Title

STORAGE OF HEAT AND COOLTH IN HOLLOW-CORE CONCRETE SLABS. SWEDISH EXPERIENCE, AND APPLICATION TO LARGE, AMERICAN-STYLE BUILDINGS

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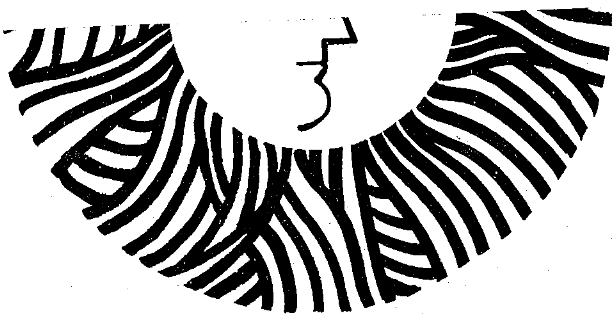

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October 26, 1979

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ABSTRACT

The Folksam office building in Farsta, near Stockholm, has operated since December 1977 with an energy use for direct space heating of only 60 kWh/m^2 [19,000 Btu/ft^2], which is only half the Stockholm average for new buildings. To this 60 kWh/m^2 must be added the typical electric use of another 60 kWh/m^2 for lights, equipment, fans, etc. Even though Stockholm has 3580 deg-day (C), new Swedish buildings are so well insulated that their temperature floats upwards during most winter working days. In the Folksam building, this surplus heat from 40 full-occupied hours per week is stored in hollow-core concrete slabs, and then is used to compensate for the heat losses during the remaining 128 unoccupied hours. The energy transport/storage system necessary to keep the indoor temperature comfortable, summer and winter, is called Thermodeck, and is described in detail.

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*Written while visiting College de France, 75005 Paris.

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I INTRODUCTION

Concrete floor slabs have a large heat capacity (100 Wh/m^{2}K - where K stands for Kelvins, i.e. degrees centigrade), but this is normally poorly coupled to the room air. In the "Thermodeck" system described in this report, the supply air is distributed via hollow cores in the floor slabs. In this way, the concrete mass is made available for the storage of heat.

Modern Swedish buildings are so well insulated that their temperature floats upwards during a typical occupied winter day, even though their buildings are relatively small by American standards, since every office must have a window.

Table I shows the net winter heat gain in modern Swedish buildings, which is 15 W/m^2 for 8 occupied hours. Figure 2 shows that in a normal office, with an insulated suspended ceiling, this 15 W/m^2 will raise the temperature to an unacceptable level within an hour or so, making it impossible to continue storing the heat gain (free energy) in the structure. But with Thermodeck, the full 8-hour heat gain can be stored with a temperature rise of about 2°C, which is readily acceptable to the occupants (1). During the winter, this stored heat is used to compensate for night losses and often even weekend losses.

During the summer, daytime heat gain is again stored in the slabs. In Stockholm, the outdoor air temperature seldom exceeds 30°C (86°F), and the minimum temperature at night is usually 18-20°C, so the slabs can be cooled by circulated night air (and thus made ready for the next morning) without the need of air conditioning. In roughly half of the U.S., nights are not cool enough to pre-cool the building, and off-peak air conditioning would still be required, but the concrete heat capacity will still handle the daytime load. Only enough peak air conditioning is needed to dry outside ventilation air. This peak load can be made negligible with a water-permeable heat exchanger (discussed in Section IV).

II THERMAL BEHAVIOR OF BUILDINGS

II.1 Computer Simulations, the BRIS Program

The temperature variations in different parts of a room effect one another in a complex manner through visible and infrared radiation, and convection. Even small temperature changes in heavy structural components store or emit large amounts of energy.

This gives rise to problems involving six or more coupled equations at each surface of space (plus diffusion through each wall), which can only then be solved by numerical methods with the aid of computers.

The use of computers in this kind of study was started at the Division of Heating and Ventilation at the Institute of Technology in Stockholm. The first example of such use dates from a 1957 study of an exterior wall exposed to solar radiation.

Since then, the BRIS program has evolved*. Today, it offers a very flexible choice of objects being simulated (2,3), and has been very well calibrated. Throughout the years it has provided a useful tool, not only in several research projects, but also in design work and in the developing of new technical systems like the Thermodeck system. These new systems have required experiments to measure different parameters for use in additional procedures in the BRIS program. This experimental work has also been performed at the Royal Institute of Technology (Division of Heating and Ventilating), supported by the Swedish Board of Technical Development.

II.2 Thermal Mass

Early studies of summer conditions utilizing simulation methods pointed to the strong influence on cooling requirements of suspended ceilings and soft carpets. Most of the heat storage capacity is concentrated in the floor/ceiling slabs. When they are insulated the room temperature becomes sensitive to heat gains or losses. Thus, a prompt compensation has to be made by extracting or supplying heat. Nevertheless, carpets and suspended ceilings have dominated building design and are a major reason why so much energy is used in buildings.

If the suspended ceiling is partly removed and less insulating carpets are used, a large storage mass becomes available. Simulations have made it clear that if the room temperature is allowed to float within a band of +/- 1-2°C, the heating or cooling requirements are radically reduced. Figure 1 shows a building floating around 22°C with two different time constants $\tau = RC = 50$ hours, or 100 hours. (Here R is the thermal resistance, C the thermal mass). We see that when τ is doubled, (from 50 to 100 hours) energy demand is reduced to zero. The calculation was made using the following assumptions:

1) In winter, since there is little sunlight in Sweden, the ambient conditions vary little during a 24-hour period.

2) In the simplified model, the solar heat gain was set to 0 and the outdoor temperature was assumed to be constant = 0°C (= average for the heating season in the middle of Sweden). The internal gains during office hours are assumed to be constant and large enough to cover the losses for the whole 24-hour period. This is roughly consistent with the 1975 Swedish building standards (see Table I).

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*With support from the Swedish Council for Building Research.

The indoor temperature is then calculated, assuming an exponential (50 or 100 hour) relaxation towards equilibrium.

Figure 1 is of course oversimplified. Its approximations have been checked with the BRIS program. This showed that for light construction (low RC values in the simplified model) the agreement was fairly good, while for the heavy construction, discrepancies were found. The simplified model assumes, among other things, that the heat transfer to the storage mass takes place without any resistance (room temperature = mass temperatures) and that the mass temperature is uniform. Reality and the BRIS program are more complicated. The heat transfer is restrained by the resistance at the surfaces, and the conduction within the mass (slab) takes place gradually. In order to obtain the necessary heat transfer during occupied hours in a conventional office building, one must accept a temperature difference between room and slabs that could lead to discomfort (i.e., too warm) at the end of the day.

In the Thermodeck system described in Section III and Figure 4, the transfer area is about doubled and the convective heat transfer is increased by forced convection in the hollow ducts. The heat transfer thus can take place with a smaller difference in temperature.

In Figure 2, four cases are shown, as modelled with this BRIS program, for the rise in air temperature during an 8-hour pulse of internal gain of 15 W/m^2. Case (a) is an office with plenum and carpet, case (b) is the same office, with Thermodeck, case (c) is a room with bare slabs and case (d) is the same bare room with the Thermodeck system.

The Folksam office building in Farsta is closer to case (d) than to case (b), but it is comforting to note that one can improve sound absorption by maintaining a rug on the floor and acoustical tile on the ceiling and still have case (b).

For design purposes, case (d) can be approximated as

$$T = \Delta T_o + \frac{W}{C_p} t, \qquad (1)$$

where $W = 15$ W/m^2 and $C_p = 120$ Wh/m^2 (Table I, note c), so

$$T = 1^\circ + 0.125 \frac{^\circ C}{\text{hour}} t. \qquad (2)$$

The ΔT_o term, (1°C), can of course be compensated for by starting the day with a 1° pre-cooled slab. The important term is the rise of 1/8°C/hour.

For case (b) -- rug plus acoustical tile -- only the offset is larger; the rate of rise is still on 1/8°C/hour.

For summer design we will later [Section IV.1] use a more conservative internal load of 40 W/m^2. The temperature equation (with a rug on the floor,half way between cases [b] and [d] is then

$$T = 3^{o} + \frac{1}{3} \times \frac{1^{o}C}{hour} t, \qquad (3)$$

giving an 8-hour rise of $8/3^{o}C = 2.667^{o}C \cong 5^{o}F$.

Agreement between calculation and measurement. Hourly temperatures outside, in an office, and at several points in the air distribution system and thermodeck, have been measured at Farsta, and used as input to the BRIS program. Calculated temperatures agree well with measured ones (within tenths of a degree).

Table I shows theoretical heat gains and losses for winter- and summer- conditions for an office module of area $10m^2$ in a new Swedish building (like the Folksam Farsta building discussed below).

The seasonal balance for winter conditions shows a net residual loss of 403-156 = 247 kWh/office or 25 kWh/m^2 [or ≅ 8000 Btu/ft^2]. Assuming heat storage for only 24 hours, and a floating temperature, this value of 25 kWh/m^2 represents the lowest possible requirement of supply heat. By contrast, if the indoor temperature is presupposed to be constant during the whole period, no heat gain could be saved from day to night. Only the part of the heat gains covering the actual losses during the office hours is then utilized. The winter losses would then equal the night losses, 403 kWh/office (40 kWh/m^2), nearly twice as much as when the storage capacity is fully utilized.

In Section III.5, we shall see that in contrast with this predicted 25 kWh/m^2, the actual use is 60 kWh/m^2, and we shall discuss this difference.

III. THE FOLKSAM OFFICE BUILDING IN FARSTA (near Stockholm)

III.1 General Facts

The Thermodeck system is installed in a new extension of an existing building, as shown in Figure 3.

Each floor is 17 m x 75 m = 1275 m^2. There are 7 floors, for a total floor space of 8800 m^2 (about 95,000 ft^2). However, on each floor, an unoccupied core of area $3400m^2$ is not conditioned, leaving $5400m^2$ of perimeter space served by Thermodeck. This is 70% of the total area.

Each office module occupies 2.4 m along the facade. Other facts are found in the notes to Table I.

Supply air: 140 m^3/hr are suppliedto each m^2 of office (70 m^3/hr through each of two diffusers). Of this, 15% is fresh air (as prescribed by the code SBN-75) and 85% is recirculated. No heat recovery from outdoor air is utilized.

Table I. Heat balance for winter and summer days in Stockholm for an office module of area 10 m^2 occupied by one person. In winter the lights + office machines average 30 W/m^2, in summer, with daylighting, only 6 W/m^2. Other characteristics are given below in the notes to the table.

	Units	Winter	Summer
Outside Temperatures			
Daytime avge.	°C	0°	20°
24-hr. avge.	°C	-3°	17°
Cold 5-day period	°C	-18°	-
Design, summer	°C	-	25°
Design, summer rel. hum.	°C	-	50%
Thermal loads for 10 m^2 (2.4 m along facade)[a]			
Winter UA(wall) x (22°C - 0°C)	Watts	-28	-
Summer UA(wall) x (30°C - 22°C)	"	-	10
UA (window)[b] x (22°C - 0°C)	"	-66	10
Solar gain through 1.5 m^2 (8-hr avge)	"	30[g]	100[f]
Lights and ofc. machines (30 W/m^2 winter)	"	300	60
1 Person (sensible heat only)	"	100	100
Controlled outside air, 20 m^3/hr, ΔT=22°	"	-146	20
Infiltration 5 m^3/hr, ΔT=25°	"	-40	-
Total during occupied hours	"	150	300
Thermal loads during unoccupied hours			
Windows and wall, from above, ΔT=25°	Watts	-100	-
Infiltration (from above) ΔT=25	"	-40	-20[e]
Total during unoccupied hours	"	-140	-
Temperature rise of concrete[c]			
Rate during occupancy	°C/hr	0.13	0.26
Rise during 8 hours	°C	1.0	2.0
Drop, over 16-hour night	°C	-1.9	d
Season heat gains: 150 W x 40 hr/wk x 26 wk		+156 kWh	e
loss: 140 W x 16 hr/day x 180 day		-403 kWh	
Season net heat loss:		247 kWh	
		= 25 kWh/m^2	
		≈ 8000 Btu/ft^2. (in English units)	

Table footnotes on next page

Footnotes for Table I

a. Office Module Dimensions 2.4 m along facade x 4.2 m deep = - 10 m^2 (= 108 ft^2). Ht = 2.7 m, Wall area = 6.5 m^2 facade minus 1.5 m^2 window = 5 m^2.
Wall insulation, 0.15 m of mineral wool
U = 0.25 W/m^2 °C (= . 044 Btu/hr ft^2 °F);

b. Triple-glazed windows. 1.5 m^2 (22% of facade area); U = 2.0 W/m^2 K (=0.35 Btu/hr ft^2 °F), UA = 3W/K

c. A Thermodeck slab of 10 m^2 weighs 4 000 kg and has a heat capacity of roughly 1 000 Wh/K. We add 20% for facade, partitions and furniture = 1 200 Wh/K. If heat conductivities were infinite, the rate of rise of room temperature would be

$$\frac{dT}{dt} = \frac{\text{heat gain}}{1\,200\ \text{Wh/K}} = \frac{150\text{W}}{1\,200\ \text{Wh/K}} = \frac{1}{8}\,\frac{{}^{o}\text{C}}{\text{hr}}.$$

Using actual simulation (Fig. 2) we see that the temperatrue rises 1 to 1.5 °C rapidly so that a gradient is set up, after which it indeed rises 1/8 °/hr.

d. During summer, night cooling of concrete comes from forced cool outside air, not just the 20 W of infiltration.

e. Summer coooling requirement of 320 W/office. In Sweden this can be supplied free by forced night ventilation through Thermodeck. If supplied by electric a/c with C.O.P. = 3.2 at 100 W_e for 500 hours/year, bill is 50 kWh/ $10m^2$.

f. Window assumed shaded in summer.

g. We assume 50 W/window on SW window + 10 on NE, avge = 30.

The primary heat energy for the supply air is hot water from the Stockholm district heating system.

To avoid a sensation of cold from the windows, a small electric radiator (100-200 W depending on window size) with an individual thermostat installed under each window. We emphasize that these radiators are only to trim the office for personal comfort and are much smaller than a conventional 400 W water-heated radiator (4).

Before we describe the Thermodeck building in detail, we point out the remarkable decrease over 15 years in energy use by Swedish buildings. The original 10,000 m^2 building was built in the early 1960's, and has averaged a need for 250 kWh/m^2 of hot water for space heat. In 1975, the new Swedish Building Norm (SBN) cut this to 180 kWh/m^2 for new buildings, and with Thermodeck it has been possible to reduce hot water use to 30 kWh/m^2. In the particular case of the Folksam Farsta building, 8800 m^2 of new Thermodeck building was added to the original hot water meter in the winter of 1978. On the other hand, the load was partly reduced because the controls in the old building were adjusted at the same time. With the floor area nearly doubled, and the winter 11% colder than average, the total hot water bill increased by only 20%! These gains are noted in Figure 7.

III.2 Design and Construction of the Thermodeck System

As in most conventional systems, the supply air is distributed in a duct along the corridor ceiling, but the Thermodeck system differs from a conventional system in one respect. As shown at the top of Figure 4, each slab is connected to this duct via one or two bends plus a damper. The air passes through the 18.5 cm-diameter hollow cores in the slab (back and forth three times) before entering the room through a diffuser. Such precast slabs are marketed in Sweden by AB Strangbetong, in America by Spiroll, Flexicore, Spandeck and Spancrete (5), and Airfloor of California markets a floor which could be used to achieve the same storage.

Most of the pressure drop takes place in the damper which is in the corridor. The noise from the damper is greatly reduced in the hollow core slab, so the noise level in the room is very low. Therefore, it is possible to reduce the area of the distribution duct (increase the air velocity) along the corridor without getting any noise problems in the office rooms. This could make it possible to reduce the height of the floor. The fan power needed to circulate air through the Thermodeck proper is only 0.15 W/m^2 (15 milliwatts/ft^2), which is 5% of the supply fan power (6).

The exhaust air system is a conventional one not affected by the Thermodeck system.

Should the Thermal Mass be used in the Supply or the Return? A dozen Thermodeck buildings have been designed or built in Sweden, all of them with the thermal storage in the supply air. But of course, the storage works equally well if used in the return air, with a conventional supply. The whole latter system is then more conventional, at least for Americans (7). The Swedish choice is cheaper and conserves more energy because it requires responsiveness on the part of the occupant. Placing the mass in the return air permits a responsive cooling system, but costs more money and energy.

The quantitative considerations are explained in Figure 2, which shows that in an office, each 100 W increase in internal gain produces a prompt 1°C rise in air temperature, followed by a slow rise of 0.1°C/hour. Thus, if a low afternoon sum comes out from behind a cloud and pours 1000 W into an office through an unshaded window, the office temperature will quickly climb 10°C unless the occupant closes a blind or pulls down a reflective shade, or unless the office is protected with automatic shading.

Conservationists will consider it an advantage that the occupant or the shading system has to respond, because this saves air conditioning; but other designers will prefer to make their HVAC systems more responsive than the occupants or the building. In this case, they will want to install office thermostats and control supply, following the same reasoning which caused the Swedish buildings already to have a small occupant controlled radiator. In any case, the considerations above show that conference room and other high-load areas will need controlled cooling.

III.3 Operation

- Winter

The supply air is preheated, if required, and is conducted through the hollow ducts in the slab before being introduced into the room. Every work-day morning, say at 0600, the fan plant is started, so that the air temperature and hence the temperature of the slab can be sensed. If the slab is too warm, the supply air temperature is lowered, and the control system, between 0600 and 0800, tries to lower the slab temperature to the proper starting value. If the slab is too cool, the supply air temperature is heated in order to establish the proper starting temperature. At 0800 the lights come on and the staff arrives, and the slab temperature is now presumed to be about 20-21°C. Depending on the local individual heat load, the room temperature will now increase gradually. Most of the offices are occupied and have a net heat gain.

Heat transport will then take place from the warmer room air to the cooler slab surface. As was seen in Figure 2, this heat transport is several times greater than that in a conventional system for the same acceptable rise in air temperature.

In an unoccupied, unlit office, heat transport will take place from the slab to the room air.

- Summer

In summer, the outdoor temperature variation (≈ 10°C) between day and night, is exploited. At night, the cool outside air cools the slab so that the next day it will both cool the warm outside air pasing through the slab, and also cool down the room directly. Buildings with reasonable heat loads do not require any conventional refrigeration equipment. The fans are kept running at night until the determined slab temperature is attained. Just as in winter, the fans are re-started at 0600 in order to monitor and control the slab temperature.

III.4 Measured Temperatures and Energy use at Farsta

Since April 1978, a few selected offices of about 10 m^2 floor area have been carefully measured (about 10 different temperatures in each room and another 10 in the air conditioning system).

Figure 5 shows a 24-hour period in a room facing SW in the summer. The outdoor air temperature varies between 12°C and 30°C and the air going into the system has about the same temperature. The supply air, after passing through the slab cores, has a much smaller variation (22.5 +/- 0.5°C) and the room temperature during office hours increases from 220°C to 23°C.

In Figure 6, temperatures from a winter week are plotted. During this period, the outdoor temperature varied between -2 and -10°C. On Friday afternoon, when the internal gains end and the fans and radiators are turned off, the indoor temperature starts to fall from 24°C. By about Monday morning, 20°C is reached. Fans are turned on (the ventilating air system runs with 100% recirculation) and the air is heated one or a few °C depending on the outdoor temperature. At 0800 Monday morning, the temperature level is still about 20°C. Each weekday the occupied offices climb 2-3°C in temperature, and empty rooms remain about 20°C. Each night the indoor temperature falls 1-2°C. By Friday afternoon, the cycle is complete.

III.4 (cont.) Measured Energy Use at Farsta, 1978

The 8800 m^2 were fully rented, and the new heating system reasonably debugged by December 1977.Table II give energy use in 1978. Note that Stockholm has 3600°C degree days (base 17°C); this corresponds to 6480°F degree days (base 62.6°F).

We note that there is poor agreement with the prediction of Table I that the building should need only 25 kWh/m^2 of office space, which is 25 x 0.77 = 17.5 kWh/m^2 of rentable space. Instead, we measured 60 kWh/m^2. The discrepancy is discussed in III.5.

TABLE II. Energy Measurements from January through December 1978. The entries are in kWh/m^2 of rentable space, of which office modules account for only 70%.

		$\frac{\text{kWh}}{\text{m}^2}$	a.
1.	Electricity		
	a. Total site electricity	90	
	b. Building use (fans, pumps, elevators	20	
	c. a-b = Tenant-metered kWh	70	
	d. Average lights, office machines	40	
	e. c-d = Electric Radiators (measured)	30	
2.	Hot water for Space Heat	30	
3.	Total Space Heat [1e + 2]	60	a.

(a) To convert kWh/m^2 to Btu, multiply by 317, i.e., the total 60 kWh/m^2 = 19,020 Btu/ft^2.

We note, nevertheless, in Table III, that the heating costs were pleasantly small, about \$0.20/ft^2 per year.

TABLE III. Annual Costs for Space Heat per m^2 of rentable space.

	a. Kroner kWh	b. kWh used	c. Annual Cost [a x b] (Kr.)
Electricity	0.20	30	6
Hot Water	0.10	30	3
Total:		60	9

NOTE: 1 Swedish Kroner is \$0.23, so Kr/m^2 is about \$0.20/ft^2, or \$20.00/office/year.

III.5 Corrections and Excuses

Table I predicted a seasonal heating requirement of 25 kWh/m^2 of office which is 17.5 kWh/m^2 of rentable space (see Section III.1). Table II shows that 60 kWh/m^2 were actually used. We shall now explain half of the discrepancy by making several real world corrections.

	kWh/m^2
1. The prediction of table I was:	17.5
2. Swedish experience is that 30% of the offices are unoccupied on any given weekday. This doubles the predicted demand:	17.5
3. We must correct for 2.6 weeks of vacations which adds:	4.0
4. The fans are on, outside of office hours, 3 hours/day; during this time there is leakage of fresh air into the ventilation system which accounts for another:	4.0
5. In addition, there are inevitable losses from radiators left on and heating coils through which water is circulated to avoid freezing. Coils were placed too close to outside air inlest:	?
These effects raise the prediction to at least:	43.0

So we have accounted for about 2/3 of the heat bill. The discrepancy, about 20 kWh/m^2, costs only about 3 Swedish Kroner/m^2 (\$0.07/ft^2) and is hardly worth tracking down. In practice, most of it should disappear in the second and later years of the buildings use, when the heating system controls are debugged and better adjusted.

IV. APPLICATION TO LARGE BUILDINGS IN THE U.S. AND CANADA

American buildings are larger than Swedish ones. In the winter it is then attractive to use Thermodeck to transport heat from a warm core to a cold perimeter.

In addition, the cooling season is longer, and much of the U.S. is not blessed with cool nights, so we must discuss off-peak air conditioning.

IV.1 Cooling

For American cooling demand, we shall assume an internal gain from lights, people, and office equipment of 4 W/ft = 40 W/m^2. Equation 2 then gives a temperature rise of 1/3°C/hour, or, in 8 hours, 2.677°C - 5°F. Over this 8 hours, most office workers will readily accept this rise.

General space/building cooling can then be deferred until evening, when it is free roughly half of the time in the U.S., and requires only off-peak chillers for the less fortunate.

Of course, some daytime cooling may be needed to dry required fresh air. On a warm Miami afternoon, for example, 10 m^3/hour (6 cfm) of fresh air per person represents a drying/cooling load of ≅ 150 W (thermal) per person. The 150 W can be further reduced to 40 W/person by installing a permeable air-to-air heat exchanger, e.g., the Lossnay unit marketed by Mitsubishi. With a chiller with a coefficient of performance of 3, electric power is then a negligible 15 W/person.

By deferring the need for air conditioning to nights and weekends, the builders can install smaller chillers, which can run 12 hours overnight, instead of 8 hours during the weekday.

The building manager can avoid peak power charges for air conditioning. (For every kilowatt of lights and equipment, chillers with a C.O.P. of 3 normally demand another 330 watts).

The local electric utility can defer investing in new power plants and transmission and distribution equipment. This saving is eventually a saving to society. If it is a gas-turbine peaking plant that is deferred, we defer investing $500/kW. If it is a new base-load plant, we save about $2000/kW of reliable power available at the customer's meter.

And the country saves energy by deferring necessary cooling until evening, since both chillers and cooling towers are then more efficient, and base-load plants consume only 11,000 Btu/kWh, contrasted with 15,000 - 18,000 Btu/kWh required by a gas turbine.

IV.2 Heating

As compared with new Swedish buildings, new American buildings have higher losses, mainly because windows are at best double glazed (triple glazing is required in Sweden), and the area of the windows (22% of the floor area at Farsta) may be larger in America. Further, new Swedish building practices have reduced uncontrolled infiltration to the range 0.2 to 0.3 air changes per hour; we do not know if current American practice is that good. But solar heat gains may be much larger in America. (A few cloudy hours of daylight during January and February in Sweden cannot give much heat!) Hence, even a small "conventional" Thermodeck building in the U.S. can store daytime gain and then heat the building the next morning or next week, just as in Sweden.

But we can do even better by connecting up the Thermodeck cores so that energy can be transferred directly from hot offices to cold ones. In a small building, without a core zone, this means that the difference in a temperature between offices on the south and north is evened out. Indeed, Thermodeck capacity for horizontal heat transfer is so great that it permits putting large windows on the south facade, and distributing the "passive solar" gain around the building.

If the building has an occupied central core, with offices, lights, and equipment, then in theory, it should be able to weather the coldest American winter without using any central plant energy directly for heating. Table II already showed us that the Folksam Farsta building (with no core offices) generated internally about half of the energy required to make up all losses. If we consider a building where half the area is occupied core, we double the gains per unit loss; further, we have already pointed out that hollow-core concrete slabs are good horizontal conductors, so we can transport the heat from the core to wherever it is needed on the perimeter.

V. WINDOWS AS AIR COLLECTORS

In Sweden, about 500 "exhaust-air" windows are sold annually. These are triple glazed windows, with a black/silver venetian blind mounted in the air space between two of the panes. In winter, the blind, black side out, acts as a collector. The air space around the blind has duct connections above and below, permitting air warmed by the blind to flow up into the wall. Several buildings have now been designed combining the exhaust air window with Thermodeck storage. We then have a solar heated building where the windows serve as air collectors and the floor slabs are the storage media.

VI. RESIDENTIAL BUILDINGS

In Sweden, Thermodeck does not look very attractive for apartment buildings. Internal loads are low (so there is less energy to store in winter), and air-conditioning is not needed in summer.

In America, it has been used successfully in the Iowa home of L. Hodges (8). Residential internal loads are still low, but can be supplemented with direct solar gain, or with air-collector windows; and the large, well-coupled thermal mass means that air conditioning can be avoided entirely in the West and North, and moved off-peak elsewhere.

VII. ECONOMICS

Since hollow-core precast concrete is already widely used, its cost is clearly competitive with other methods of construction (7). Furthermore, it costs about the same to cuple the cores to corridor ducts as it does to install horizontal distribution ducts. But the Thermodeck system permits a smaller HVAC system, thus reducing first cost.

Table IV gives some average costs of a Swedish office block. We see that Thermodeck is estimated to be about 10% cheaper in life-cycle cost, taking into account building costs plus space conditioning. Similiar considerations for U.S. buildings are given in reference 7.

TABLE IV. Average costs of a Swedish Office Building. Taken from studies by Bahkco and Strångbetong.

	a	b
	Conventional ($\$/m^2$)	Thermodeck ($\$/m^2$)
1. First cost	500	470
2. Annual Heating ($\$/m^2$)	(2.5)	(1.5)
3. Present Value[c] of Annual Heating	25	15
4. Life-Cycle Cost (1 + 3)	525	485

(a) Includes air conditioning and 400 W hot water radiators

(b) Includes only 100 or 200 W electric radiators

(c) We assume that (interest) - (fuel escalation) = 10% per year

In Figure 7, we compare space heat, and site electricity for other purposes, used by the Farsta Thermodeck building, with use by existing office stock in three countries, and with use by the average new Swedish office building conforming with the modern SBN 75 (Swedish Building Norm, 1975). The line between Swedish stock and SBN 75, labelled $\$20/m^2$, indicates that the new buildings cost $\$20/m^2$ more than the pre-1975 designs, and there is no additional first cost for the Thermodeck design.

For comparison with U.S. buildings, in addition to the U.S. stock line, we include the line at the top of the figure, labelled "A.D. Little Study". This corresponds to the calculated use (9) of a 1970-style office building in Omaha, built and operated energy-intensively. Energy use of the same building was then recalculated (9) to conform to ASHRAE voluntary standard 90-75, and the result is replotted much lower, indicating a 2/3 reduction in space heat, and a smaller reduction in electricity, for no increase in first cost.

We conclude from Figure 3 that rapid, universal progress is being made in designing more efficient office buildings, and that Thermodeck buildings are leaders in this progress.

IX. ACKNOWLEDGEMENTS

One of us (A. H. Rosenfeld) worked on this paper while visiting the College de France in Paris. We gratefully acknowledge the support of CNRS through IN2P3, the hospitality of Prof. Marcel Froissart, the assistance of Dr. Michel Rodot and Groupe "RAMSES" (Orsay), of the Solar Department (PIRDES) of CNRS, and a fellowship from the U.S. National Science Foundation.

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1) Berglund and Gonzales, "Human Response to Temperature Drifts", ASHRAE Journal, August 1978.

2) Brown, G "Simulation by Digital Computer Program of the Temperature Variation in a Room". Proceedings of the First Symposium on the Use of Computers for Environmental Engineering related to Buildings. National Bureau of Standards, U.S. Government Printing Office, Washington, D.C. (1971)

3) Isfalt, E.,Punttila, A. and Rodseth, A, "Investigation of Three Computer Programs for Calculation of Indoor Climate". Royal Institute of Technology, Department of Heating And Ventilating. Stockholm A4-Series nr 9 (1977)

4) The radiant heat difference between the conventional 400 W radiator and the 100 W "trimmer" is supplied by the warm floor and ceiling slabs.

5) Precast, prestressed hollow-core slabs are marketed in many countries. Of the ten buildings which are now completed or under construction in Sweden, all but two use precast hollow-core slabs. The other two have cast in situ floors. The Thermodeck thermal storage aspects are protected under U.S. Patent # 4,124,062.

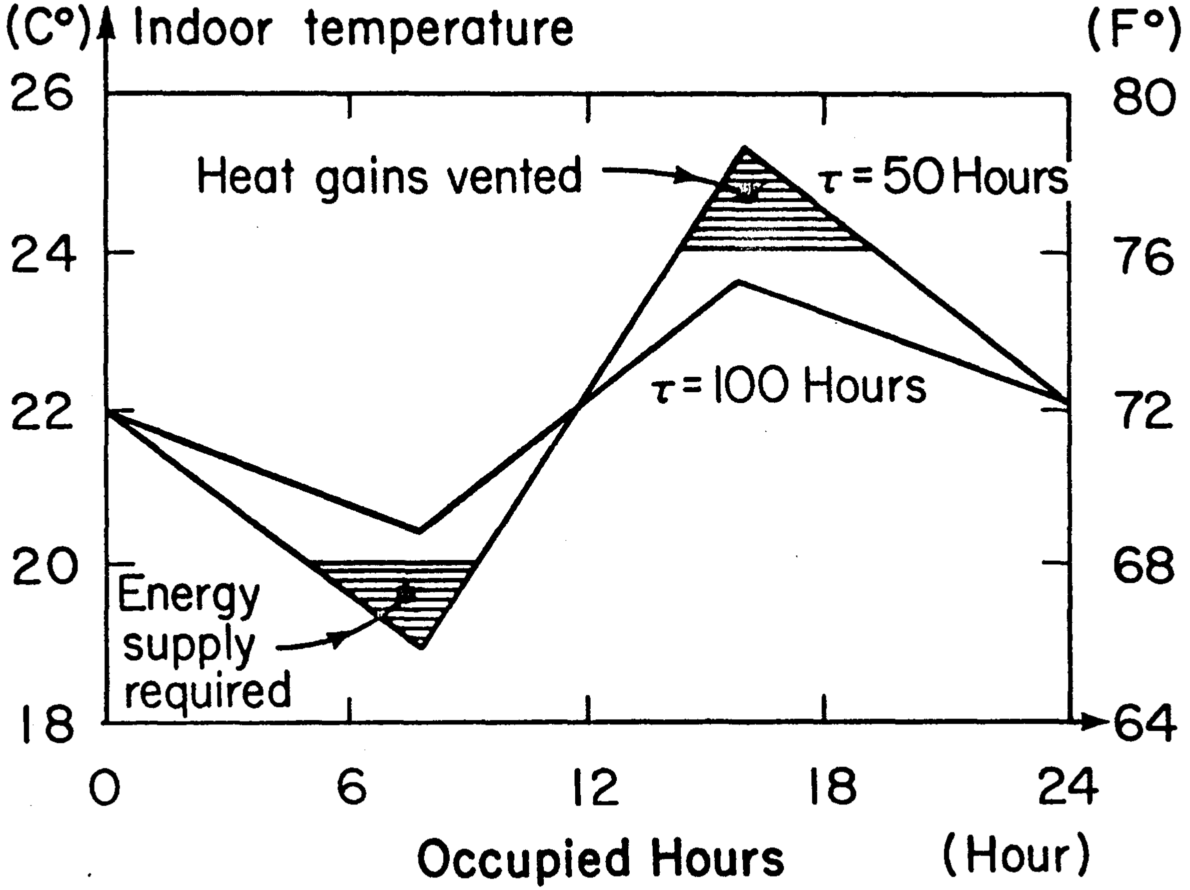
6) The following table gives supply system pressure drops and the equivalent W/m^2, assuming 140 m^3/hr of ventilation air into each 10 m^2 module (70 m^3 through each of two diffusers), i.e. 14 m^3/hr per m^2 of floor. Then Watts/m^2 = Pascals x 14/3600 = mm (water) x 14/360. We ignore motor/fan efficiency, which is actually about 60%.

	Pressure (mm-water)	Power (W/m^2)
Filter and Heating Coils	30	1.2
Dampers, Vertical and Corridor Ducts	20	0.8
Balancing dampers for each office	3	0.1
Hollow Core	3	0.1
Diffuser	3	0.1
TOTAL:	59	2.3

7) Dean, E. T. and Barnaby, C. F., "Alternatives for Utilizing The Thermal Mass of Structural Systems for Energy Conservation". Report to BEV Program, Lawrence Berkeley Laboratory, August 1979

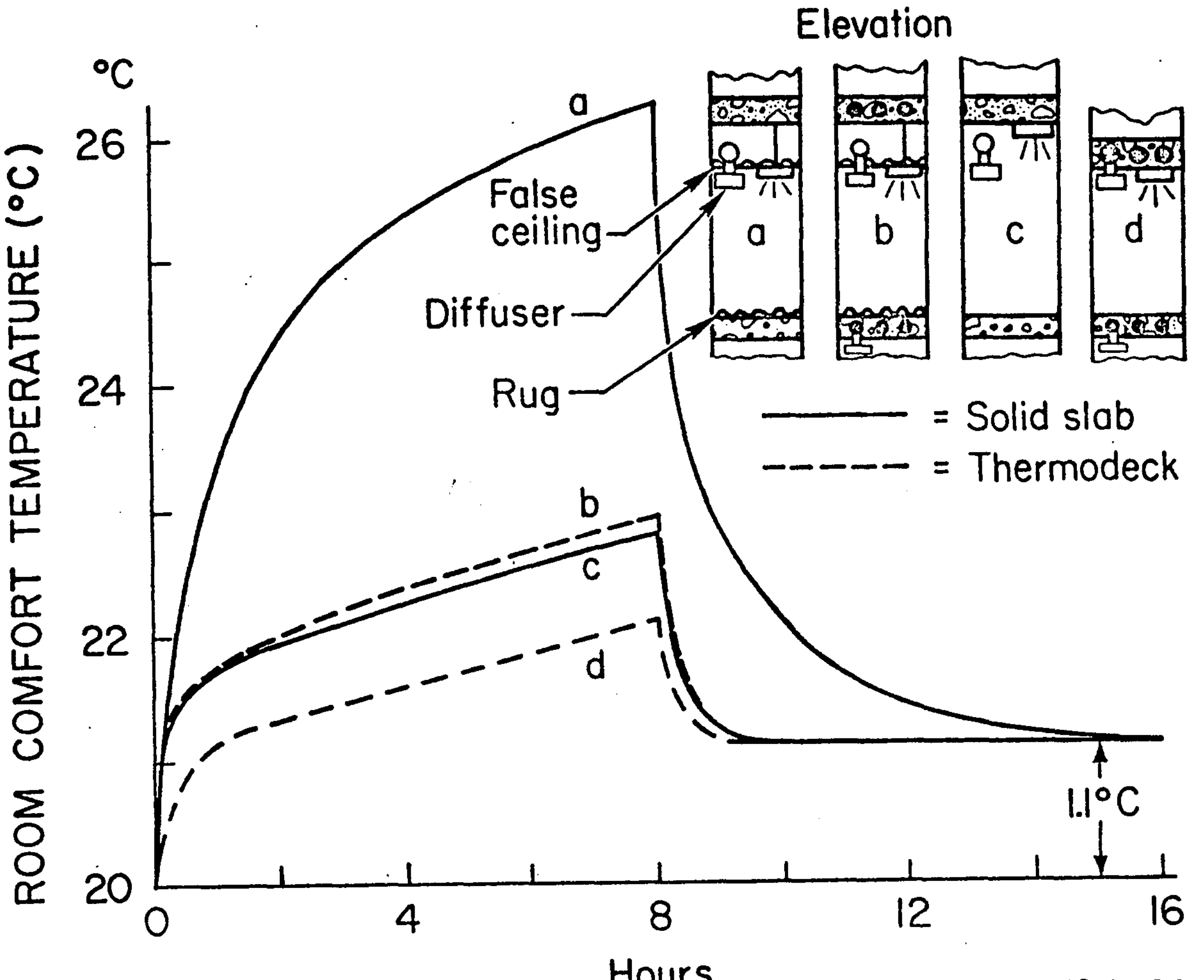
8) Block, D. A. and Hodges, L., "Use of Concrete Cored Slabs for Passive Cooling in an Iowa Residence" Proceedings of Kansas City ISES Conference, p. 488, (1979)

9) Little, A.D., "Energy Conservation in New Building Design - An Impact Assessment of ASHRAE Standard 90-75" FEA Conservation Paper 43B, FEA/D-76/078



XBL7910-13103

Fig. 1 Variation in indoor temperature T_{in} during a 24-hour period. T_{in} is calculated by a simplified model. All energy is supplied during 8 hours from internal gains. In a heavy building (τ = 100 hrs) the T_{in} range will fall within comfortable limits and no heat has to be supplied at night. If τ falls to 50 hrs, heat must be both supplied and rejected. The "straight lines" are really 50 or 100-hour exponentials.



XBL7910-13104

Fig. 2 Response/relaxation curves calculated by the BRIS-program for equal rooms with two different slabs, each with a heat capacity of 100 Wh/m^{2}K. The surroundings are assumed symmetric on all sides (as in an office in the core of a building). 15 W/m^2 of lighting (50% radiation) is turned on for the first 8 hours of each run. The cases are as follows:

a. 20-cm thick solid concrete slab, with rug, insulated, suspended ceiling, and plenum. Resistances assumed were: rug -- 0.1 (W/m^{2}K)$^{-1}$; insulated false ceiling -- o.5; plenum -- 0.17.

b. Same as a., but slab is 30 cm. thick Thermodeck.

c. 20 cm. thick concrete slab, but bare -- no rugs, suspended ceilings, plenum.

d. Same as c., but slab is 30 cm. thick Thermodeck

FIG 3

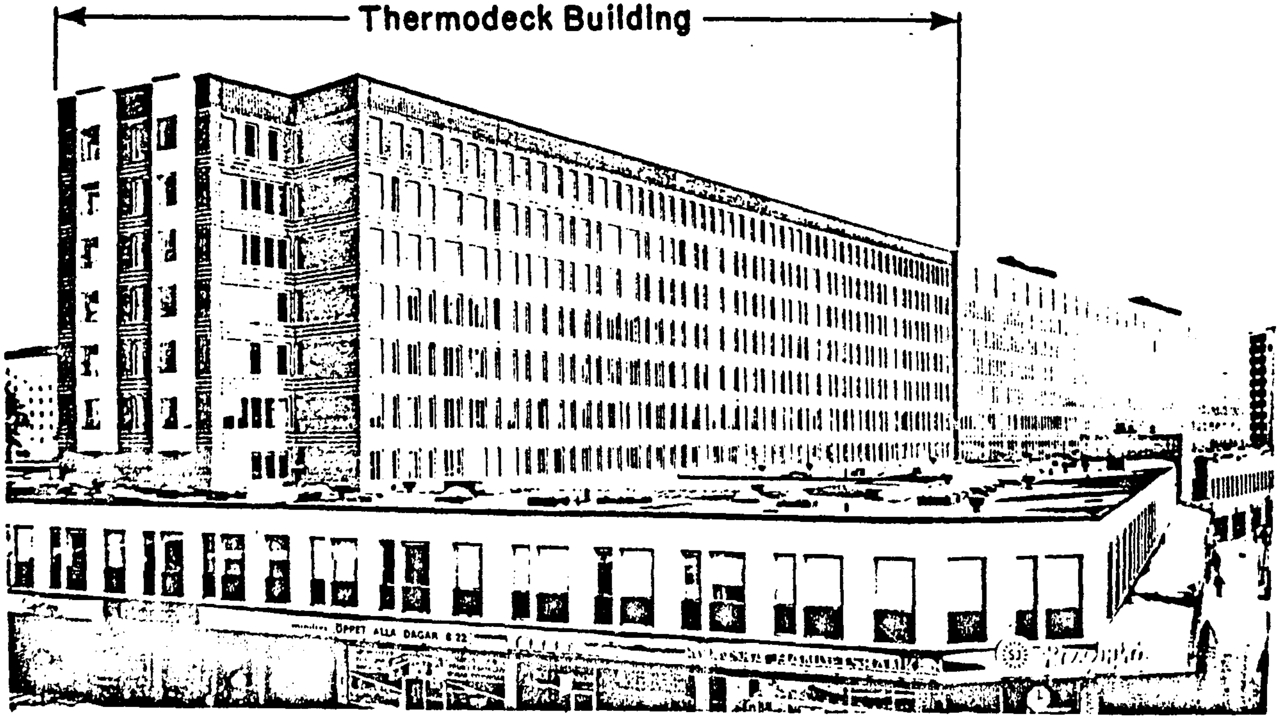
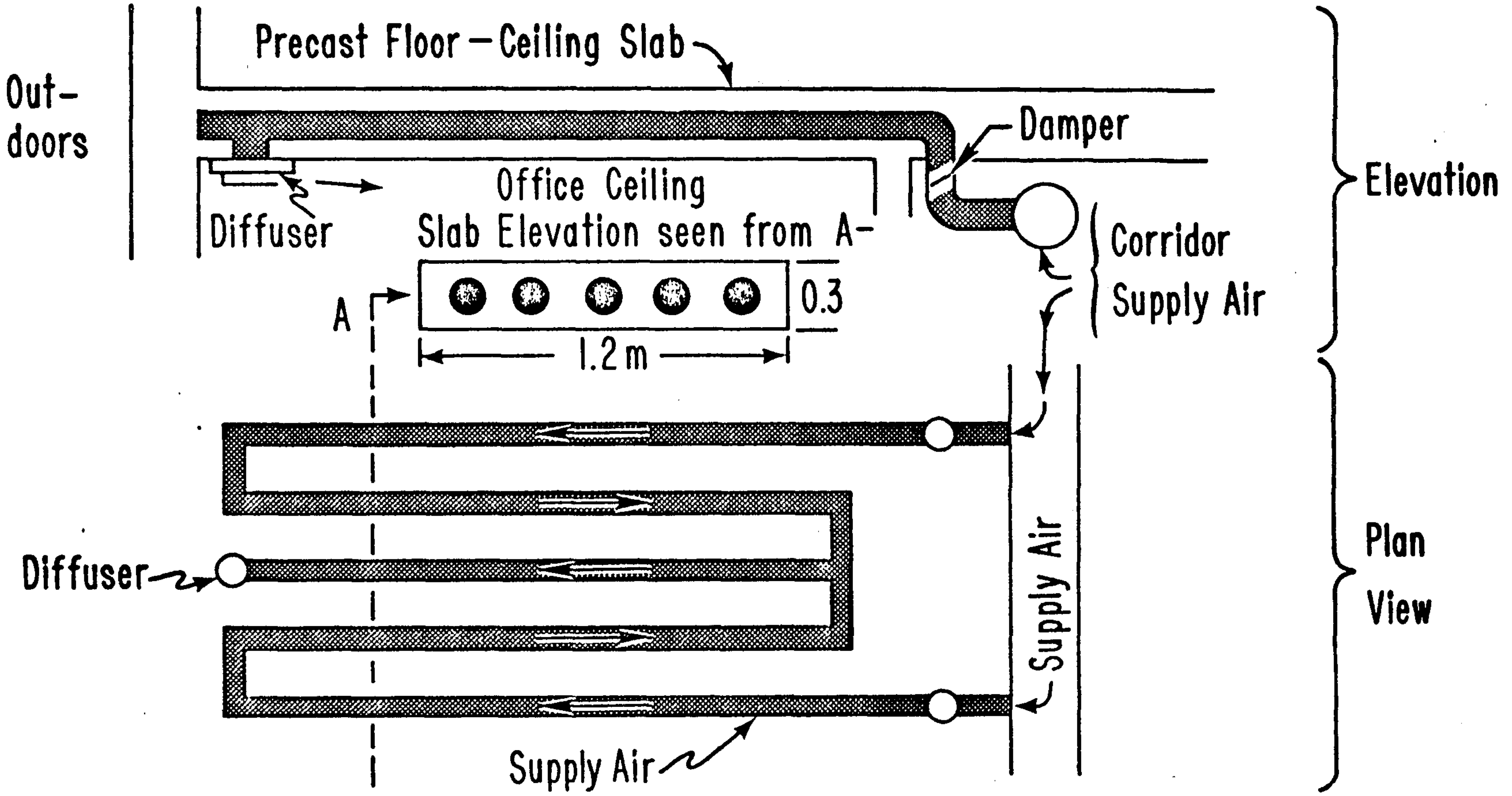


Fig. 3 The Thermodeck extension to the Folksam office building in Farsta.

FIG 4



XBL7910-13105

Fig. 4 Connections of supply air to the slab. Each 10 m^2 office module is 2 slabs wide (2.4 m) and 4.2 m deep.

FIG 5

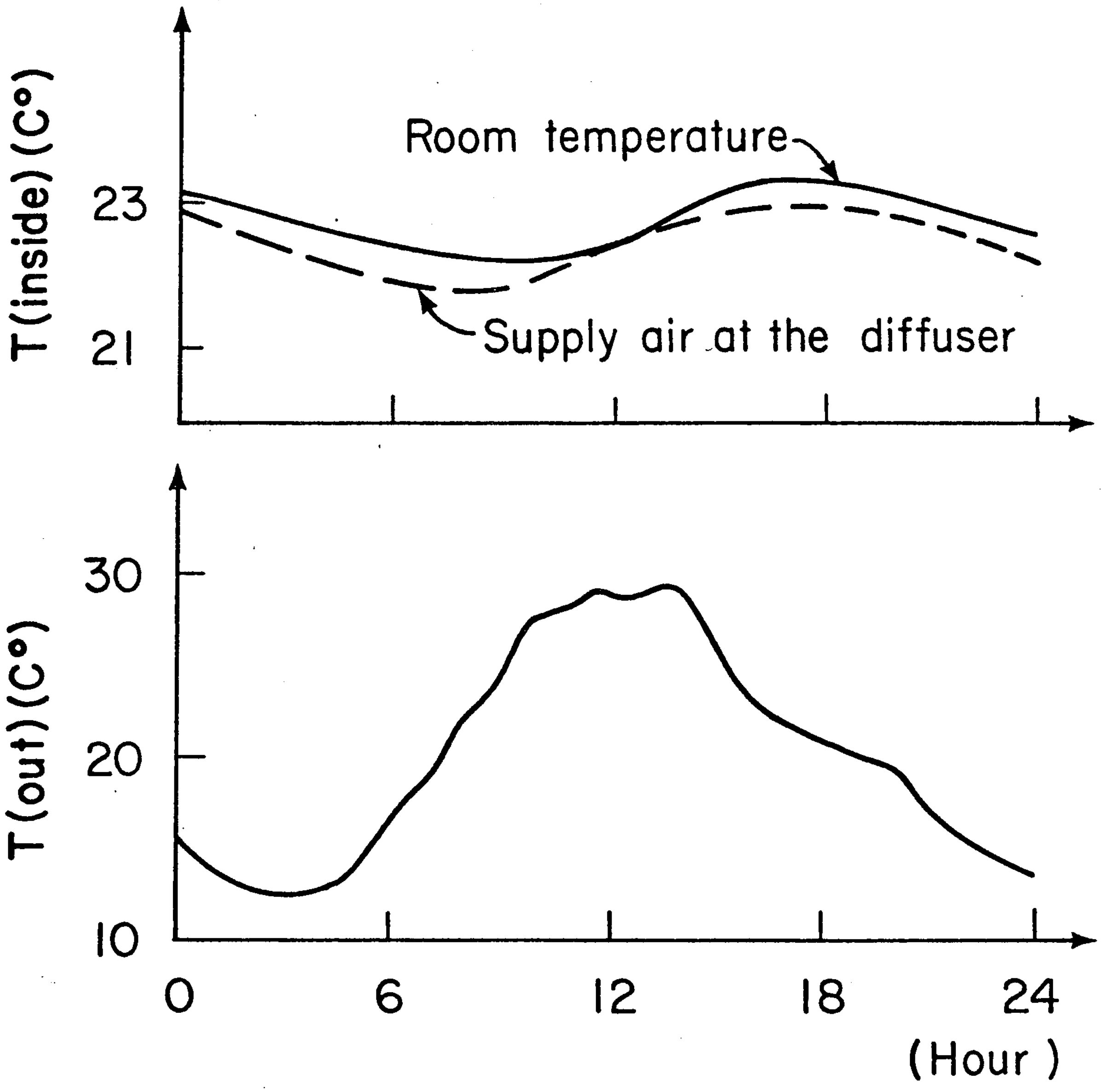


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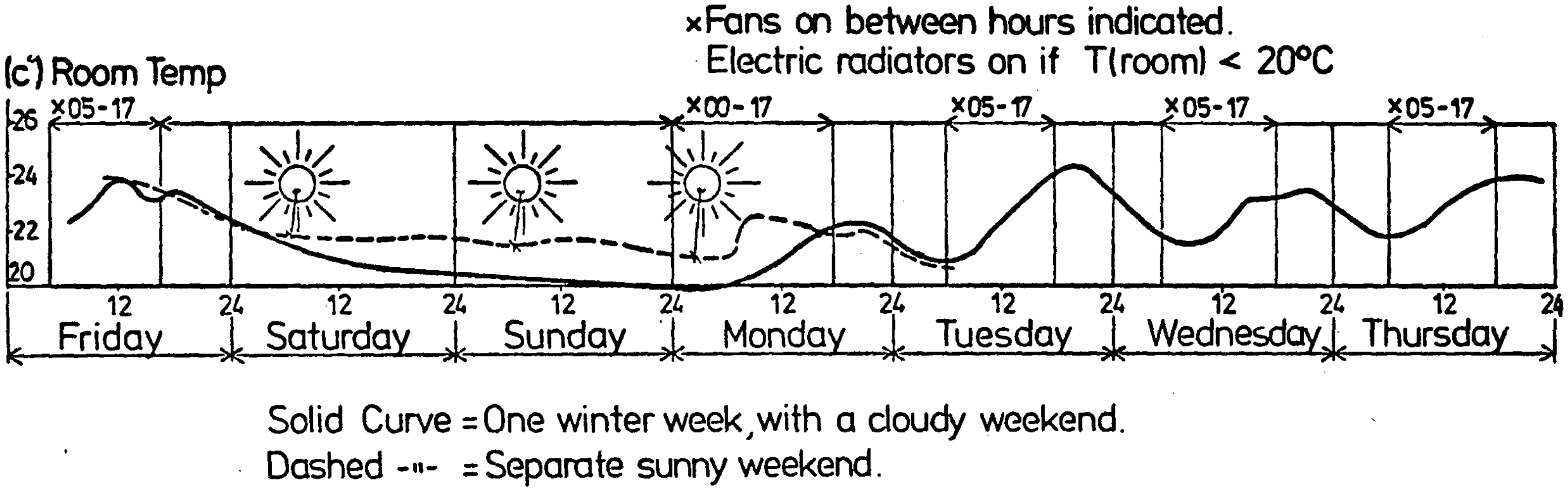
Fig. 5 Measured temperatures in a SW-facing office of 10 m^2 floor area during a summer day at the end of a 5-day period fo warm sunny weather.

FIG 6



×Fans on between hours indicated.
Electric radiators on if T(room) < 20°C

Solid Curve = One winter week, with a cloudy weekend.
Dashed -"- = Separate sunny weekend.

XBL7910-13107

Fig. 6 Measured temperatures in a NE-facing office during a winter week
T(out) varied between -2 and -10 °C.

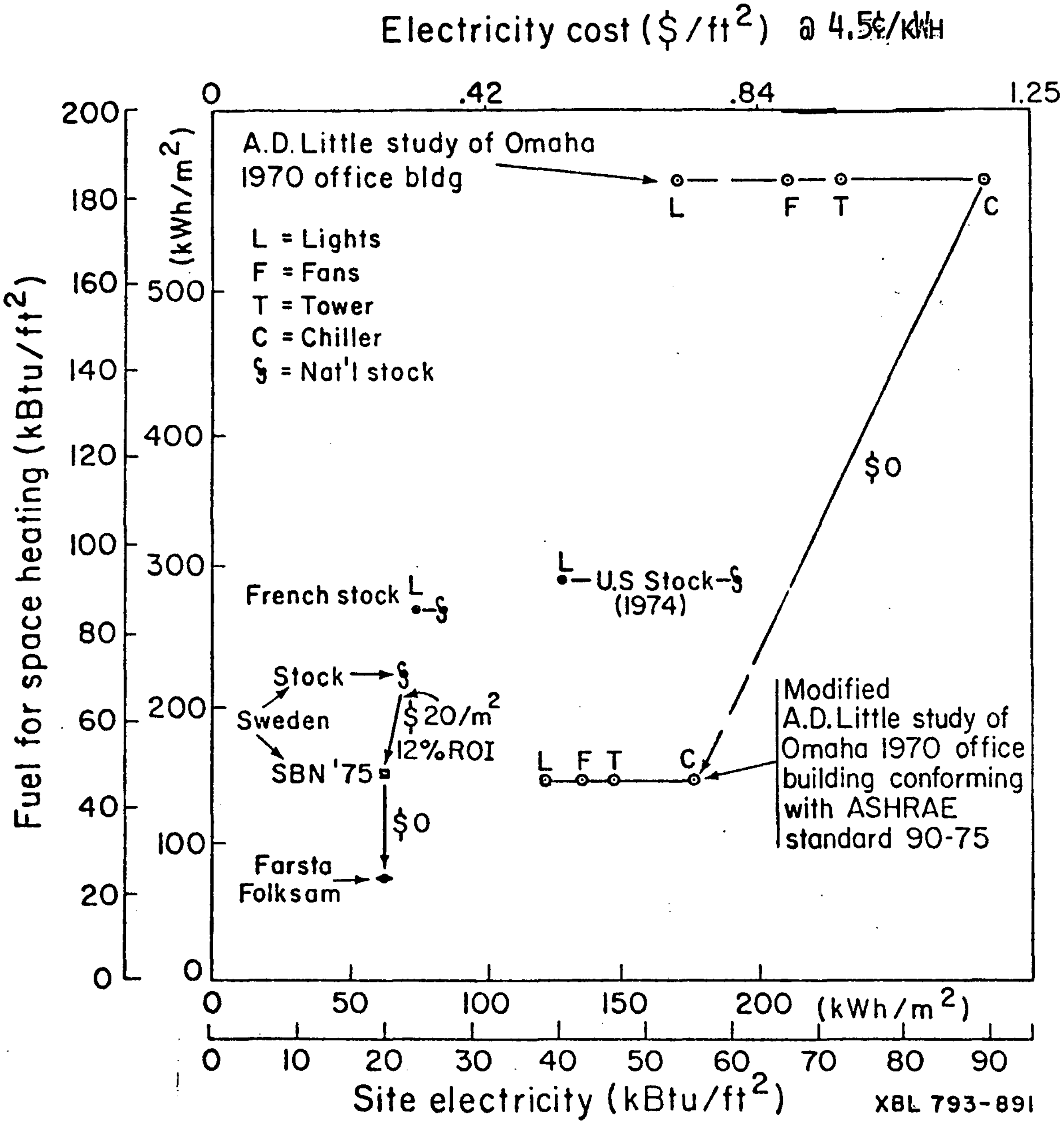


FIG. 7. ENERGY USE IN OFFICE BUILDINGS: FUEL FOR SPACE HEATING VS. SITE ELECTRICITY (I.E. 1 KWH$_E$ COUNTED AS 3600 KJ = 3414 BTU)