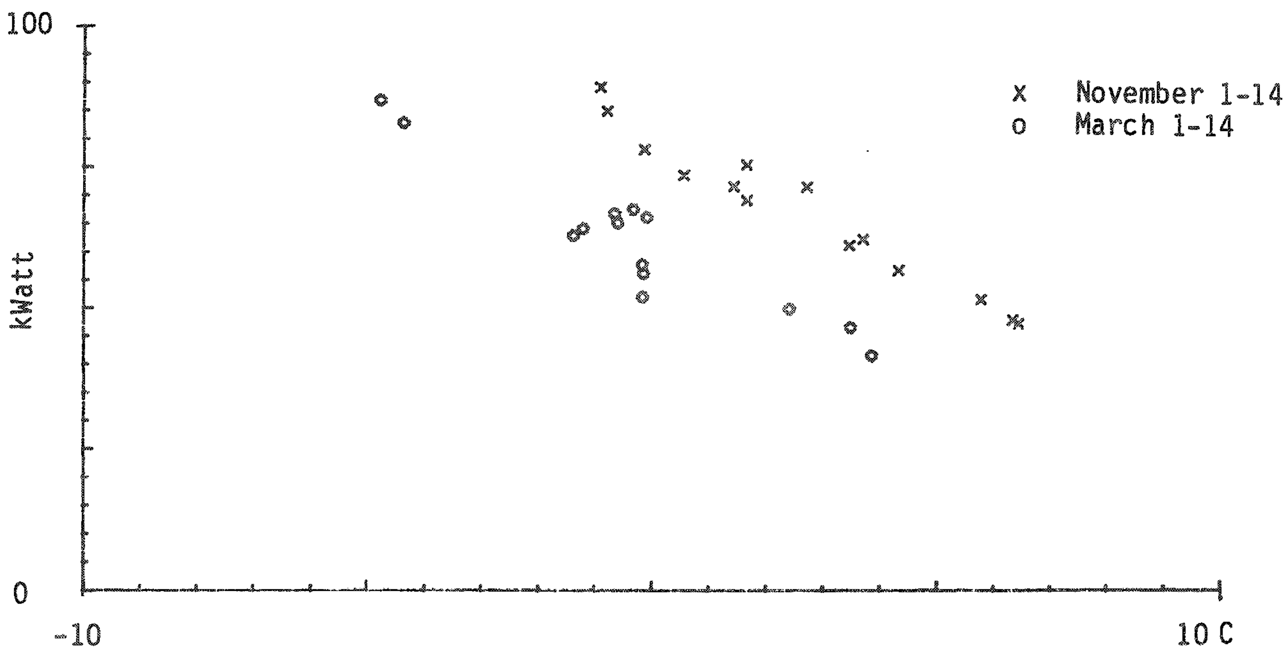

Figure 4. Daily average power to radiators in the Konsolen building as a function of daily outdoor temperature for November 1-14, 1985, and March 1-14, 1986.