THERMAL PERFORMANCE OF THE NORRIS COTTON FEDERAL BUILDING IN MANCHESTER, NEW HAMPSHIRE

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ABSTRACT

The Norris Cotton Federal Office Building is a medium-size 7-story government office building of approximately 11,000 m^2 (117,000 ft^2) total floor space. It is located in Manchester, New Hampshire and has been designed to demonstrate a number of energy saving concepts.

Some of the major energy conserving features of the building are the use of solar collectors; heavy masonry construction with exterior insulation; small overall window area; heat recovery from heat pumps, chillers, a natural gas-powered engine/generator, and the ventilation system; modular boilers; thermal storage tanks; and a variety of energy conserving lighting systems.

The staff of the National Bureau of Standards (NBS) has been monitoring the performance of the building since it was occupied in September, 1976. This paper will describe the building's thermal performance for the first three years of operation. The energy consumption in the building is presented and compared to the original design goal of 625 MJ/ (m^2•year) (55kBtu/ (ft^2•year))*. The differences will be explained using the results of thermographic measurements and measurements of air exchange rates in the building along with analysis of the weather data and building operational problems that have occurred since 1976. It has been found that it is difficult to actually achieve designed-for performance in this buildings because its experimental mechanical system is unusually complex and its construction details are unconventional.

Key words: Air-cooling; air leakage; energy; heat-recovery; insulation; measurement; office-building; radiant; solar; space-heating.

INTRODUCTION

The Norris Cotton Federal Office Building (NCFOB) is a medium-sized 7-story government office building of approximately 11,000 m^2 (117,000 ft^2) total floor space. It is located in Manchester, New Hampshire and has been designed to demonstrate a number of energy saving concepts.

NBS has been involved with the NCFOB since 1973 when the building was in the design phase. Through the use of the NBS Load Determination computer program (NBSLD), a number of design options were examined and specific recommendations for conserving energy were made to the designer/architect [1,2,3]. The building was completed and occupied in September, 1976. Since that time, NBS has monitored the building's performance. The project has involved not only an analysis of building energy consumption but also a study of the effectiveness of the various lighting systems, an economic analysis of designing, building, and operating such an energy conserving building [4], and a determination of the response of the occupants to the building.

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* 1 kBtu = 1000 Btu

This paper describes the building's thermal performance over the first three years of operation. It describes the building shell and the heating, ventilating, and air conditioning (HVAC) system and discusses the way in which the equipment has been operated. Also, the results of special air and heat leakage experiments are presented. Finally, based on observed experiences, recommendations are made that may be of use in other similar projects.

BUILDING DESCRIPTION

The building shell is nearly cubical in shape, thus providing a low surface to volume ratio (See Figure 1). Its exterior walls are constructed with relatively heavy, 30 cm (12 in) thick masonry blocks which are insulated on the outside rather than inside. The insulation has a heat transfer coefficient (U value) of 0.34 W/($m^2 \cdot °C$) (0.06 Btu/($h \cdot ft^2 \cdot °F$)). This wall construction creates a thermal "flywheel" effect which reduces peak heating and cooling loads. Since windows tend to be net heat losers in northern climates, overall window area makes up only about 6% of the total exterior wall. Each window is double-glazed and surrounded on the outside by granite fins that provide shading in summer and reduce convection heat losses due to wind. The air gap between glazings is 2-3 cm (approximately 1 in) and contains a set of adjustable louvers that control solar gain and reduce convection. The windows have a U value of 3.3 W/($m^2 \cdot °C$) (0.58 Btu/($h \cdot ft^2 \cdot °F$)).

The building's mechanical system, shown schematically in Figure 2, consists of a number of interconnected subsystems. On the first three floors, various types of water-to-air heat pumps handle the heating and cooling loads. There is a total of 57 heat pumps with a combined capacity of 350 kW (1200 kBtu/h) heating and 280 kW (79 tons) cooling. In a building of this size and shape, excess heat is usually generated, even in winter, in the building's core by lights, office machines, and occupants. In conventional buildings, this heat is usually removed by ventilation or air conditioning and rejected to the outside. In the Cotton Building, core heat pumps transfer the excess heat to water which is then used by perimeter units for heating outer office areas. Thus, the only heat that must be added to a given floor is the net difference between the core cooling and the perimeter heating requirements. The core of the sixth and seventh floors and the entire fourth and fifth floors are cooled through the main ventilating ducts by a combination of outside air and air which has been cooled by a chilled water coil. Two central chillers, a 210 kW (60 ton) electric reciprocating unit and an 88 kW (25 ton) absorption machine provide the chilled water. The perimeter areas of floors 5, 6 and 7 are heated and cooled by fan coils and the fourth floor perimeter is heated by base-board finned tube radiators.

In addition to purchased electricity, other energy comes from 350 m^2 (3800 ft^2) of solar collectors; four 55 kW (187 kBtu/h) gas-fired, modular boilers; two 105 kW (360 kBtu/h) oil-fired boilers, and heat recovery from a special double-bundle condenser on the main electric chiller. Also, a 150 kVA, natural gas-powered engine/generator provides power for the electric chiller and simultaneously produces waste heat which is recovered and used to drive the absorption chiller.

Three 38 m^3 (10,000 gal) water tanks provide for thermal storage in the form of heated or chilled water. Ordinarily, the mechanical equipment would have to be sized to meet peak loads. However, by making use of the smoothing effects associated with thermal storage and heavy masonry walls, the equipment can be sized more for average loads [5].

Various types of lighting systems are used throughout the building. The fourth floor uses high pressure sodium lamps. The fifth floor uses lighting that is built into furniture and illuminates only the task areas thereby reducing "wasted" light. The remaining floors all use fluorescent lighting systems with various lamp spacings and lens arrangements.

ENERGY CONSUMPTION

Energy data for the first three years of operation have been analyzed. Figure 3 shows the gross energy consumption for this period. The bottom (dashed) line represents fuel oil consumption, the middle (dotted) line represents gas plus oil, and the top (solid) line represents electricity plus gas plus oil. Thus, the top line is the total of all purchased energy inputs while the difference between each line represents energy consumption by type. These curves have been adjusted slightly to account for differences between actual weather and design year weather as will be discussed in more detail later. The dot-dash-dot line is a plot of the actual total energy consumption without adjustments.

The curves of Figure 3 clearly demonstrate that the building's main thermal requirements occur during the winter heating seasons. More importantly, however, it can be seen that the gross energy requirements are declining. This is most readily apparent by the lower peaks associated with each successive heating and cooling season and is mainly attributed to improvements in building operation. During the first year, several minor control problems were corrected such as, simultaneous heating and cooling of a space by adjacent heat pumps, and improper set-points and adjustments in the controls. Such problems are typical of any new building; but, in this particular case, the extra complexity created proportionately more problems. Major events which have impacted energy consumption are shown on Table 1 and are cross-referenced on Figure 3. These events are discussed in detail later.

Figure 4 is a plot of energy consumption as a function of average monthly temperature and can be thought of as an indication of the building's sensitivity to outside air temperature. The squares indicate the most recent data taken during the third year of operation (which began September 1, 1978). The data points for the first two years have been replaced with "best fit" straight lines. The upper solid line and the dashed line below it depict the characteristics of the building during the first and second winter heating seasons, respectively. The fact that the second year sensitivity line is lower than that for the first year is indicative of improved performance. There was also a slight improvement in cooling performance for the second year compared to the first year. But, because of the relatively short New England summers, there were only a few data points for each cooling season. Attempting to fit separate curves for each summer would have resulted in a standard deviation of the same general magnitude as the difference in seasonal performance. Consequently, the dotted line that extends to the right represents the first two summer cooling seasons combined. The squares representing the third year are generally lower than the lines that have been fitted for previous years thus indicating even further improvement.

Much of the original design work for the building involved simulations. That is, a mathematical model of the building was input to a computer along with weather data. The resulting output was a prediction of building thermal loads. Weather data for the year 1962 were selected because it is considered to be a typical year for the location based on historical weather data. The actual weather that has occurred since the building became occupied has been generally more severe than in 1962. The sensitivity curves of Figure 4 can be used to produce a correction factor to account for these temperature differences. By multiplying the slope of the appropriate heating or cooling lines by the difference between actual and 1962 air temperatures, correction factors can be derived which when subtracted or added, as appropriate, to the actual energy, produce adjusted values. The adjustments tend to be rather small in most cases as can be seen by comparing the upper two curves of Figure 3 where the solid line has been adjusted for temperature and the dot-dash-dot line has not. Total energy consumption, both adjusted and actual, is tabulated at the top of Figure 3. From the original design study, a goal was set for an annual energy budget of 625 MJ/m^2 (55 $kBtu/ft^2$). Annual consumption has been higher than this; but, from the observed trends, it appears likely that the building will soon meet this goal.

THERMOGRAPHIC ANALYSIS

During the first winter of operation (1976-77), energy consumption was higher than expected and many of the occupants seated near exterior walls complained of feeling cold. This prompted NBS engineers to conduct special studies of heat and air leakage through the building's exterior walls. During the week of February 14-18, 1977, thermographic equipment was used at the building in an attempt to determine the location, if any, of serious heat leaks in the building.

Thermography is a technique for "viewing" surface temperatures through infra-red (IR) radiation. IR radiation is emitted by virtually all objects. The intensity and spectrum of the radiated IR is a complex function of surface temperature and surface optical properties. However, for most building materials with the surface temperatures that normally exist, there is a reasonably direct correlation between surface temperature and total radiated energy.

The IR scanner looks and acts much like a closed circuit TV system. A camera picks up an image which is then converted to a voltage signal. The camera, however, is sensitive not to visible light but to IR. Electronic circuitry conditions the camera's output signal to produce a visible image on a cathode ray tube (CRT). For black and white CRT monitors, the IR intensities are translated to varying shades of grey. For color units, the intensities are broken down into 10 levels which are each arbitrarily assigned a color. The color assignments are chosen much like a rainbow spectrum with colors ranging from dark blue for cooler objects to bright yellow for warmer ones. For the tests conducted at the building, color images were used because they offered higher resolution. In this paper, the actual images have been replaced by line drawings which are intended to portray the same results.

Measurements were made during the evening and generally on the inside of the building. The outdoor temperature was near -7°C (20°F) during the test periods which imposed a sufficient temperature difference across the building walls and windows so that differences in the surface temperature due to differences in insulation effectiveness in the building structure could be detected. Although some measurements were made on the outside of the building, in general they were of little value in doing the qualitative analysis. The primary reason is that the surface temperature across the outside of the building varied due to other factors beside insulation effectiveness such as retention of absorbed solar radiation by the more massive parts of the facade, variation of air flow and wind velocity around the building, and differences in angle factors between the various surfaces on the facade and the IR camera. As a result, measurements of a more exact nature could only be made on interior wall surfaces.

One of the areas analyzed was the east wall on the first floor. Figures 5a and 5b show both an actual photograph and the results of a thermogram of the same area. Based on the difference between inside and outside dry-bulb temperature and the designed insulation values of the insulated concrete wall and double-glazed window, it was calculated that the wall should have been several degrees warmer than the window. However, it was observed that portions of the wall near the floor were at temperatures equivalent to the surface of the window (this phenomenon was found to exist at several locations throughout the building, often to a greater extent than is shown in Figure 5b). In order to obtain additional insight into this phenomenon, the thermographic equipment was moved outside the building and a thermogram was taken from the outside of the same section of the wall as shown in figures 5a and 5b. It was felt that if the insulation in this space had been omitted or damaged so that heat loss here were purely a result of increased conduction and convection, the area under the window would have indicated a temperature as warm as the glass. However, the thermogram (Figure 6b) revealed this to be one of the coldest areas in the scan, much colder than the adjacent glass. Thus it appeared that thermal conduction through the insulation was not the cause of the cold inner surface since the outer surface would have been much warmer than it actually was.

A probable cause that would explain why both the inner and outer wall surfaces were cold even though insulation was in place is the leakage of air into the building. Negative pressure within the building, created in part by a natural stack effect, causes cold air to be drawn in through window frames, cracks in the mortar and walls, breathing holes and openings that may have inadvertantly been left open during construction. As this cold air seeps through the wall, it comes into direct contact with the inner masonry blocks and causes cooling. In support of this theory, the suspended ceiling was removed near the wall as shown in Figure 7a. Cold air was found to be leaking into the ceiling space at a location where a steel supporting structure extended through the insulation (circuled area in Figure 7a). The corresponding thermogram, Figure 7b, shows this location as being quite cold. Subsequent examination of visual photographs taken during the building's construction showed that (1) steel struts extending through the insulation are used to support the granite facade overhangs on this floor and the glass fiber insulation was pieced together around the struts with no special precaution taken to seal against air leakage and (2) several cracks existed in the exterior of the masonry wall before application of the insulation. These cracks appear to have resulted from either pipes built into the wall or defective mortar joints.

Based on these findings, a general survey was made of the entire building. This consisted of spot temperature measurements of wall sections, additional thermograms, and qualitative examination by simply feeling walls and ceiling plenums for cold temperatures and leaking air. It was found that cold surfaces were more numerous on the first three floors and that they generally occurred on the east and west walls. However, all exterior walls had sections that exhibited, to some extent, the same problems found on the second floor. Even the north wall on the third floor was found to be substantially cooler than expected. This was surprising since there are no windows on the north wall and the construction is different than on the other three. Air must have been infiltrating the cavity space here along some path different than that on the other three walls.

Some areas were free of this cold air problem. Figures 8a and 8b for example, were taken along the east wall of the sixth floor and the results were indicative of what should have existed throughout the building; a much warmer wall and floor surface than window surface.

Independent of the thermographic study, measurements of air change rates in the building were made using a tracer gas and are discussed below. The results indicated higher air change rates on the first three floors than on the upper four floors. This was consistent with the thermographic findings that indicated more cold air in the cavities on the lower three floors.

AIR INFILTRATION

Along with the thermographic study conducted in February, 1977, tests were conducted to determine the rate at which outside air was entering the building [6]. Subsequently, the outside air dampers were modified to reduce excessive leakage and the building's facade received extensive caulking. Two years later, in February, 1979 (after the modifications had been made), the air exchange rate was remeasured. The 1977 test represents a more in-depth study because an examination was made not only of the overall building air exchange rate but also of the air exchange between various floors inside the building. The results of this test will be discussed first.

A tracer gas technique was used to measure air exchange rates [7,8]. Sulfur hexafluoride (SF_6) was injected into the building and its concentration levels were monitored closely. By determining the rate at which the gas dissipated, it was possible to calculate the rate at which outside air was replacing air in the building. SF_6 was used because it can be detected at extremely low concentrations. Thus, only a minute quantity of gas was needed. The result was an odorless, non-toxic mixture (essentially pure air) which could be safely used in an occupied building.

Floors 1-3 and 4-7 of the building are served by separate ventilating systems. The main features of these systems are represented schematically in Figure 2b. These diagrams include only elements which control the main airflows to and from the building.

SF_6 was injected into the system immediately upstream from the return fans F2 and F4 in Figure 2b and monitored near the same points.

The ventilating systems were operated with the outside air dampers, D1 and D4 in Figure 2b, closed to obtain nominal 100 percent recirculation. This also required opening of dampers D3 and D6. In the first measurements, SF_6 was introduced only to the main ventilation system of floors 4-7. In this way any air rising from the lower floors due to the stack effect would be essentially free of tracer. It was felt that comparison of measurements obtained this way with measurements obtained with tracer distributed throughout the entire building would provide an approximate estimate of the relative amounts of air leakage to floors 4-7 from the outside and from the lower floors. The results after adding SF_6 to floors 4-7 and then to the entire building are shown on lines 1 and 2 of Table 2. An apparent air exchange rate of 0.72 changes per hour was obtained for floors 4-7 when the air from the lower floors contained no tracer and 0.54 air changes per hour when tracer was introduced to the entire building. This suggests that an air change rate on the order of 0.1-0.2 was due to air rising from the lower floors.

The air exchange rates in floors 1-3 were higher than in the upper floors when operating in the nominal 100 percent recirculation mode. This is consistent with the findings of the thermographic study where the lower three floors seemed to have a greater problem with cold walls.

In the final tracer measurements, the outside air dampers to floors 4-7 were opened and operated in the variable air volume (VAV) mode. The dampers to floors 1-3 were not opened because of problems in supplying sufficient heat to these floors. Under these conditions, the air exchange rate for the upper floors was higher than to the lower floors as might be expected. The results are shown on line 3 of Table 2.

The air exchange rate in floors 1-3 was lower when the outside air dampers to the upper floors were opened than when the whole building was operated nominally with 100 percent recirculated air. The reason for this apparent decrease is not known. It suggests that 1) possibly there was some unidentified leakage path from the upper to the lower floors, or 2) the building was operating under a slight negative pressure when all the outside air dampers are closed, and opening dampers raised this pressure to where it was more nearly equal to the outside pressure.

Weighted average air exchange rates for the entire building were calculated assuming that floors 1-3 represented 3/7ths of the building volume and floors 4-7, 4/7ths. The results are shown in Table 2. Air exchange rates of the order of 0.7 to 0.8 changes per hour were obtained with complete recirculation and 0.9 to 1.0 air changes per hour with the upper floors operating in the variable volume mode. These estimates include air exchange due to toilet exhausts and possibly a special exhaust from the 4th floor as well as natural leakages. According to the ventilation design for the building, the combined toilet exhausts amount to 1.873 m^3/s (3968 cfm). This corresponds to 0.24 air changes per hour for a 28,000 m^3 (1,000,000 ft^3) building. The exhaust from the medical examining room on the 4th floor is given as 0.7513 m^3/s (1592 cfm) or about 0.1 air changes per hour when averaged for the entire building.

To determine how much air leaked into the building from the basement 200-220 ml of SF_6 were released in the basement and concentrations were monitored on the upper floors. Small increases in tracer concentration were observed on floors 1-3 and 4-7, but they were too small to be measured quantitatively under the conditions of the experiment. A slightly greater increase was observed in the penthouse near the elevator. This suggests that the elevator shaft is one of the leakage paths.

During the 1979 test, measurements were taken over a two-day period. On the first day, the building was operated with the outside air dampers closed, much like the first phase of the 1977 test. Minor changes occurred throughout the day in the operation of certain exhaust fans and dampers but were judged to have minimal effects.

The following day, the outside air dampers to both systems were opened and the ones to floors 4-7 were operated in the variable air volume mode. In 1977, this configuration could not be achieved because heating problems prevented opening the dampers to floors 1-3. Therefore, when making comparisons between 1977 and 1979 air exchange rates, the first case (dampers closed) is of greater importance since this configuration was substantially the same for both tests. The second case is important for energy calculations, however, since it is more representative of the way in which the building is actually operated.

The results of the 1979 test are shown on lines 4 and 5 of Table 2. With the outside air dampers closed, the air exchange rate was 0.75 air changes per hour for floors 1-3 and 0.39 for floors 4-7. The weighted average for the building was 0.54 air changes per hour which is a decrease of about 28% from the 1977 value of 0.75. Presumably, much of this improvement is due to the caulking and modifications to the air dampers. However, it was approximately 7°C (13°F) colder at the time of the 1977 measurements compared to 1979.

Concurrent with the 1977 tests, were measurements of CO_2 concentrations within the building. Air samples were collected in small balloons at a time when the main ventilating system to floors 4-7 was shut down. Sampling points were not selected to be representative of the entire floor. Instead, samples were taken from rooms containing the most people. Thus, it was felt that maximum CO_2 levels were observed. The highest level of CO_2 recorded in these measurements was 2400 ppm or about 5.5 times the measured outdoor level. This concentration was obtained on the fourth floor in a room where several people were taking an examination.

At present there is no consensus as to the extent to which outside air may be restricted to save energy without jeopardizing indoor air quality. However, from the point of view of CO_2 alone, analysis on each of the floors indicated that even with the make-up air dampers closed, most of the building met CO_2 levels implicit in the 0.0071-0.0118 $m^3/s \cdot$person (15-25 cfm/person) ventilation rate for office space as recommended in ASHRAE Standard 62-73 [9]. After the 1977 tests, the building was caulked and make-up air dampers were tightened. These changes reduced the overall ventilation rate by about 20 to 30%. However, the building is typically operated with variable make-up air dampers operating and maintaining ventilation levels well above 0.0071-0.0118 $m^3/s \cdot$person (15-25 cfm/person).

It should be noted that ASHRAE Standard 62-73 was prepared before energy conservation became a recognized national priority; the Standard is currently under revision.

BUILDING OPERATION

After the building went into operation, certain differences between actual and anticipated equipment performance and building loads became apparent, creating a need to modify the original control plans. The problem was perhaps more exaggerated in the case of the Cotton Building by system complexity and the retrofitting of the solar collectors. The following is a discussion of some of the more significant changes.

Double Bundle Condenser

The electric chiller in the building is equipped with a condenser that has two sets of heat exchanger coils. The first set is used either in a conventional manner to "dump" rejected heat to an evaporative cooling tower (evaporative cooling mode) or, alternatively, in a special mode to store this heat in any one of the 38 m^3 (10,000 gal) tanks (hot storage mode). The second set is tied directly to the heating loop and was intended to be used to meet the reduced heating loads that occur during periods of night set-backs (space heating mode).

So far, no rejected heat has been recovered from either coil bundle of the condenser other than in the evaporative cooling mode. In the space heating mode, the chiller was intended to act essentially as a heat pump. It would extract heat from the storage tanks at temperatures as low as 7°C (45°F) and supply it, along with the compressor work, to the heating loop at a temperature of approximately 41°C (105°F). It was calculated that the water at this relatively low output temperature would be sufficient to meet most of the reduced heating loads that would occur during the night set-back periods. However, because the heating loads have generally been higher than expected, this feature has not been of use. During mid-winter, set-backs have been eliminated and loop temperatures have been raised to well above maximum condenser operating temperatures. During off seasons, there is ample energy available for the solar collectors to meet the heating loads.

The other unused feature, the hot storage mode, was rendered ineffective by the addition of the solar collectors. Without the collectors, hot storage would have been effective during mild weather when simultaneous heating and cooling would be required. But, with the collectors installed, there is enough energy available from the solar collectors during these times to meet loads.

Cold Storage

Another intended feature associated with the central chillers was the ability to store chilled water. Here, the chillers were to operate at full capacity during evenings and off-peak periods. The excess chilled water was to be stored in one of the 38 m^3 (10,000 gal) water tanks. During peak cooling periods when the load exceeded chiller capacities, this stored water was to be used to augment the chillers, thereby supplying the additional needed cooling.

The chilled storage feature has been disappointingly ineffective. Original operating specifications called for the chillers to maintain tank water temperatures of 4°C (40°F) or lower. However, the presence of safety interlocks designed to prevent the evaporators from freezing caused the chillers to cycle before the chilled water temperature reached the designed temperature. This made it impossible to bring the storage tank temperature to less than 8-10°C (47-50°F). Aside from a loss in chiller efficiency due to cycling, the amount of stored cooling was too small. As a result, cooling reserves were usually exhausted well before peak afternoon cooling loads occurred. Furthermore, since the tank (located in the basement, seven floors away from the chillers) and its associated piping could not be by-passed, heat gains through insulation placed an extra burden on the chillers. During the summer of 1979, the chilled water tank was manually by-passed. To help meet peak loads, building operators made maximum use of cool night air and the building's thermally massive walls. By pulling the building down to a reasonably low temperature overnight, the chillers were generally able to maintain acceptable comfort levels throughout the day. This change seems to have noticably reduced summer energy usage.

Engine Generator

Before the addition of the solar collectors, the primary power source for the electric chiller was to be an electric generator driven by a natural gas-powered engine. This engine was equipped with a heat recovery system that collects heat which otherwise would be rejected through a radiator and exhaust stack. The waste heat was to be stored in one of the 38 m^3 (10,000 gal) tanks and was ultimately to be used to operate the absorption-cycle chiller. When the collectors were added, it was felt that they would be able to supply the heat needed to drive the absorption machine. Consequently, the engine/generator was down-graded to an auxiliary power source for the electric chiller to be used only during evenings and cloudy days.

During the first summer of operation, it became evident that the engine/generator could not produce sufficiently high storage tank temperatures to operate the absorption machine. Evidently, the engine's heat output was not great enough to overcome the combined affects of jacket losses, heat exchanger efficiencies, and storage and piping losses. In an attempt to produce more heat output, additional loads were placed on the generator by switching portions of the Motor Control Center (an electric switchboard that supplies power to water pumps and air handlers) from purchased power to generator power. This did indeed increase heat output by making the engine work harder. However, as the storage tank neared the design operating temperature of 107°C (225°F), a safety interlock designed to prevent engine overheating would activate causing water to be diverted to a cooling tower which simply dumped the heat and prevented the water loop from reaching the design operating temperature. Adjusting the interlock may have produced higher temperatures, but it also would have jeopardized the engine's warranty and reliability. As a result, it was decided that no further attempt would be made to utilize the waste-heat system.

Solar Collectors

As mentioned previously, the solar energy system was not included in the original design of the HVAC system. This fact is perhaps an underlying cause of many of the control and equipment problems experienced at the building. At the time the collector system was added, much of the architectural and HVAC design was firmly set. Consequently, integration of the collectors with the rest of the system was subject to a number of constraints. For example, available roof area severely limited overall collector area. Also, collector piping was tied into the main system in such a way that the collector's output could only go to the basement storage tanks. Such an arrangement has a disadvantage. If the storage tanks temperature is too low for use, the entire volume of water must be increased in temperature before any useful heat can be extracted. This results in an expenditure of collector energy that perhaps could otherwise be used directly for meeting building loads. Furthermore, the large tank and piping heat losses tend to reduce overall collector effectiveness.

The collector output, even at 107°C (225°F), was expected to be sufficient to drive the absorption chiller during summer days. Thus, as mentioned above, the central scheme was changed to discontinue the use of the engine generator whenever the measured solar radiation was above a minimum value. However, the collector system, like the engine/generator, was unable to produce sufficiently high storage tank temperatures to operate the absorption machine. In addition, the collector output could not be augmented by the auxiliary boilers. Thus, if the collector were not able to supply enough 107°C (225°F) water to meet 100% of the load plus losses, the system was designed to switch over to full auxiliary, namely the engine/generator.

At this point, the building operator was faced with a serious problem: the absorption chiller could not be used because its only two heat sources were both incapable of producing the required operating temperatures. Furthermore, because loads were higher than expected and the cold storage system was ineffective, the electric chiller, alone, could not meet peak cooling loads. Without the absorption chiller, building comfort was jeopardized. It was therefore necessary to modify the plumbing so that two oil-fired boilers could be used to fire the absorption chiller directly. The solar collectors are now not being used for cooling.

For space heating, the solar collectors have only been of use during off seasons when outdoor air temperatures are relatively mild. This is because during severe cold weather, it has generally been necessary to raise the space heating water loop temperature to a level above the normal operating range of the collector subsystem. At present, the solar collectors are used mainly during spring and fall for space heating and domestic hot water and during summer for domestic hot water only.

CONCLUSIONS

Over the three years that the building has been in operation, a number of problems have occurred. Fortunately, building officials have been fairly successful at correcting or circumventing these problems so that the building, although operated differently than originally intended, performs reasonably well. Based on the study completed to date by NBS:

1. It is possible to design, construct, and operate a medium-sized office building in a northern climate to use no more than 625 MJ/(m^2•year) (55 kBtu/(ft^2•year)).

2. Designing a building as an experimental laboratory to compare the performance of a variety of energy conserving concepts is in general not compatible with an objective of designing a low energy use building. In this building, a number of different energy conserving sub-systems are installed and interconnected in such a way that the overall mechanical system is complex and difficult to control.

3. When unusual construction details exist, it is important that building designers, construction firms, and inspectors use extra care to guard against unintentional thermal bridges and air leakage paths.

4. Problems have been experienced in this building with retrofitting a solar subsystem to a mechanical system that was not originally designed for it.

5. Even operating the ventilation system in a complete recirculation mode, CO_2 levels were within or close to the levels implied by the 0.0118-0.0071 m^3/s·person (15-25 cfm/person) ventilation rates recommended for office space by ASHRAE Standard 62-73.

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9. "Standards for Natural and Mechanical Ventilation," ASHRAE Standard 62-73, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 345 E. 47th St., New York, New York 10017, 1973.

ACKNOWLEDGEMENTS

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Table 1. Building Operating Changes

KEY*	EVENT	DATE COMPLETED
A	Building occupied	September 1976
B	Thermostats modified to prevent simultaneous heating and cooling	March 1977
C	Oil burners connected to absorption chiller	May 1977
D	Outside air dampers modified	October 1977
E	Heating system loop temperatures raised, no night set-backs	December 1977
F	Return to night set-backs	April 1978
G	Collectors begin supplying energy to DHW and space heating water loop during spring and fall	May 1978
H	Engine generator no longer used	August 1978
I	Building facade caulked	December 1978
J	Chilled water storage not used	May 1979

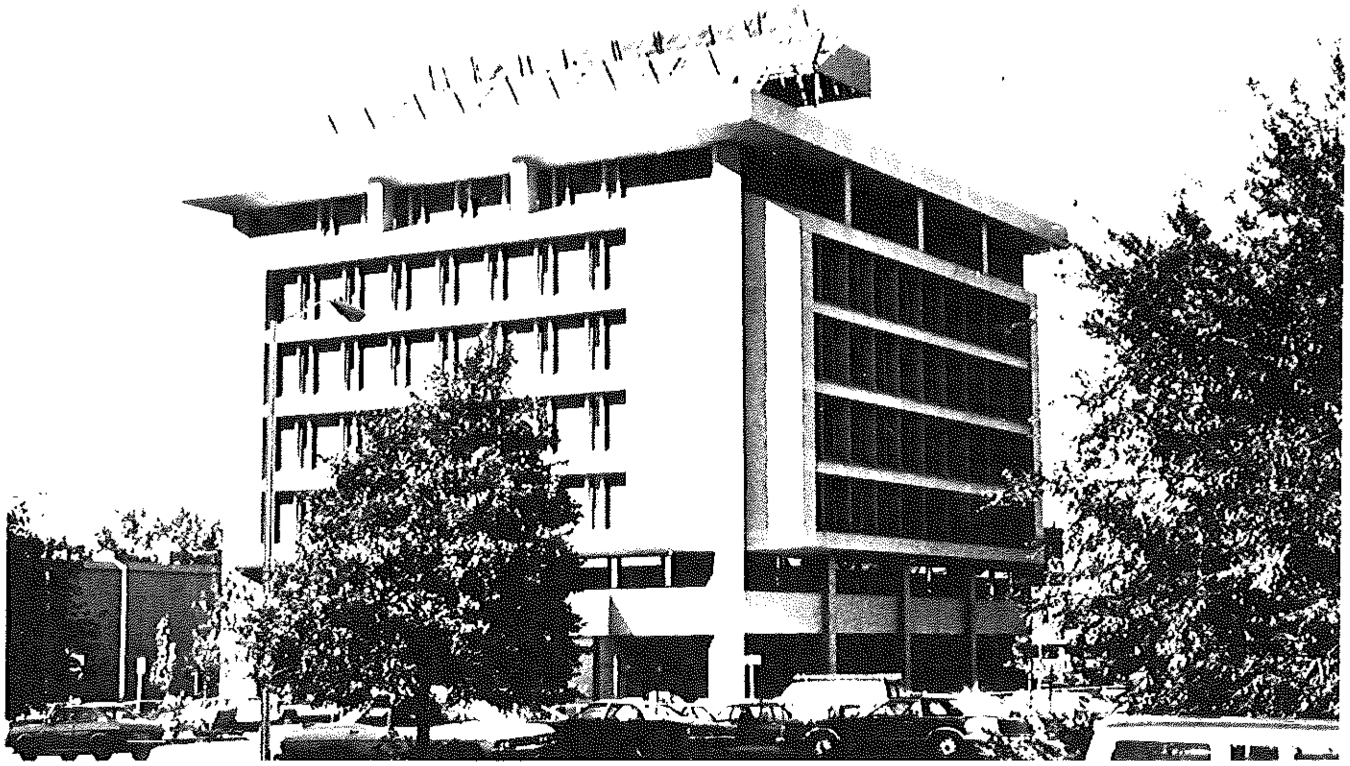
* NOTE: Letters are cross referenced on Figure 3.

Table 2. Results of Air Exchange Measurements

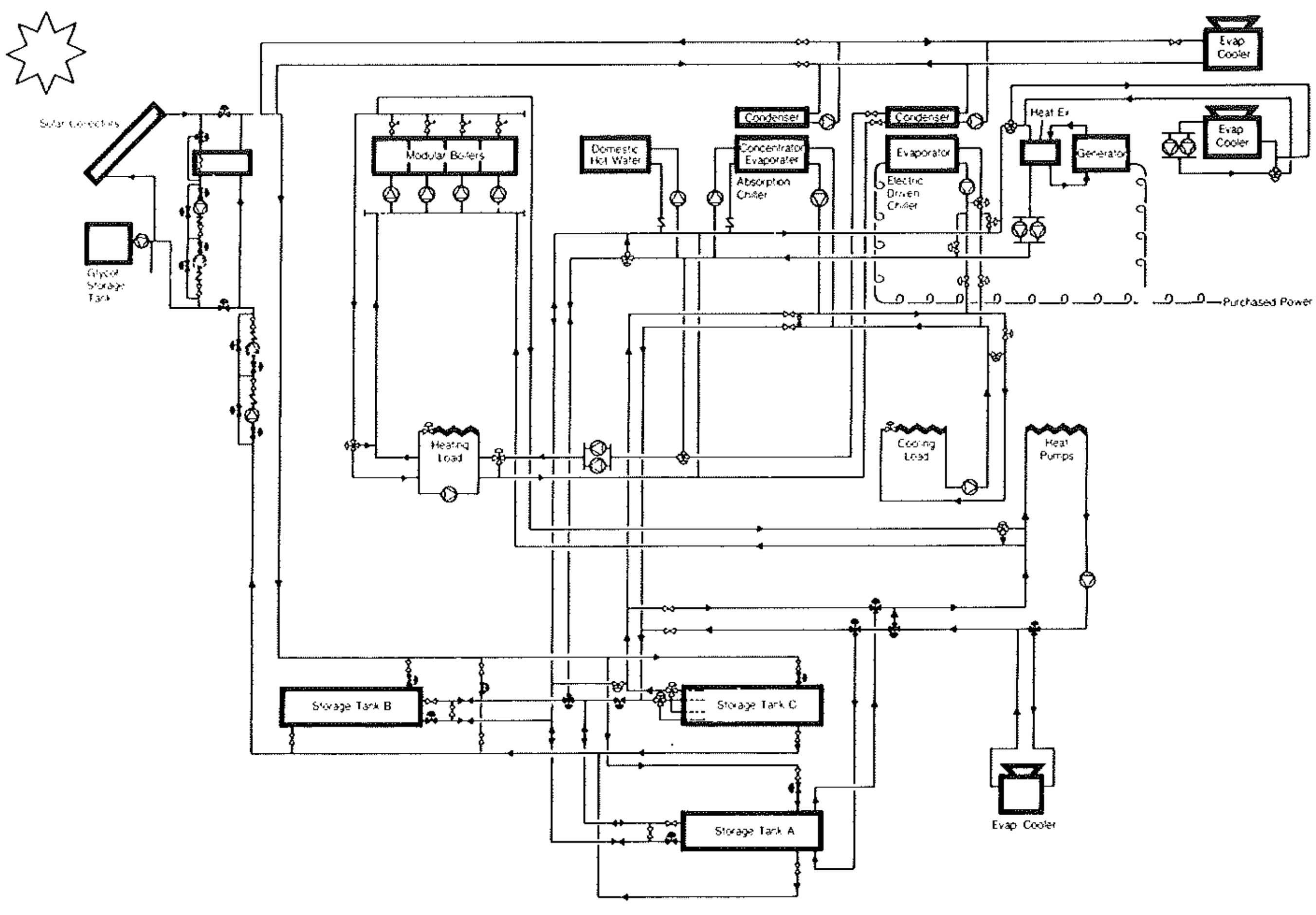
	FLOORS 1-3		FLOORS 4-7		BLDG.	
DATE	AIR CHANGES/HR	DAMPERS	AIR CHANGES/HR	DAMPERS	AVERAGE	NOTES
1. Feb 77	-	-	0.72	Closed	-	1
2. Feb 77	1.05	Closed	0.54	Closed	0.75	2
3. Feb 77	0.80	Closed	1.09	VAV	0.97	2
4. Feb 79	0.75	Closed	0.39	Closed	0.54	2
5. Feb 79	1.20	Open	0.86	VAV	1.01	2

NOTES: 1) Tracer added to upper floors only

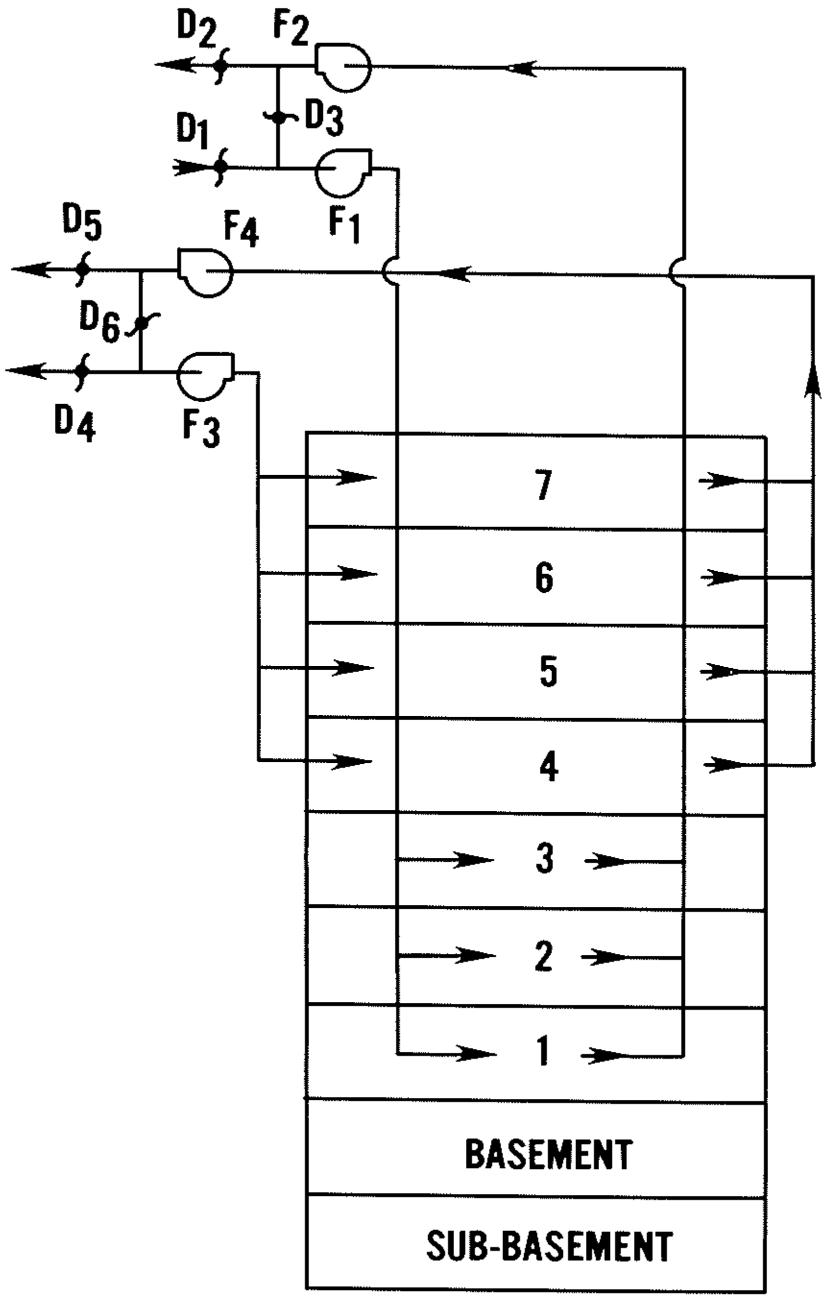
2) Tracer added to whole building



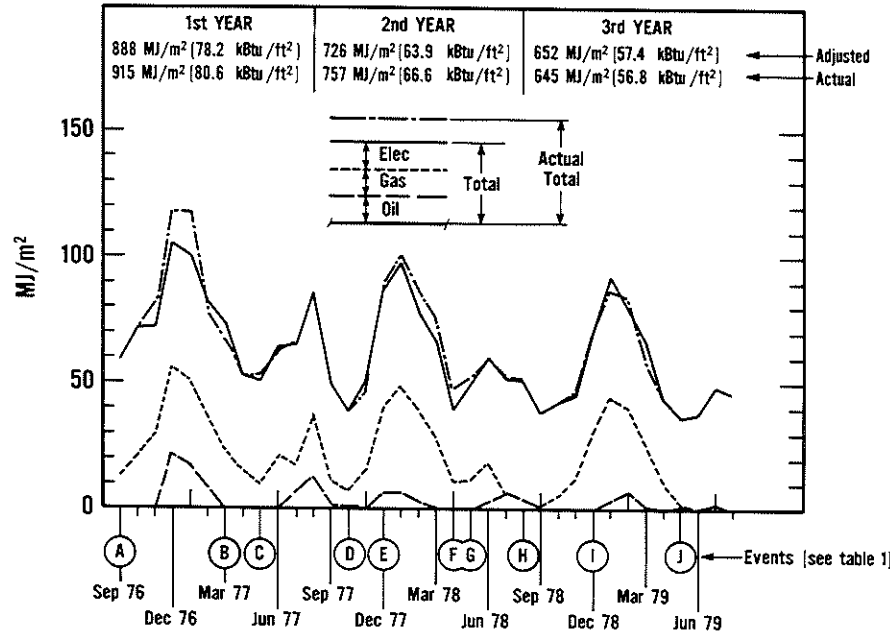
1. Norris Cotton Federal Office Building, Manchester, New Hampshire



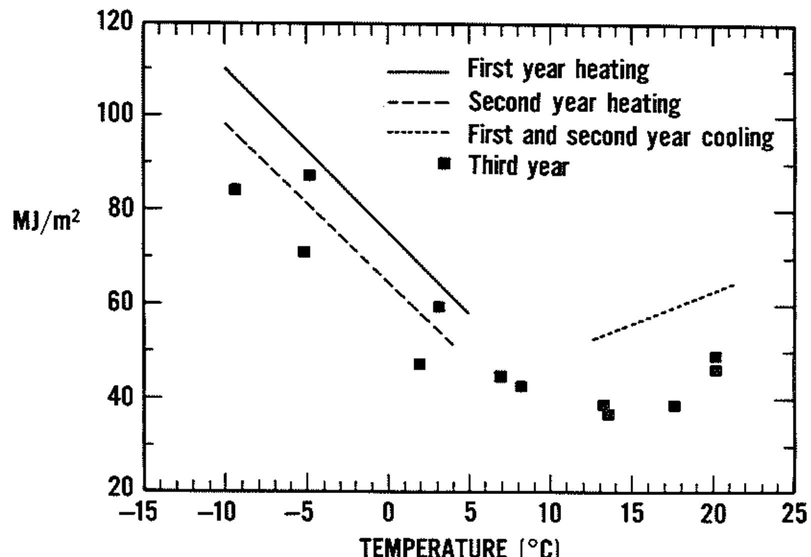
2a. Mechanical System Flow Diagram



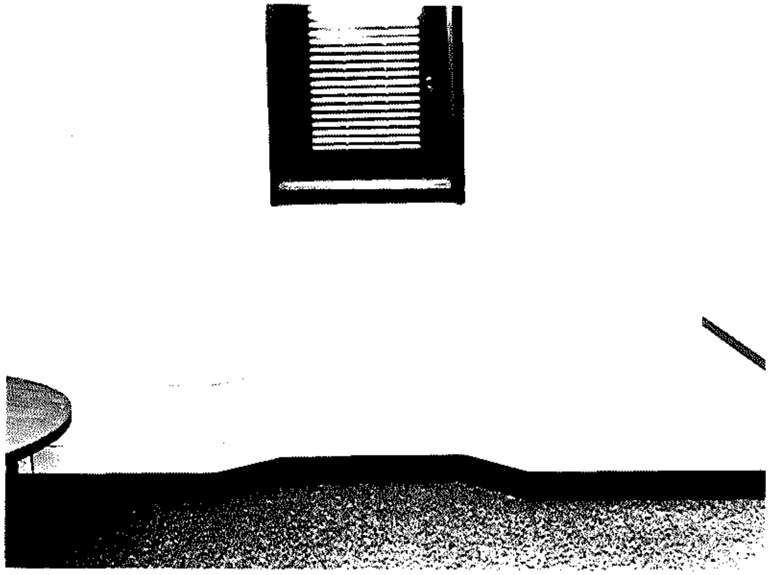
2b. Mechanical System Ventilation Diagram



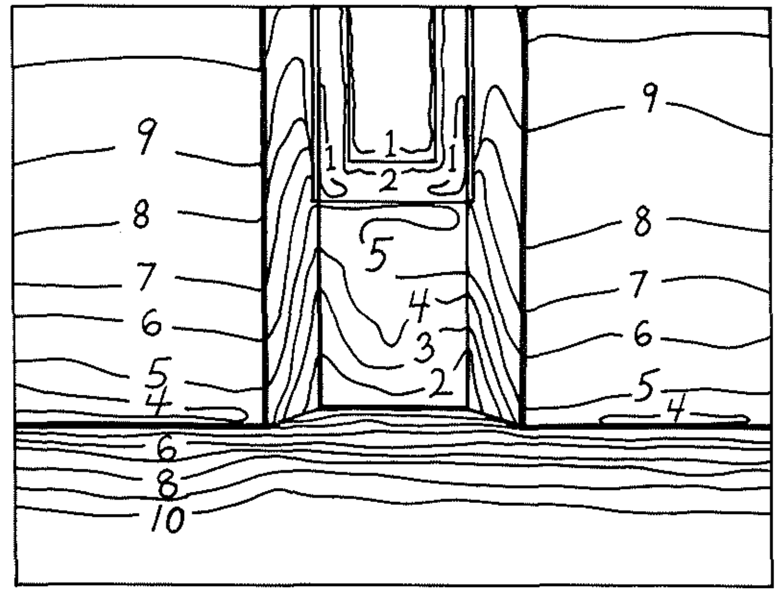
3. Gross Energy Consumption Adjusted to Account for Difference between Design Year and Current Weather. Actual, Unadjusted Total is Represented by Upper Dot-Dash-Dot Line.



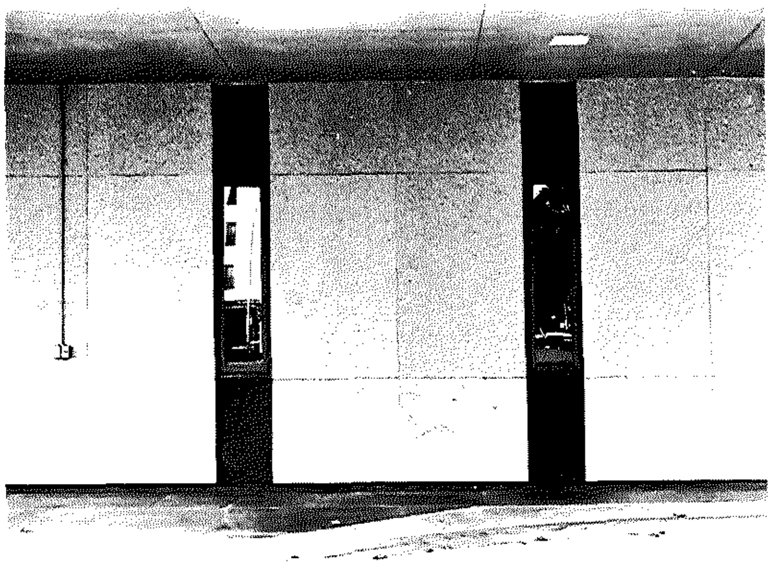
4. Building Sensitivity.
Gross Energy Consumption vs Outside Air Temperature



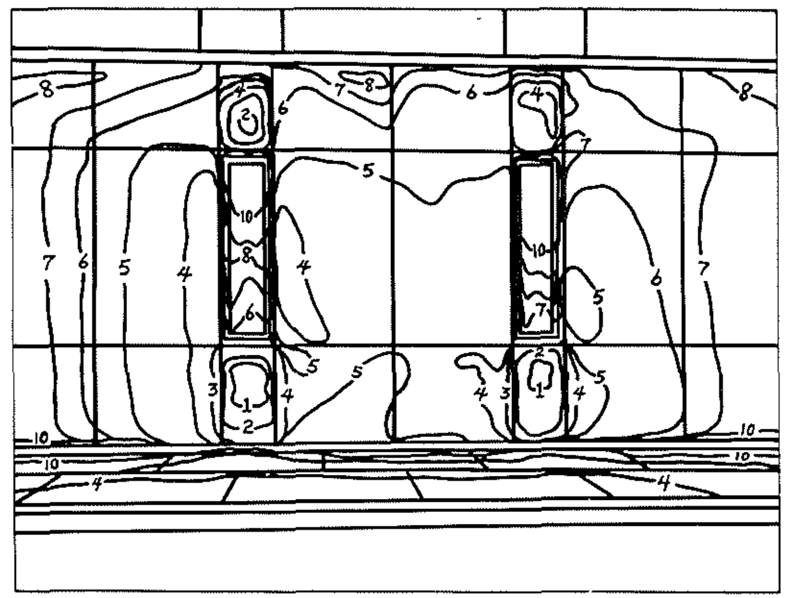
5a. First Floor East, Interior



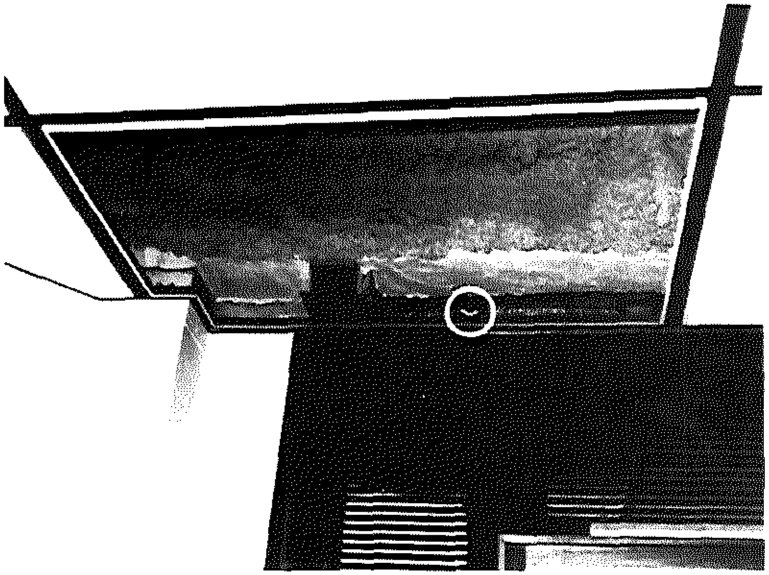
5b. Results of Thermogram:
1 = coldest isotherm 10 = warmest isotherm



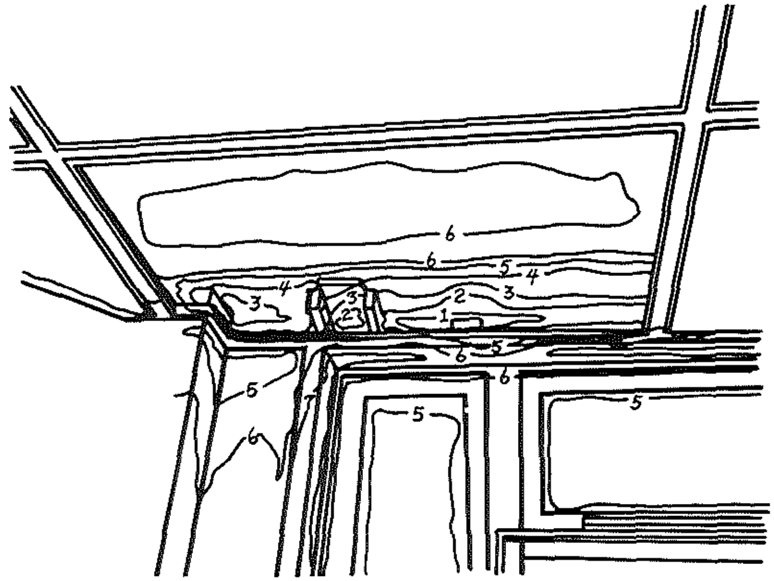
6a. First Floor East, Exterior



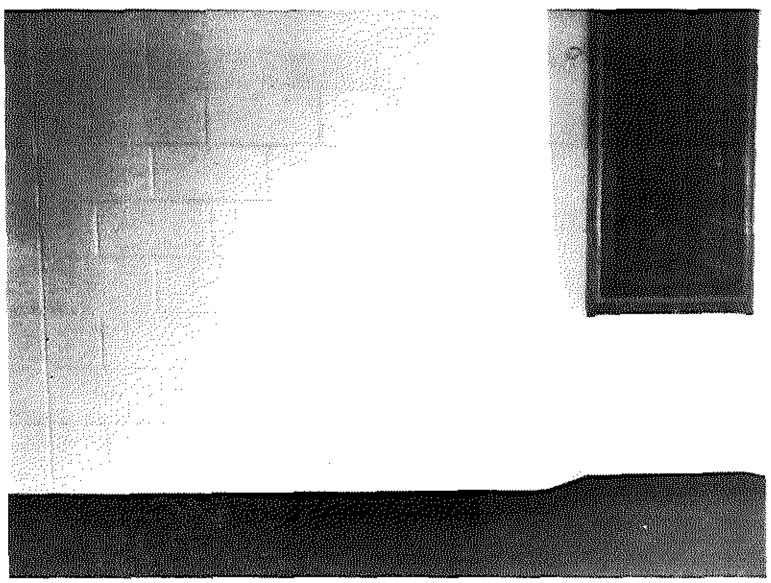
6b. Results of Thermogram:
1 = coldest isotherm 10 = warmest isotherm



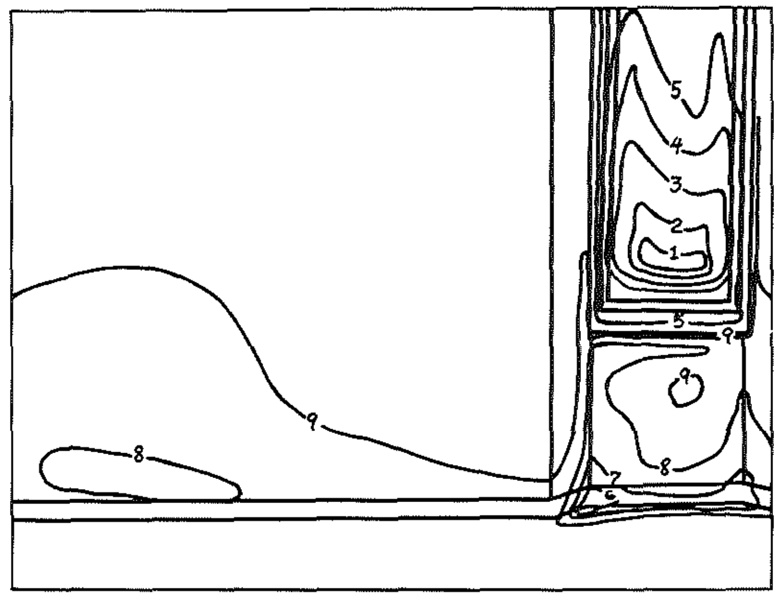
7a. Second Floor Ceiling Area With One Tile Removed. Note: Circled area is where a stell member that extends through the wall and was found to be an air leakage path.



7b. Results of Thermogram: 1 = coldest isotherm 7 = warmest isotherm



8a. Properly Insulated Wall



8b. Results of Thermogram: 1 = coldest isotherm 9 = warmest isotherm

SESSION VIII QUESTION AND/OR COMMENT

Carroll

a. W. Rudoy, University of Pittsburgh

Q: Would you comment on the possible sources of the difference between the three programs.

If the Hastings Model used a slab floor, would you comment on its effect or the results, particularly with the effect on the radiation to the walls and ceiling?

A: No response

Gujral, P., R. Clark, and D. Burch

a. Michael E. Dexter, Syska & Hennessy, Inc.

Q: You have chosen a massive wall with exterior insulation for residential buildings conditioned only at night and located in a sever cooling climate. In this case mass will delay heat gain from the nOn conditioned period until the conditioned period. This could easily increase both cooling energy consumption and cooling system peak electrical demand during the conditioned period despite the increased COP of the cooling system at night. Furthermore, building mass and temperature setback are often incompatible. Buildings such as this with negligible internal heat generation generally should be very responsive if conditioned less than 24 hours per day. This maximizes the savings due to temperature setback. Thus mass might be better applied outside the insulation. Better still might be a mass-less building in this case. Please discuss conceptually how the selection of a massive wall with exterior insulation was made. Also present the expected savings in cooling system energy consumption and peak electrical demand.

A: The night mechanical cooling scheme for an individual building results in some energy savings from the increased COP of the cooling system, but as you have indicated may result in increased energy usage dependent upon many parameters. The building tested was designed to be utilized in conjunction with other buildings of the same type, all cooled at different times by the central cooling plant. The advantage here is that the peak load of the central cooling plant is drastically reduced.

The substantial energy savings occurs with the night ventilation scheme, which clearly requires the insulated interior thermal mass. For the building to be operated for a full year, substantial energy savings occurs because night ventilation cooling may be utilized for all or part of the year depending on the climate.

b. Sherwood R. Peters, LBL

Q: The information obtained indicates that there is a large benefit from mass inside of insulation. To make this information useful it appears highly desirable to have analytical tools available. It is assumed that there was an analysis of the design before it was modeled. Reference to that analytical work if published or inclusion of a summary of an analytical method as part of the paper would make the results much more useful to extrapolate to other designs.

A: See references (3) (4) and (5).

c. Paul E. Condan, LBL

Q: Why did you report a 1% design day temperature cycle for a whole month? It seems to me that this is far too stringent a test. Had you used a driving schedule in which you drove the building with the 1% design day only occassionally you would have had a more realistic test. (In your verbal answer to this question, I thought you said that the 1% design day occurs 200 or 250 days per year. This seems to contradict my understanding of the definition of a 1% design day).

A: The month of design days were used to bring the test structure from its initial condition 70°F(21.1°F) to the steady-periodic state reported. During the summer months, in the field, the building would require only a few days to respond accordingly to a design day. Investigation of the weather data indicated that the design day temperatures were attained or exceeded for as much as a seven (7) day continuous period.

d. Dean C. Patterson, Brick Institute of America

Q: Was any data gathered utilizing deurnal cycles typifying United States climates?

A: No. However, it is recommended that further tests be conducted for the United States climates.

P.A.D. Mill

a. Doug Burch, NBS

Q: (1) What are the maximum outdoor temperature and wind speeds for an exterior survey which will provide sufficient thermal resolution to permit defects in a building envelope to be identified?

(2) Wouldn't it be better to carry out infrared surveys of building envelopes from the inside instead of the outside in order to avoid the problems of reduced instrument sensitivity due to cold surface temperature and the wind scrubbing away temperature differences?

A: No response

Richtmyer, May, Hunt & Hill

a. J.H. Klems, LBL

Q1: What is the level of lighting power consumption and what lighting standards were used in design, i.e, how many W/ft^2 and ft-candles?

A1: The installed lighting power consumption for all but floors 4 and 5 is 19.8 W/m^2 (1.84W/ft^2). The fourth floor level is 18.3 W/m^2 (1.70 W/ft^2) and the fifth floor level, because it uses task lighting, varies as a function of worker (module) density.

During design, a basic criterion of 2 W/ft^2 average, 70 foot candles in work areas and reduced levels in lounge, passageways, and equipment rooms was established. Since the design of this building, GSA has further adjusted lighting levels.

Q2: What fraction of the energy demand is lighting?

A2: Of the electrical energy consumption, overall lighting comprises 37% of the annual total (24% main floor lighting, 13% stairways, garages, etc.). Of the total of all purchased energy, lighting makes up 26% annually (17% main floor lighting, 9% stairways, garages, etc). These figures are based on building performance during FY79.

Q3: What was the occupant reaction to the lighting, amount of daylight, and amount of window area?

A3: With the exception of the fourth floor, occupants were generally satisfied with the lighting. The fourth floor occupants were dissatisfied with the bright yellow, nearly monochromatic, light emitted by the high pressure sodium lamps. In response to a questionnaire that was circulated in March, 1977, 93% of the four floor respondents were "somewhat dissatisfied" or "very dissatisfied" with the lighting. The results of a later questionnaire administered in mid-November, 1977 indicated that the overall level of acceptance had improved from 63% to 73% for the number of respondents who said they were satisfied with the lighting. For the fourth floor, the numer of respondents who were less than satisfied decreased from 93% to about 80%.

In regards to windows, 81% of the respondents to the March, 1977 questionnaire who had windows in their work areas said they could not see as much of the outside world as they would like. Twenty percent of all the respondents preferred working under natural light, 4% preferred artificial light, and 11% indicated no preference. However, when asked if they were able to use natural light, 94% of all the respondents said never.