NBS BUILDING SCIENCE SERIES 133

Performance of the Norris Cotton Federal Office Building for the First 3 Years of Operation

U.S. DEPARTMENT OF COMMERCE • NATIONAL BUREAU OF STANDARDS

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Prepared for the
Architecture and Engineering Systems Branch Buildings Division
Office of Buildings and Community Systems
Department of Energy
Washington, DC 20545

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

Issued August 1981

Library of Congress Catalog Card Number: 81-600082

National Bureau of Standards Building Science Series 133
Nat. Bur. Stand. (U.S.), Bldg. Sci. Ser. 133, 140 pages (Aug. 1981)
CODEN: BSSNBV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1981

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402
Price $5.50
(Add 25 percent for other than U.S. mailing)

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by

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Abstract

The Norris Cotton Federal Office Building is a medium-size seven-story Government office building of approximately 11,000 m^2 (117,000 ft^2) total floor area. It is located in Manchester, New Hampshire, and was 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.

A team from the Center for Building Technology, National Bureau of Standards (NBS), has been monitoring the performance of the building since it was occupied in September 1976. The project has involved not only an analysis of building energy consumption, but also a study of the effectiveness of the various lighting systems, a determination of the response of the occupants to the building, and a cost analysis of the construction and operation of an energy conserving building. This report will describe the building's performance for the first 3 years of operation.

Key Words: Building models, computer; energy conservation, user acceptance; energy conservation in commercial buildings; lighting measurements; performance data for commercial office buildings in New England; solar energy in commercial buildings.

PREFACE

This report is one of a series of reports documenting National Bureau of Standards (NBS) research and analysis efforts in developing energy and cost data in support of the Department of Energy (DoE)/NBS Building Energy Conservation Criteria Program. The work described in this report was supported by DoE/NBS Task Order No. A008-BCS under Interagency Agreement No. EA 77A 01 6010.

Cover photo:

The Norris Cotton Federal Office Building

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DISCLAIMER:

The mention of company names in this publication is done only to identify firms awarded General Services Administration contracts for services rendered in the planning and construction of the Norris Cotton Federal Office Building. In no case does such identification imply endorsement or recommendation by the National Bureau of Standards.

Facing page:

Aerial view of Manchester, New Hampshire, with Norris Cotton Building in center of photograph

1. INTRODUCTION

In the fall of 1972, architects Nicholas Isaak and Andrew C. Isaak of Manchester, New Hampshire, were awarded a contract by the General Services Administration (GSA) to design a Federal office building to be constructed in Manchester. At that time, the construction industry was becoming acutely aware of the term "energy crisis." The "energy crisis" was not yet dominating the headlines, but its implication was clear: The age of cheap fossil fuels was over. Energy consumption, which had been taken for granted in the past, had become an important design parameter.

GSA's Administrator Arthur F. Sampson responded to the challenge posed by the energy crisis by designating the Norris Cotton Federal Building an "energy conservation demonstration project." The purpose of this project was to (a) dramatize the firm commitment of the Federal Government to the conservation of energy in the design, construction, and operation of Government buildings; (b) provide a laboratory for the installation of both recognized and innovative energy conservation technologies (with a goal of obtaining at least 20 percent energy saving with reference to comparable buildings); and (c) inspire others in the building industry to pursue energy conservation as a goal.

In January 1973, the consulting engineering firm of Dubin, Mindell, Bloome, and Associates, of New York City, was awarded a contract to develop a set of recommendations for the design and construction of the Norris Cotton Building. Staff members of the National Bureau of Standards (NBS), at the request of GSA, collaborated with Dubin, Mindell, Bloome, and Associates in evaluating the effect of various building parameters on the building's annual energy consumption. This was done by using the National Bureau of Standards heating and cooling load calculation program, NBSLD [1,2]. Based upon the resulting recommendations, the firm of Isaak and Isaak prepared working drawings and specifications for the buildings. The mechanical/electrical design, which included the design of the heating, ventilating, and air-conditioning systems, was in turn subcontracted to the R. D. Kimball Company of Cambridge, Massachusetts. Staff members from NBS also assisted the R. D. Kimball Company in sizing various components of the heating and cooling systems.

GSA designated NBS to be responsible for designing and operating the instrumentation system which would allow the determination of energy consumption as well as other pertinent performance characteristics of the building and its systems. In this connection, NBS drafted specifications to be used for purchasing and installing a computerized data acquisition system [3]. The building was completed and occupied in September 1976 and designated as the Norris Cotton Federal Office Building (NCFOB). Since that time, NBS staff members have been monitoring the building's performance.

Facing page:

Southwest exterior of the Norris Cotton Building

2. BUILDING DESCRIPTION

2.1 CLIMATIC AND GEOGRAPHICAL DATA

Manchester, New Hampshire, is located along the Merrimack River, 97 km (60 mi) north of Boston, Massachusetts, at an altitude of 89 m (290 ft) above sea level. It is situated approximately at the geographical center of New England. At one time it was one of the largest mill and shoe manufacturing towns in New England. Its population, although less now than in the heyday of the textile mill activities, still exceeds half a million. The surrounding countryside is hilly and dotted with many lakes and woods. Mount Washington is approximately 140 km (90 mi) north of the town. The building site is in the center of the downtown section and is surrounded by several buildings of two to three stories, as well as an eight-story building directly to the south. Historical hour-by-hour weather data are not generally available for Manchester. Consequently, climatic data from nearby Concord, New Hampshire, 24 km (15 mi) north of Manchester, were used in the original design studies [1,2] and again in the analysis of data described in this report. The exact location of Concord is latitude 43° N, longitude 71°30', at an elevation of 104 m (342 ft).

When conducting the original design studies, climatic data for Concord for the year 1962 were used because the monthly average dry-bulb temperatures for 1962 were found to be very close to the 30 year norm values. The actual weather since the building was occupied has generally been more severe than in 1962. Figure 1 is a plot of outside air temperatures for each month of the first three years of operation. It can be seen that the actual weather (solid line) has been somewhat colder in winter yet slightly warmer in summer than it was in 1962 (dotted line). This is also apparent in figure 2 where the actual monthly average air temperatures have been plotted against 1962 monthly average air temperatures. A second order curve has been fitted for each year of operation. All years fall below the design year (solid line) in winter and, on the average, above it in summer.

Other annual norm values of climatic data of interest as reported for Concord are:

Average rainfall	0.986 m (38.3 in.)
Average snowfall	1.63 m (64.1 in.)
Average wind speed, yearly	3.4 m/s (7.6 mi/h)
Average wind speed, summer	2.9 m/s (6.5 mi/h)
Average wind speed, winter	3.7 m/s (8.3 mi/h)
Prevailing wind direction, summer	NW
Prevailing wind direction, winter	NW
Average percent of possible sunshine	54%
Average sky cover	6.1*

The ASHRAE Handbook of Fundamentals [4] lists the following percentile values used for mechanical equipment design for both Manchester and Concord, New Hampshire:

* Zero is a completely clear sky and 10 is completely cloudy.

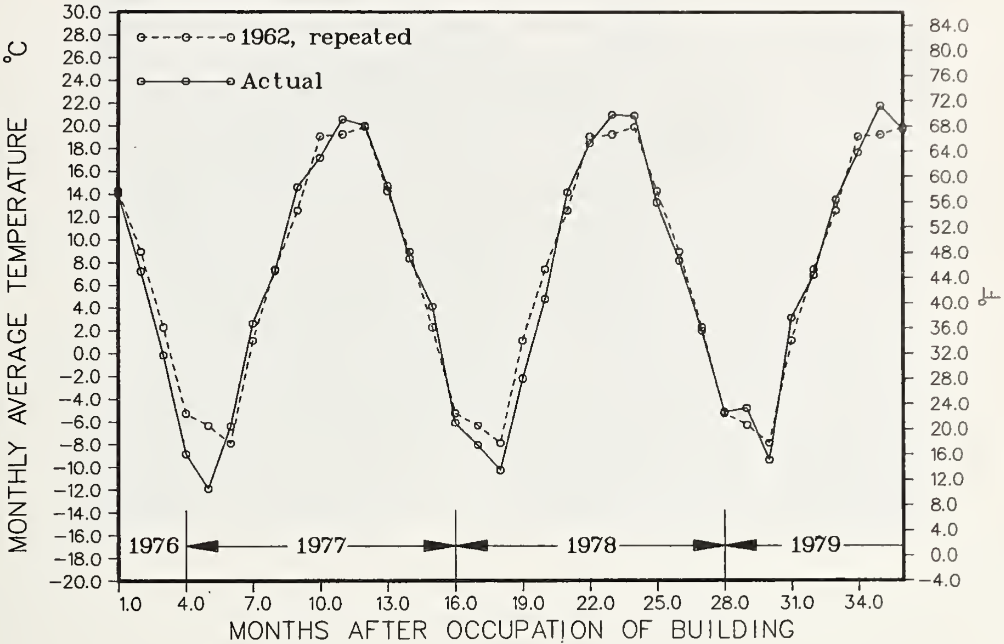

Figure 1. Average monthly outside air temperatures in Concord, New Hampshire

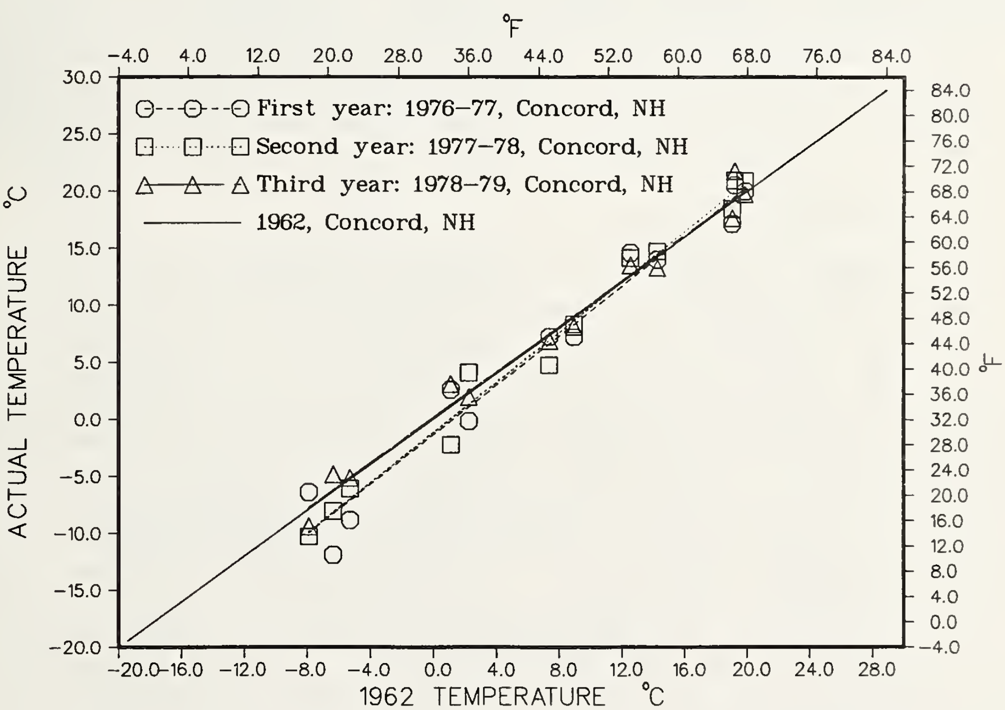

Figure 2. Actual monthly average outside air temperatures versus 1962 monthly average values in Concord, New Hampshire

Winter percentile values

	99%	97 1/2%
Concord	-25 °C (-13 °F)	-22 °C (-7 °F)
Manchester	-21 °C (-5 °F)	-17 °C (1 °F)

Summer percentile values

	1%	2 1/2%	5%
Concord	33 °C (91 °F)	31 °C (88 °F)	29 °C (85 °F)
Manchester	33 °C (92 °F)	32 °C (89 °F)	30 °C (86 °F)

2.2 BUILDING FACADE

The Norris Cotton building is shown in figure 3. The shell is nearly cubical in shape and thus has a low surface to volume ratio. Its exterior walls are constructed with relatively heavy, 30 cm (12 in) thick masonry blocks and are insulated on the outside rather than inside. The wall has an overall heat transfer coefficient (U value) of 0.34 $W/m^2 \times °C$ (.06 $Btu/(h \times ft^2 \times °F)$. This "inside-outside" construction creates a thermal flywheel effect which reduces peak heating and cooling loads. Overall window area makes up only about 6 percent of the total exterior wall with the north wall being completely windowless. 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 $W/m^2 \times °C$ (0.58 $Btu/(h \times ft^2 \times °F)$).

2.3 MECHANICAL SYSTEMS

The mechanical systems at the building can be divided into two major parts which supply different areas of the building. The first three floors are served by a unitary water loop heat pump system consisting of 57 water-to-air heat pumps in various ceiling and floor mounted configurations and having a combined capacity of 350 kW (1200 x 10^3 Btu/h) for heating and 280 kW (79 tons) for cooling. A closed water loop supplies all of the heat pumps with thermal energy for heating and acts as a heat sink for cooling. The upper four floors are served by several types of central systems. These upper floors are heated by a hot water heating system which uses fin tube perimeter radiation on the fourth floor and various types of ceiling or floor mounted fan coil units on floors 5, 6, and 7. Cooling is provided on the upper four floors by central chillers used to produce chilled water which is pumped to the fan coil units or to a cooling coil in the variable air volume (VAV) air handling unit for the core area. Untreated ventilation air is provided for two below-grade parking levels and a mechanical equipment penthouse is heated and ventilated.

Figure 3. Norris Cotton Federal Office Building in Manchester, New Hampshire

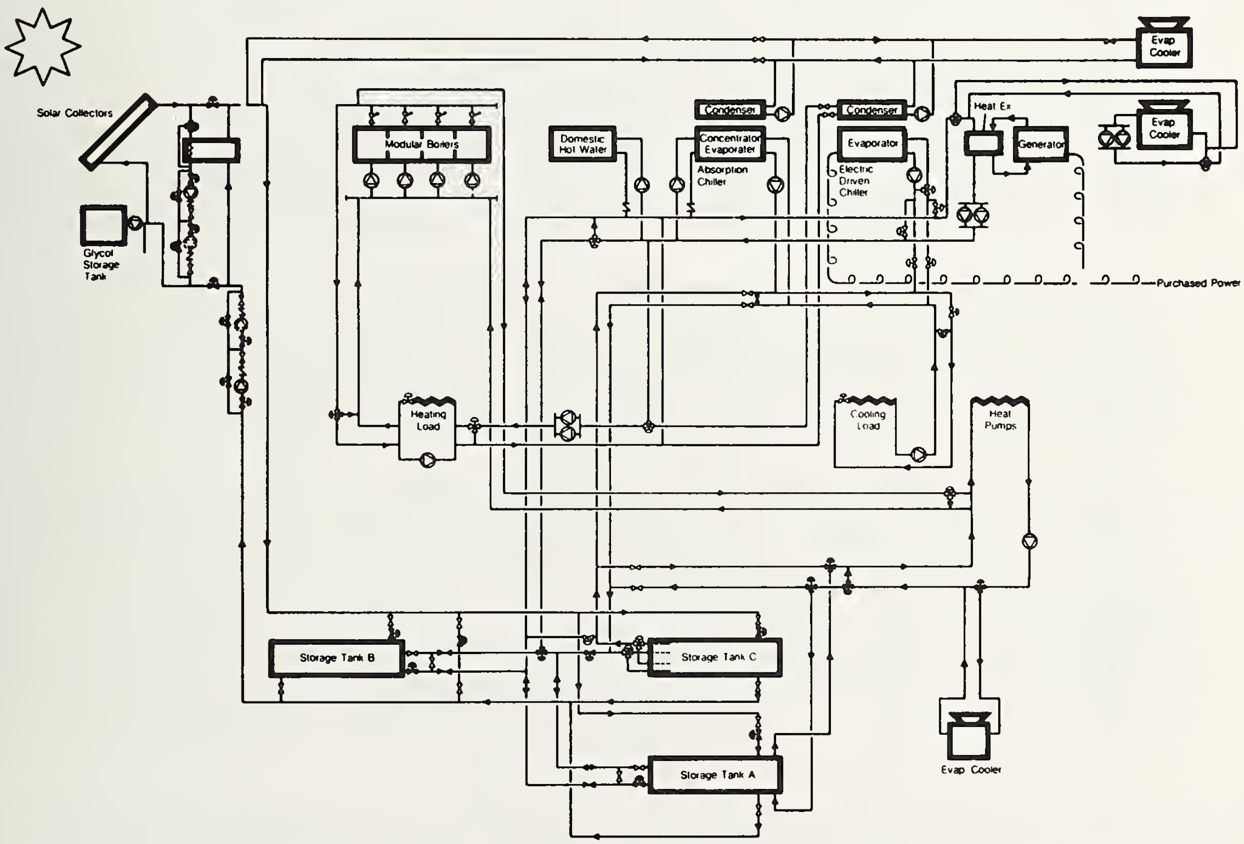

Figure 4. Schematic diagram of Norris Cotton Federal Office Building mechanical system

The building has two separate systems for handling outside air. One system, the heat pump air system, supplies ventilation air to the lower three floors by bringing outside air down from the penthouse mechanical room where the supply fan, return fan, and outside air and return dampers are located. Cooling and heating of the air is acomplished by having the air pass in parallel through six floor-mounted heat pumps before reaching interior areas of the lower three floors. This air system is a variable air volume type.

The upper four floors are supplied with ventilation air through a second air handling system also located in the penthouse. This system, which is also a variable air volume system, is configured much like the heat pump air system except that the only heating and cooling equipment in the air stream is a chilled water coil in the air handling unit. A heat pipe heat recovery system is used to preheat the outside air using energy recaptured from the exhaust air.

The building has a number of energy conversion devices utilizing natural gas, fuel oil, and electricity to provide heated and chilled water for the building water loops. Figure 4 is a schematic of the energy conversion and supply equipment. Four 55 kW (187 x 10^3 Btu/h) natural gas modular boilers and two 108 kW (370 x 10^3 Btu/h) number 2 fuel oil modular boilers can supply heating energy to the heat pump and hot water loops. A 211 kW (60 ton) electric reciprocating chiller and an 88 kW (25 ton) hot-water-driven absorption chiller provide chilled water. Electric power for the reciprocating chiller can be purchased or supplied by a 150 kVA natural-gas-fueled engine-generator set in the penthouse. Thermal energy for the absorption chiller is supplied by recovery of waste heat from the engine generator or by the oil boilers.

A solar energy system is installed on the building and includes 353 m^2 (3800 ft^2) of liquid-type flat-plate collectors mounted on the roof of the building and able to be tilted at angles from 20 to 60 degrees. In the winter, the system is operated with an ethelyene-glycol/water solution as the collector fluid and a heat exchanger is used between the collector loop and the building solar storage loop. For summer operation, water is used as the collector fluid and the heat exchanger is bypassed. Energy collected in the solar array can be stored in one of three 37.850 k≅ (10,000 gallon) storage tanks located in the basement. The design calls for solar heated water to be used to fire the absorption chiller, to be used in the hot water heating system, and solar heated water could potentially be used in the heat pump system (the control system which existed during the first 3 years of operation prevented this from happening). The solar system can also supply energy to the domestic hot water system. If no solar energy is available, the domestic hot water is heated by a natural-gas-fired storage water heater. In the summer, one tank is available as a chilled water storage tank.

In addition to engine-generator heat recovery, two other energy recovery options were designed into the mechanical systems. One was to utilize condenser water from the chillers in the hot water heating system by means of a double-bundle condenser. The other scheme was to operate the electric chiller as a heat pump to produce hot water for the hot water heating system from low temperature water stored in the tanks (false loading). These options have not proven to be feasible in the operation of the building because hot water heating system temperatures have been elevated above maximum condenser operating temperatures (41°C (105°F)) during mid-winter to insure occupant comfort. During mild weather, when the hot water heating system temperature is lowered, the solar system can supply energy to meet the heating requirements.

The building has two distinct control systems for the mechanical equipment. A pneumatic system provides basic control functions and device actuation. Linked to the pneumatic system is a minicomputer which was installed primarily for data collection. However, the computer was also designed to provide some overall control functions such as solar system mode selection, nighttime thermostat setback, and maintenance management. In addition, the computer monitors over 900 binary and analog sensors, allowing the building operators to watch critical equipment and set up alarm signals for changes of state. The computer will be described in more detail in section 2.5.

2.4 LIGHTING SYSTEMS

Various types of lighting systems are used throughout the building. The fourth floor uses high pressure sodium lamps. The fifth uses floor lighting that is built into furniture and illuminates only the task areas. The remaining floors use fluorescent lighting systems with various lamp spacings and lens arrangements. All systems will be described more fully in chapter 4.

2.5 MINI-COMPUTER DATA ACQUISITION SYSTEM

The installed minicomputer is a Johnson Controls JC-80/55 system.* It was designed to perform a number of monitoring and control functions as well as to serve as a data acquisition system (DAS). Use of the JC-80 as a DAS is accomplished by using software packages and hardware supplied with the system.

Loop Remotes: Figure 5 illustrates the system configuration for the JC-80. Each of the sensors for the instrumentation system interfaces to the computer through a cabinet called a loop remote. There are 19 loop remotes in the building. A loop remote contains up to 50 point module cards, each of which may be connected to from four to eight sensors depending on the sensor type. The loop remotes contain the circuitry to convert the sensor analog signal (electrical current) to a digital value. The loop remotes are interrogated

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* Commercial equipment is identified in this publication in order to adequately describe the data acquisition system used. Such identification does not imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the materials or equipment identified are necessarily the best available for this purpose.

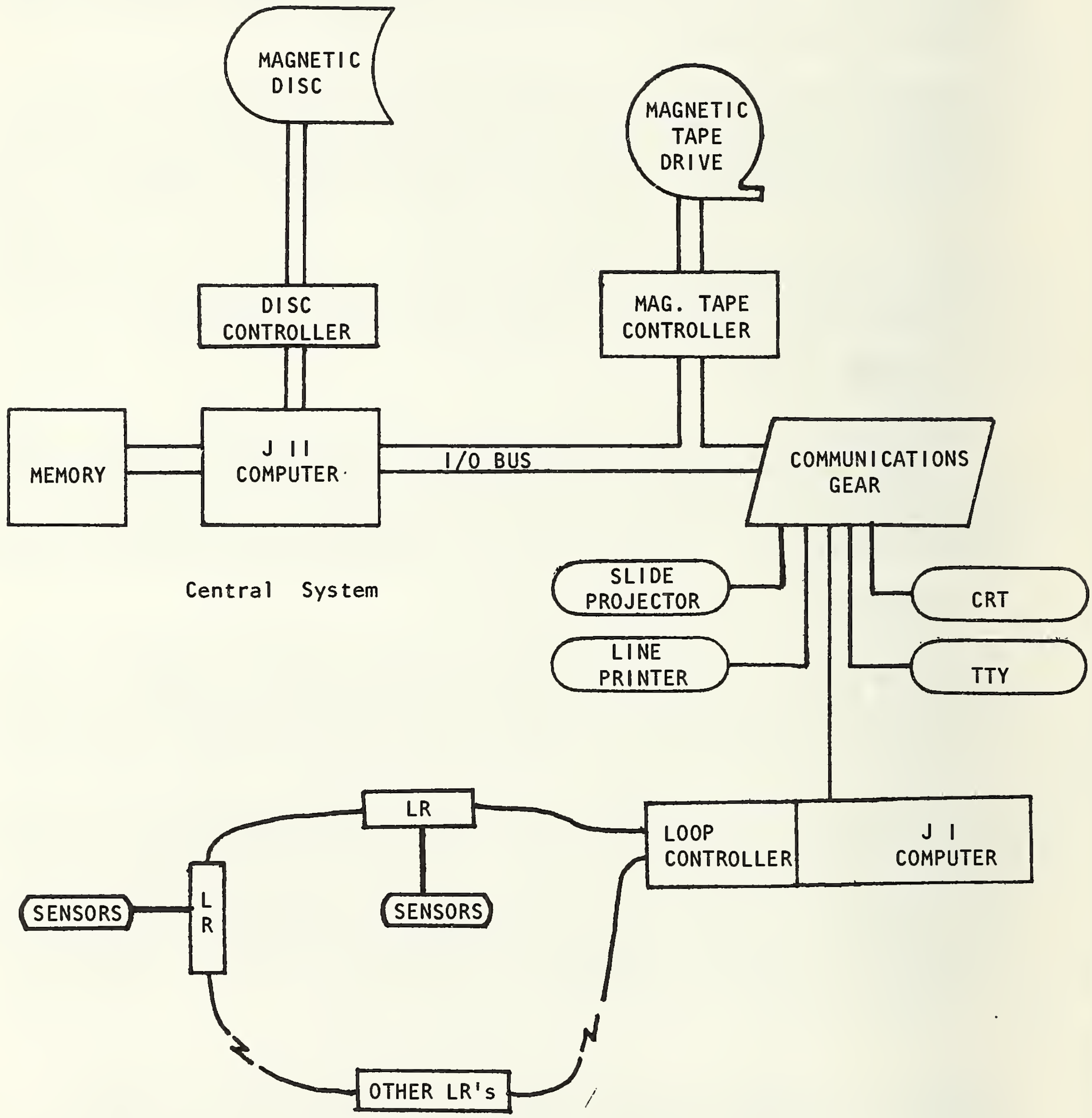


Figure 5. Diagram of Johnson Controls JC-80-55 minicomputer system configuration at Norris Cotton Federal Office Building

sequentially by the loop controller, which is actually a separate 16K (16 bit words) processor, and updated sensor values are transmitted to the central system.

JC-80 Central System: The JC-80 central system makes a scan of the system points approximately every 20 seconds. Sensor point values which have changed by an amount called the filter increment are updated and stored in the central system 1/2-megaword magnetic disc storage. The central system executes the software to convert the digital value coming from the loop controller to a digital number in engineering units by using equations appropriate to the sensor type.

A number of software programs allowed the JC-80 to function as a DAS. One of these is the calculated point software which is used to calculate a quantity using the sensor point values as input to a specified equation. The most important equation used is one which calculates an average value from instantaneous values for a particular sensor over an hours' time. The averaging equation is executed a number of times during an hour and is set up so that the average stored in the JC-80 is the average up to that point in time. The average is reset to zero at the start of each hour. The number of times the equation is applied to each point in an hour is determined by a quantity which may be called the calculated point interval (CPI). For each analog data point, there is a CPI in minutes representing the time period between applications of the averaging equation. As the specified value of calculated point interval is decreased, the value of the calculated average approaches the true average value.

A second calculated point equation is used to totalize values from pulse counters over an hours' time. Pulses are generated by contacts mechanically connected to electric watt-hour meters with the number of pulses per hour being proportional to the number of kilowatthours passing through the meter. One other calculated point equation converts air flow differential pressure values to units of ft^3/min.

In order to store hourly averaged values of the system points on magnetic tape, data logger software takes the averaged values for each hour and places them in storage locations on the system disc. Each night at midnight, the data logger routines write 24 hours of data on magnetic tape.

A cathode ray tube terminal (CRT), lineprinter, and teletypewriter (TTY) are available as peripherical devices for operator interface to the JC-80. It is possible to display or log current values of system data points on the CRT, TTY, or lineprinter. A trend log can be programmed to produce lists of system point values as a function of time.

DAS functions of the JC-80 can be influenced through the operator interfaces. Points which are written to magnetic tape by the data logger can be selected and changed and the filter increments associated with the points can be varied.

One other valuable peripherial is a modem-telephone coupler which allowed NBS to access the JC-80 from Washington, D.C. via telephone lines using an NBS terminal. This feature allowed studies to be made of the adequacy of the hourly averaging process and enabled NBS to study equipment performance on a minute-by-minute basis.

Instrumentation Sensors: The JC-80 data logger software writes hourly averaged values to magnetic tape for 720 instrumentation sensors. Of these 720 points, 107 are from binary sensors indicating on-off or mode status for various pieces of equipment in the building. Of the remainder, 98 points are kilowatt-hour points and 515 are analog points. The analog point values are derived from nine types of analog sensors, listed in table 1.

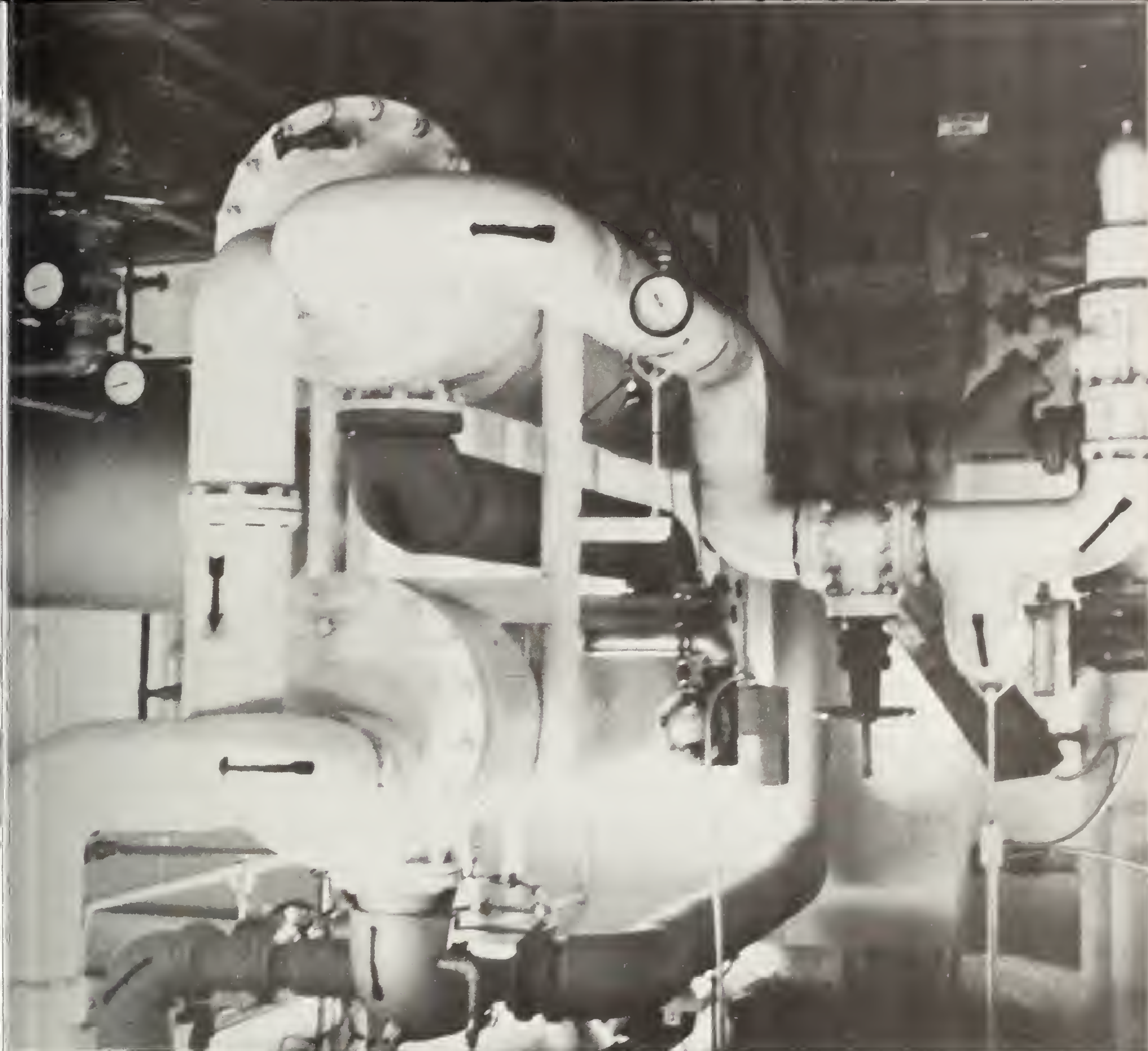
A detailed description of all the software and procedures used at NBS to reduce and analyze the data from the JC-80 system and analysis of one year of data are in reference [5].

Table 1. Analog sensor types installed in the Norris Cotton Federal Office Building

Sensor type	Quantity	Description
Liquid flow meters	79	Impact tubes combined with reversed static tube; pressure differential fed into transducer
Air flowmeters	55	Array of pitot tubes to determine average air velocity in ducts.
Liquid temperature Air temperature	286	Nichrome wire-wound resistance temperature elements.
Air dew point temperature	49	Nichrome wire-wound resistance temperature elements combined with dew-cells.
Air humidity	6	Humidity elements
Flue gas temperature	7	Thermocouples
Natural gas flow	7	Positive displacement meters
Illumination	15	Photo-electric cells
Solar radiation	5	Pyranometers

Facing Page:

Solar system piping located in the Norris Cotton Building mechanical penthouse



3. BUILDING THERMAL PERFORMANCE

3.1 ENERGY CONSUMPTION

Overall building energy consumption for the first 3 years of operation was compiled on a month-by-month basis and is shown in figure 6. The three lines represent usage during the three separate years. A decline in energy consumption is obvious. Values of total annual energy consumption per unit of floor area are given in table 2 for various 12 month periods. Again the decline in consumption is apparent. The total consumption for the third operating

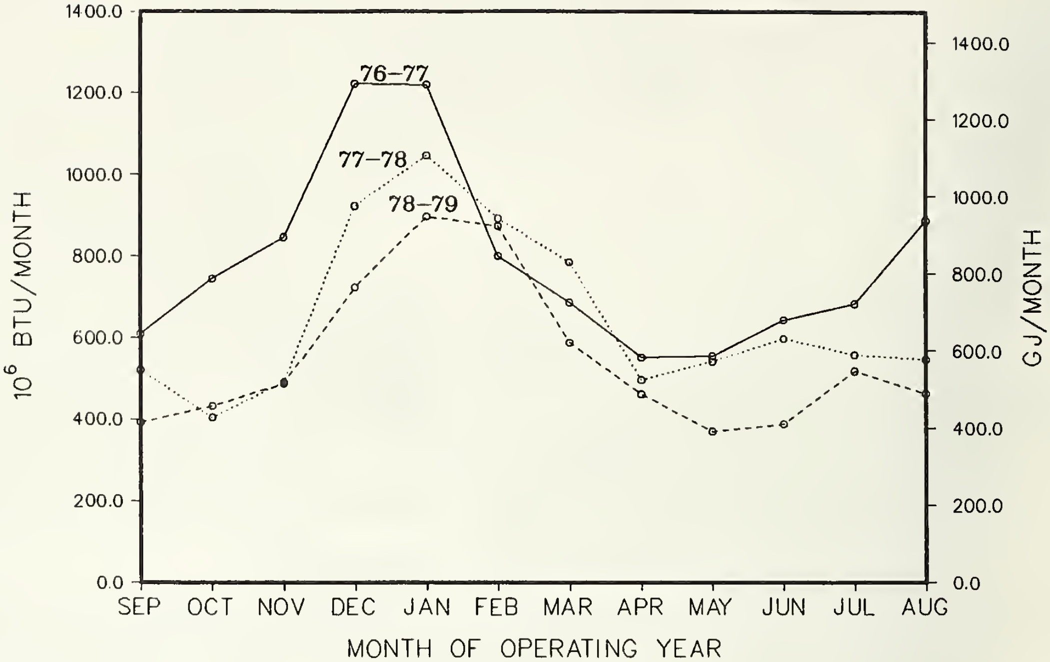


Figure 6. Total energy consumption of the Norris Cotton Federal Office Building

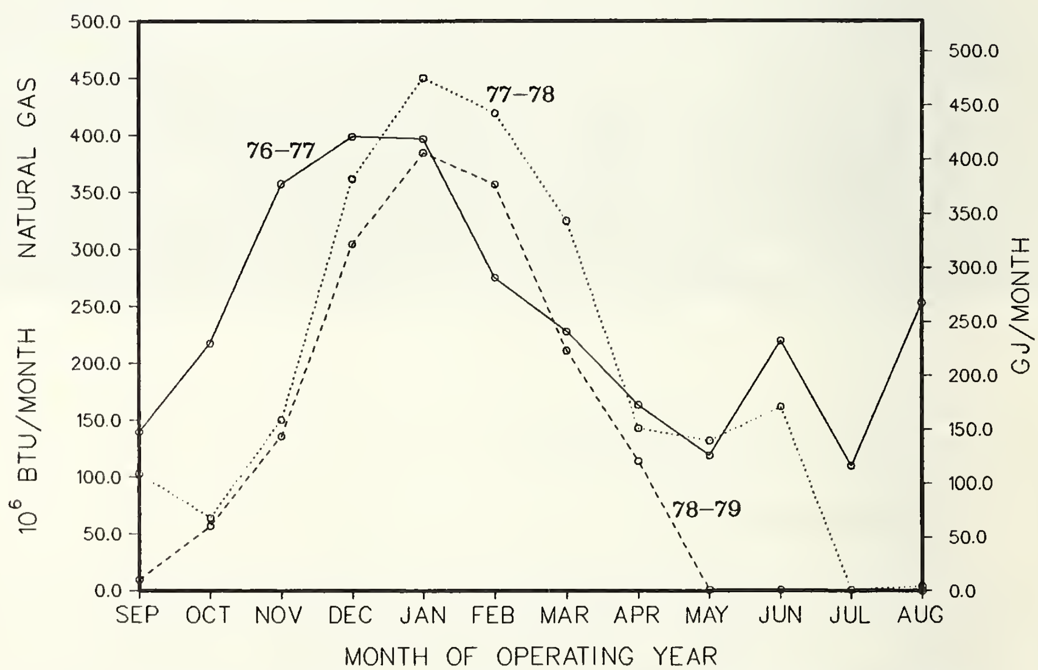


Figure 7. Natural gas consumption at the Norris Cotton Federal Office Building

year, 641 MJ/m^2 (56.2×10^3 BTU/ ($ft^2 \times yr$)), is within 5 percent of the original design goal of 625 MJ/m^2 (55×10^3 BTU/($ft^2 \times yr$)). However, even though the actual energy consumption was close to the design value during the third year, it must be emphasized that the building was still not operating entirely as designed. The operation of some mechanical equipment and the performance of the building envelope have not met design expectations. On the other hand, operating strategies not in the design have been used and have resulted in a savings in energy.

Effect of Building Operation: During the first year of operation, several minor problems occurred such as simultaneous heating and cooling of a space by adjacent heat pumps on the second floor, 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 of this experimental building created proportionately more problems. Other events which have impacted energy consumption over the 3-year period are the operation of the solar collectors, which began in the spring of 1978, the way in which the building has been cooled during the summers, and reduction in air infiltration through caulking of the building facade (December 1978) and modification of the outside air dampers (October 1977).

The building was designed to be cooled with two chillers, as explained previously. During periods of strong sunshine, the absorption chiller was to be run on solar-heated water and the electric chiller (if needed) to be run on purchased electricity. Excess solar energy would be placed in storage for later use. With no solar energy available and stored energy depleted, the electric chiller was designed to operate from electric power produced by the natural-gas-fired engine-generator. A waste heat recovery system on the engine would produce the hot water required to drive the absorption unit. Excess cooling would be stored in the form of chilled water for use at a later time.

Table 2. Norris Cotton Federal Office Building annual energy consumption

Year	Total energy used, MJ/m^2* (Btu/ft^2)*
September 76 - August 77	919 (80.6×10^3)
January 77 - December 77	813 (71.3×10^3)
September 77 - August 78	758 (66.5×10^3)
January 78 - December 78	730 (64.0×10^3)
April 78 - March 79	693 (60.8×10^3)
September 78 - August 79	641 (56.2×10^3)

* equivalent gross floor area = 10,900 m^2 (117,334 ft^2)

During the first summer, attempts were made to use the solar collectors but they were not able to heat any of the 37.85 kL (10,000 gallon) storage tanks in the basement of the building to the required minimum of 88°C (190°F) for driving the absorption chiller. As a result, the engine-generator was put into operation manually. However, the engine-generator could not produce the required waste heat to drive the absorption chiller and the electric chiller alone was not able to maintain design conditions in the building. GSA contractors spent time throughout the first summer attempting to operate the engine-generator as designed. In late July, GSA had the plumbing in the penthouse modified so that the fuel oil boilers, originally included as backup equipment, could be used to directly fire the absorption chiller. During the second year, the oil boilers were used as before, but the engine-generator was only used for a short period at the beginning of the summer. Thus, while summer oil consumption remained about the same, the second year natural gas use was greatly decreased. This trend can be seen in figures 7 and 8 where the energy use for natural gas and fuel oil, respectively, are plotted on a month-by-month basis.

With regards to the engine-generator, a modification was made prior to the start of the 1978 cooling season. Additional electrical loads were placed on the generator in order to boost the engine's heat output. However, automatic controls that were designed to protect the engine from overheating still prevented the production of usable waste heat. Before the exiting water from the engine reached a high enough temperature for full operation of the absorption chiller, the controller diverted the engine cooling loop through an evaporative cooling tower, "dumping" the waste heat without using it.

During both of the first two summers, an attempt was made to meet peak daytime cooling loads by making use of stored chilled water that had been cooled by the electric chiller during the previous evening. In concept, such a control scheme should have enhanced chiller efficiency because it allowed the chiller to operate at night when the outside air was normally cooler compared to the daytime temperatures. Another advantage of using thermal storage in this way is that high daytime demand peaks, which are usually subject to additional charges by the utility company, should have been reduced. However, this mode of operation proved to be ineffective. Safety interlocks within the chiller that protect it from freezing prevented the water in the storage tank from reaching a suitably low temperature. As a result, the storage tank was normally depleted of its cooling capacity well in advance of the peak daytime cooling period. In addition, since the tank could not be dropped from the circuit, jacket and piping heat gains tended to decrease the chiller's ability to meet the loads. During the third summer, the storage tank was not being used for chilled water. Instead, the building engineers made maximum use of cool outside air at night and the thermal capacity of the masonry walls. By starting the day with the building pulled down to a reasonably low temperature, the chiller was generally able to maintain comfortable temperatures without the need for stored chilled water.

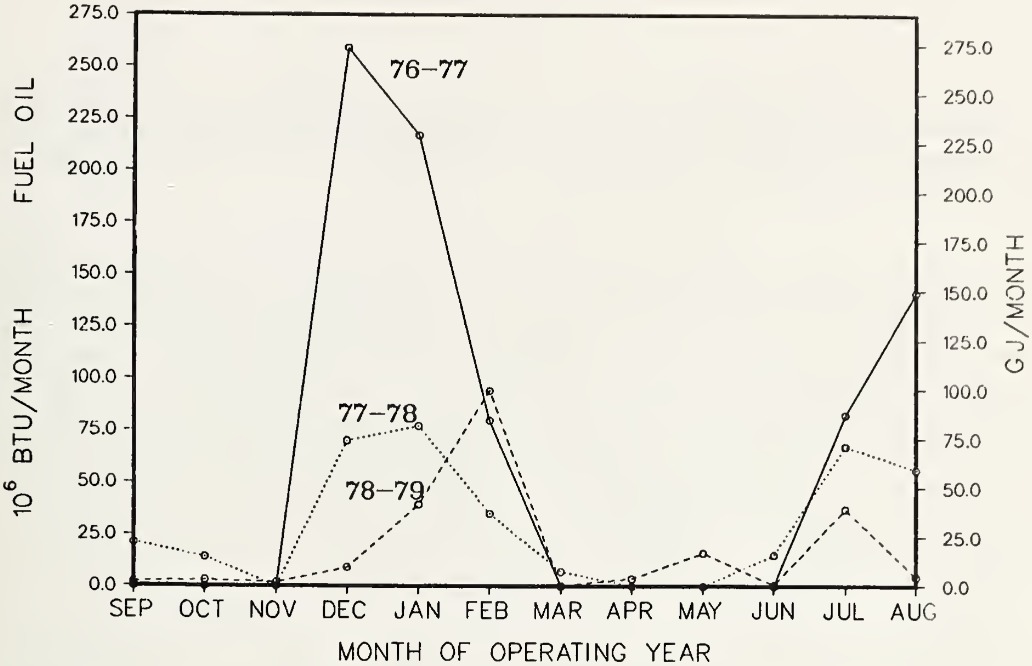


Figure 8. Fuel oil consumption at the Norris Cotton Federal Office Building

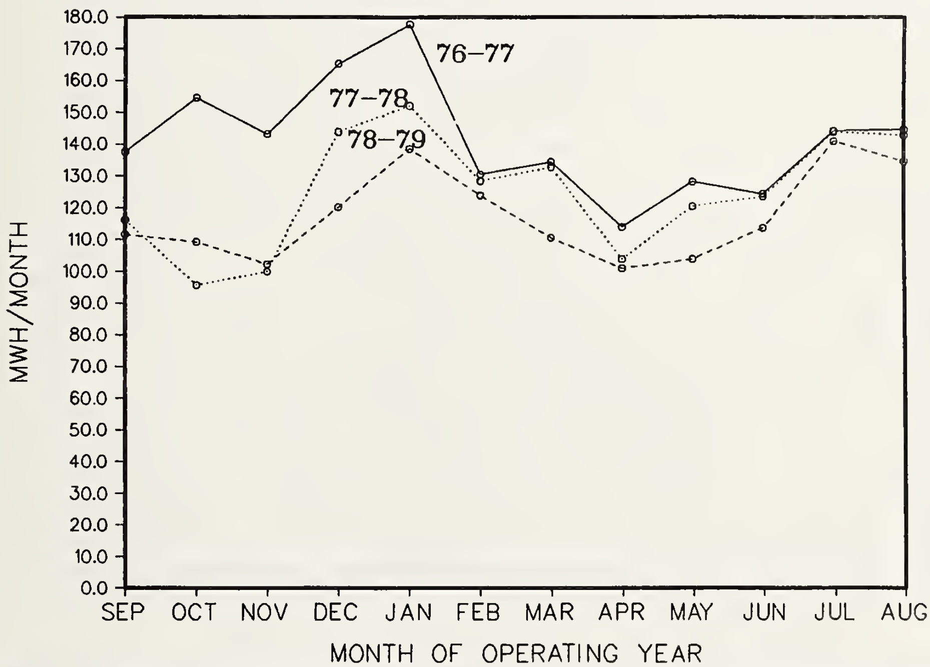


Figure 9. Electric energy consumption at the Norris Cotton Federal Office Building

Figure 9 shows the electrical energy consumption for the building on a month-by-month basis. As with the other two energy sources, the electrical consumption declined and the month-to-month variation smoothed out over the three year period.

In October 1978, a majority of the 98 kilowatt-hour meters installed throughout the building were proven to be incorrectly wired and were rewired. During November 1979, the kWh meter data were used to produce an energy balance for the electrical energy consumed at the building on a monthly basis. Even though the data include two months from the fourth year of operation, they provide a breakdown of electric energy consumption into a number of categories such as floor-by-floor lighting energy consumption, energy consumed by elevators, and electrical consumption by HVAC equipment such as pumps, fans, and chillers. Figure 10 shows the monthly consumption of electrical energy by major categories of load. The data show that the lighting load is relatively constant, as expected. Miscellaneous electrical load, which includes receptacles, elevators, and other-HVAC loads, varies through the year with a maximum in midwinter. This miscellaneous electrical energy peak is due to the use of driveway snow-melting equipment (resistance heaters). The HVAC load exhibits expected seasonal variation with its maximum in the summer.

For the third year of operation, the electrical energy consumption accounted for 73 percent of the total, natural gas, 24 percent, and fuel oil, 3 percent. Use of fuel oil to fire the absorption chiller accounted for less than 1 percent of the total.

Effect of Weather on Energy Consumption: The weather conditions in Manchester have not been the same from year to year. Thus, it is useful to normalize the data in figure 6 to the ambient temperature. By plotting energy consumption for each month versus the average monthly ambient temperature and fitting lines through the points for each year, a set of curves such as those shown in figure 11 result. The data for each year can be fit by two straight lines, one representing summer operation and one representing winter operation, with residual* standard deviations less than 150 GJ (10^6 Btu)/month. The curves for each succeeding year of operation are lower, indicating lower energy consumption. The winter curve for 1977-78 is skewed with respect to the 1976-77 and 1978-79 curves. The apparent cause of this is the way in which the building was operated during part of the 1977-78 winter. In order to achieve acceptable comfort levels in the building, the system operators kept the building in the occupied mode 24 hours per day only during the coldest months of that winter, eliminating the night set-back. This produced higher energy consumption at lower outside temperature levels. The most noticeable improvement which may be observed in this figure is for summer operation. The low 1979 curve reflects the use of early morning flushing of the upper four floors with outside air and the abandoning of chilled water storage.

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* A residual is the difference between the value of an actual data point and the value predicted by a least squares fitted curve.

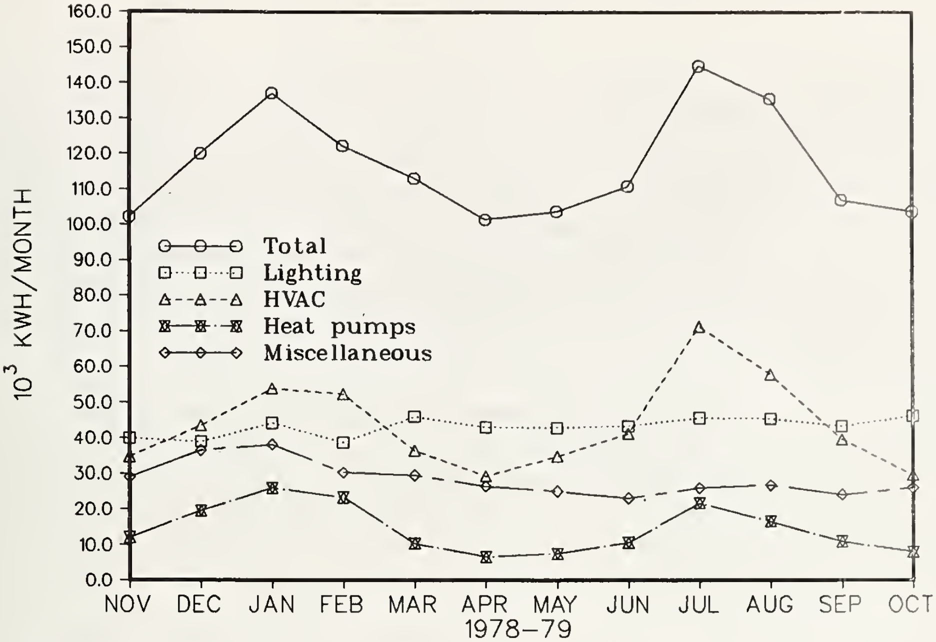


Figure 10. Breakdown of monthly electric energy consumption by load for the Norris Cotton Federal Office Building

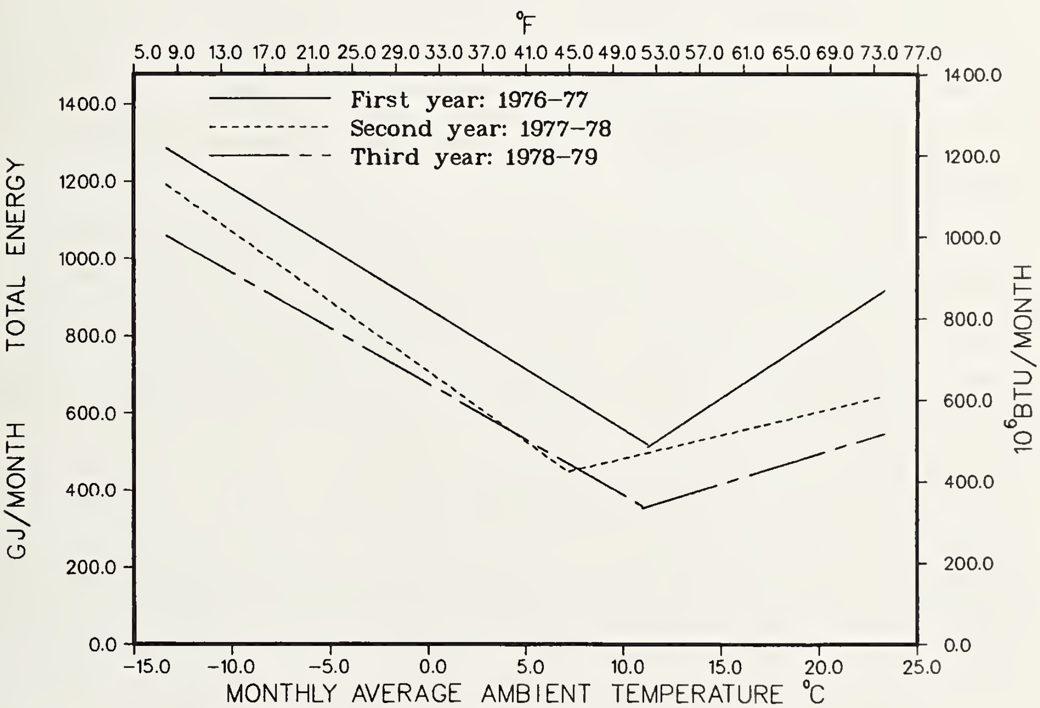


Figure 11. Measured total energy consumption versus average monthly ambient temperature for the Norris Cotton Federal Office Building

3.2 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 staff members 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 infrared (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, there is a reasonably direct correlation between surface temperature and total radiated energy.

The IR scanner used for thermographic tests looks and acts much like a closed circuit TV system. A camera picks up an image which is then converted to an electrical signal. The camera, however, is sensitive not to visible light but to IR. Electric 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 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 a higher degree of resolution. In this report, 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 variation 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 besides 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 12 and 13 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 design 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 equal 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 13). 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 12 and 13. 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 15) 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 explains why both the inner and outer wall surfaces were cold 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 into the building, it comes into direct contact with the inner masonry blocks and causes cooling. To test this theory, the suspended ceiling was removed near the wall on the second floor as shown in figure 16. Cold air was found to be leaking into the ceiling space at a location where a steel supporting structure extended through the insulation (circled area in figure 16). The corresponding thermogram, figure 17, shows the 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. More complete details on this survey are given in reference [6]. 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,

Figure 12. First floor east, interior wall of the Norris Cotton Federal Office Building

Figure 14. First floor east, exterior wall of the Norris Cotton Federal Office Building

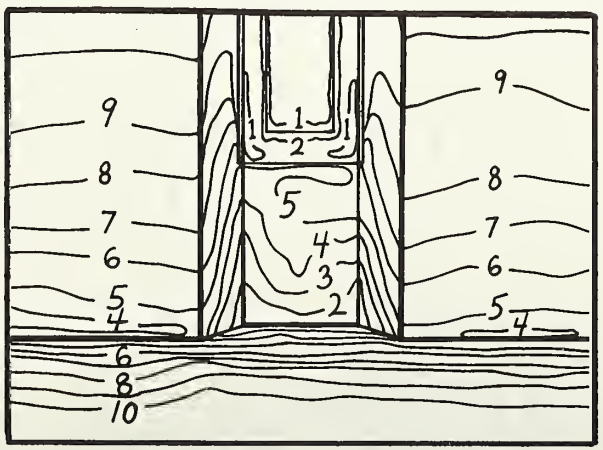


Figure 13. Results of the thermogram on the first floor east, interior wall of the Norris Cotton Federal Office Building (1 - coldest isotherm, 10 - warmest isotherm)

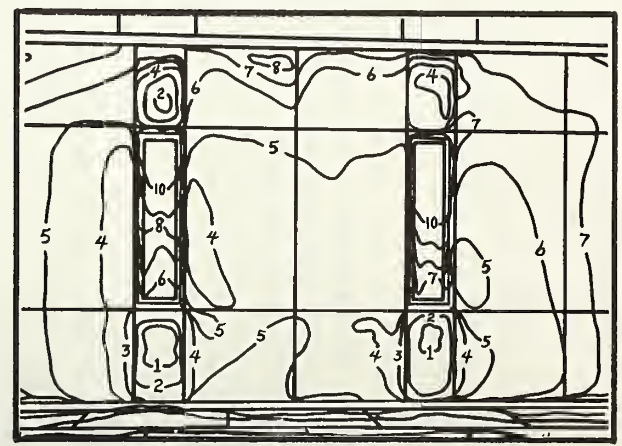


Figure 15. Results of the thermogram on the first floor east, exterior wall of the Norris Cotton Federal Office Building (1 - coldest isotherm, 10 - warmest isotherm)

Figure 16. Ceiling with one tile removed on the second floor, west interior wall of the Norris Cotton Federal Office Building

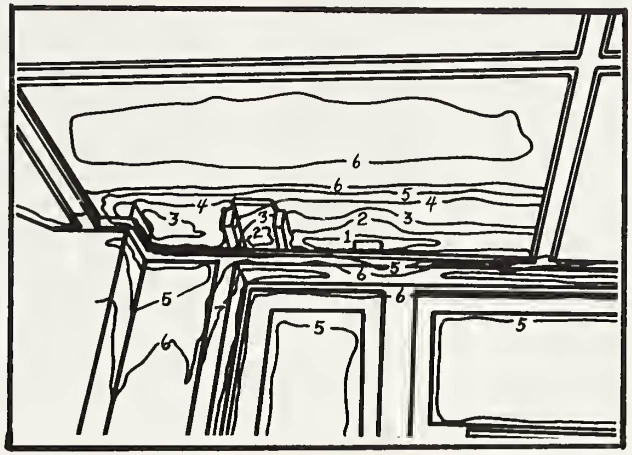


Figure 17. Results of the thermogram on the second floor, west interior wall of the Norris Cotton Federal Office Building (1 = coldest isotherm, 10= warmest isotherm)

Figure 18. Properly insulated wall, sixth floor, east interior wall of the Norris Cotton Federal Office Building

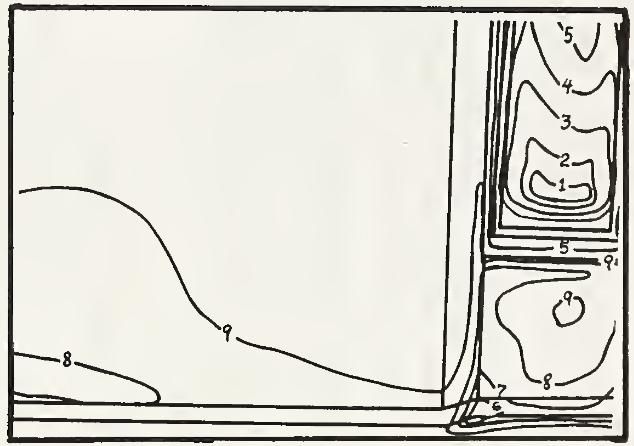


Figure 19. Results of the thermogram on the sixth floor, east interior wall of the Norris Cotton Federal Office Building (1 = coldest isotherm, 10 = warmest isotherm)

to some extent, the same problems found on the second floor. Even the north wall on the third floor was found to be substantially cool. 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.

There were some areas that were free of this air leakage problem. Figures 18 and 19 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 technique and are discussed in section 3.3. The results indicated higher air change rates on the first three floors than on the upper four floors. This was consistent with the thermographic analysis that indicated more cold air in the cavities on the lower three floors.

3.3 AIR EXCHANGE ANALYSIS

Along with the thermographic measurements made in February 1977, tests were conducted to determine the rate at which outside air was entering the building [7,8]. Subsequently, the outside air dampers were modified to reduce excessive leakage and the building facade received extensive caulking. Two years later, in February 1979, the air exchange rates were re-determined [9].

A tracer gas techique was used to measure air exchange rates [10,11]. Sulfur hexaflouride (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 which could be safely used in an occupied building.

Floors one through three and four through seven of the building are served by separate ventilating systems. The main features of these systems are represented schematically in figures 20 and 21. These diagrams include only elements which control the main air flows to and from the building. Figure 22 is a more detailed diagram showing toilet exhausts and components of the HVAC system.

Tests before Caulking of Building and Damper Modification: The results of the tests conducted in 1977 will be described first. Measurements were made not only of the overall building air exchange rates but also of the air exchange rates between the floors. These will then be compared with the results of the measurements made in 1979.

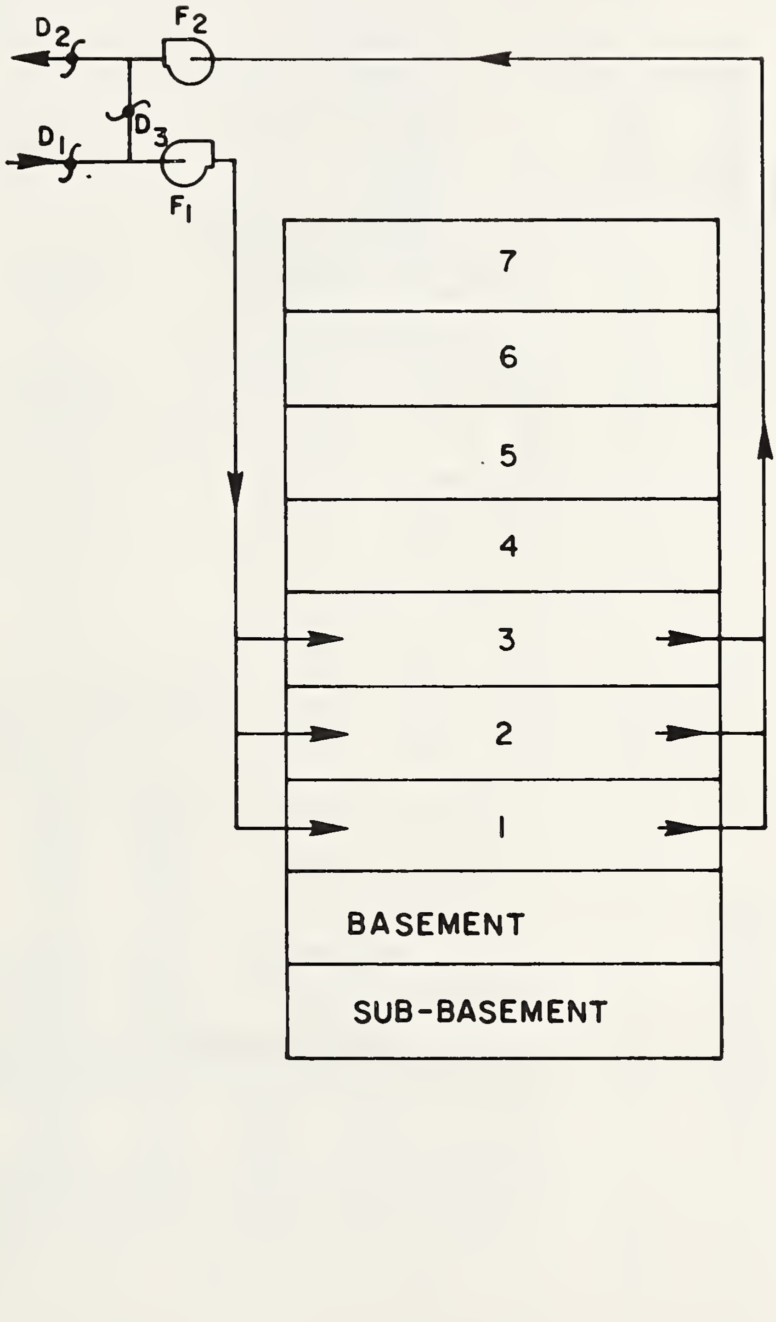


Figure 20. Simplified schematic of the main ventilation system of floors 1-3 in the Norris Cotton Federal Office Building

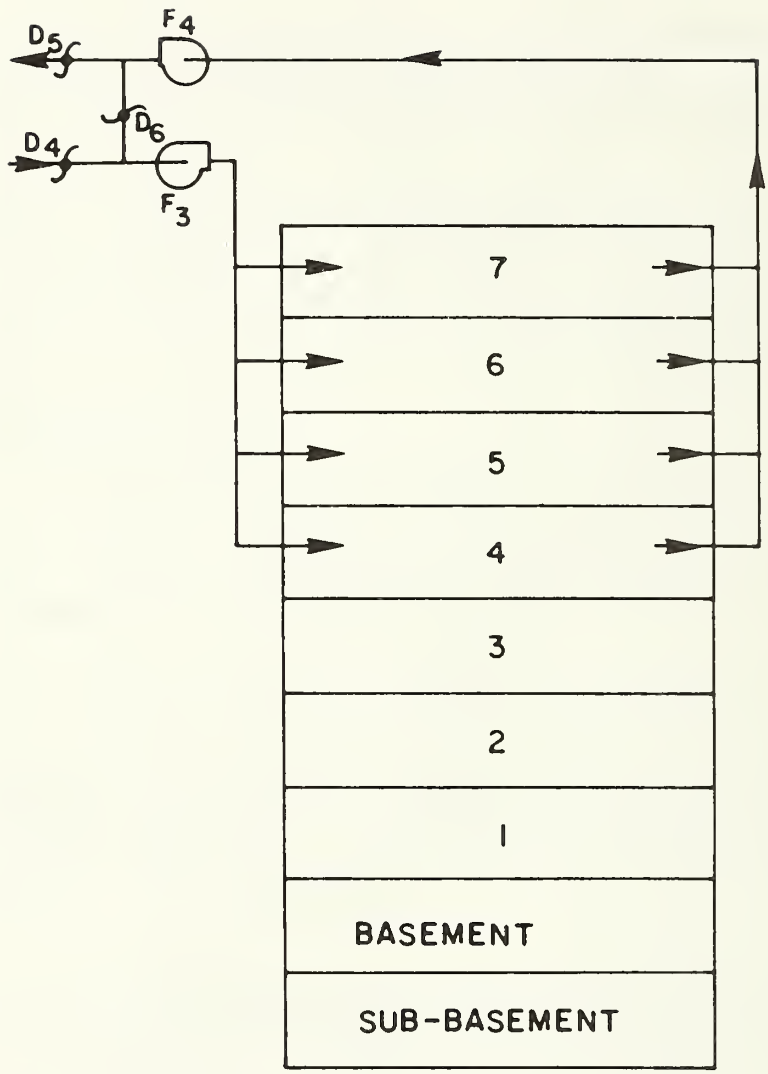
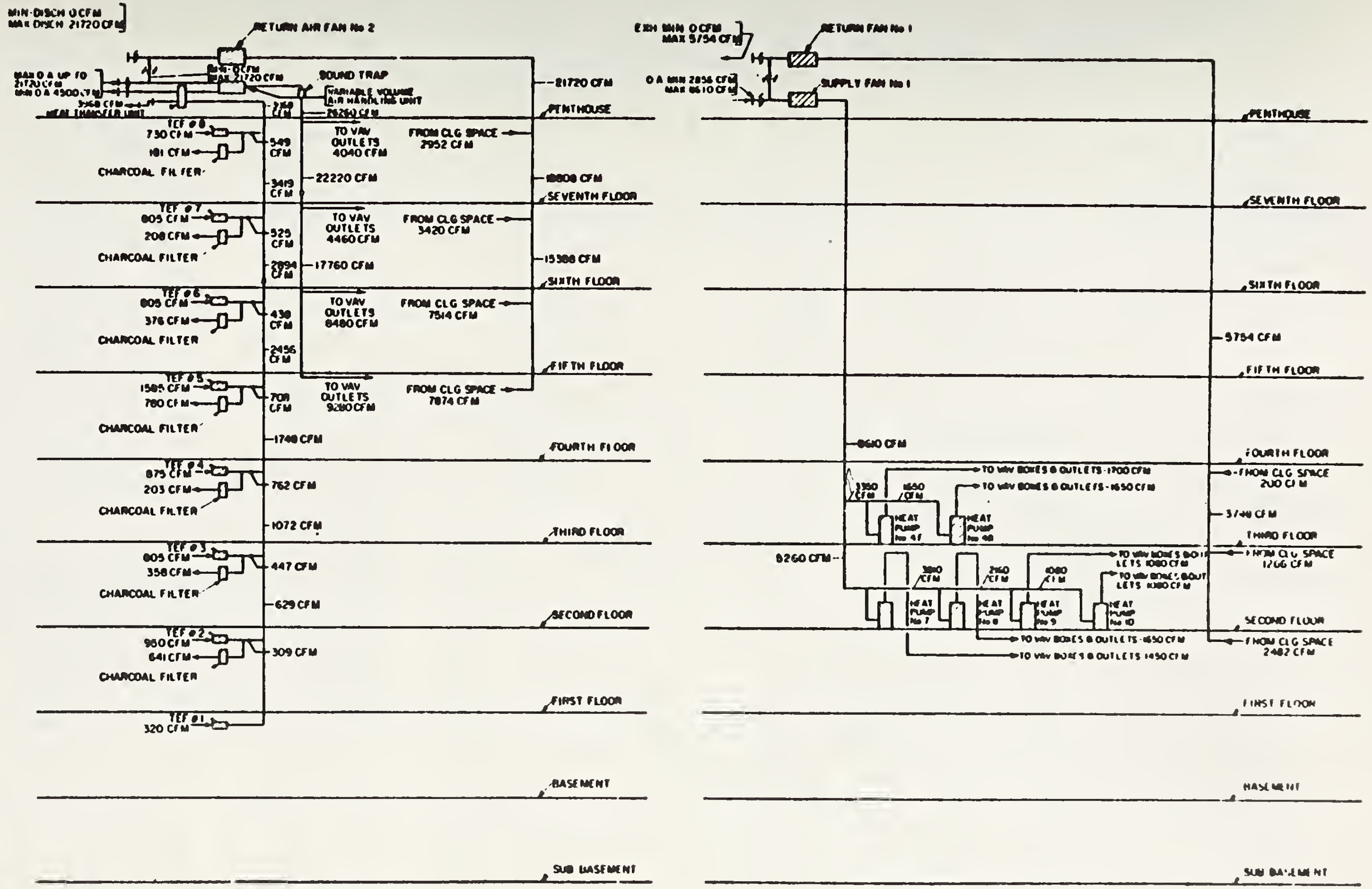


Figure 21. Simplified schematic of the main ventilation system of floors 4-7 in the Norris Cotton Federal Office Building



DUCT FLOW DIAGRAM
CENTRAL VAV SYSTEM

INTERIOR ZONE HEAT PUMP
DUCT FLOW DIAGRAM

Figure 22. Diagram of the ventilation systems in the Norris Cotton Federal Office Building

In conducting the measurements, SF_6 was injected into the ventilating system immediately upstream from the return fans, F_2 and F_4, in figures 20 and 21 respectively, and its concentration was monitored in the output of these fans. Injections of approximately 100-120 ml SF_6 for each air-handling system were required to establish initial concentrations slightly less than 10 parts per billion in the ventilated space. In repeat runs, smaller amounts were injected to bring the concentration back to the initial starting level. Initially about an hour was allowed for the tracer to distribute and for the concentration decay to stabilize, followed by an hour of concentration measurements. Thereafter, about 10 minutes were allowed for stabilization before each run.

The ventilating systems were operated with the outside air dampers, D1 and D4 in figures 20 and 21, closed to obtain nominal 100 percent recirculation while dampers D3 and D6 were open. In the first measurements, SF_6 was introduced only to the main ventilation systems of floors 4 through 7. In this way, any air rising from the lower floors due to thermal convection or any other mechanism should have been essentially free of tracer. It was felt that comparison of measurements obtained using tracer on the upper floors only with measurements obtained with tracer distributed throughout the entire building would provide an approximate estimate of the relative amount of air leakage to floors 4 through 7 from the outside and from the lower floors. The result after adding SF_6 to floors 4 through 7 is shown on line one of table 3. Tracer was then added to the entire building, and the result is shown on line two of the table. An apparent exchange rate of 0.7 air change per hour was obtained for floors 4 through 7 when air from the lower floors contained no tracer, and 0.54 air change per hour when tracer was introduced into the entire building. This suggests that approximately 0.1 to 0.2 air change per hour were due to air rising from the lower floors. The air exchange rates for floors 1 through 3 were higher than those of the upper floors when operating in the nominal 100 percent recirculation mode. This is consistent with the findings of the thermographic analysis where the lower three floors had a greater problem with cold walls.

In the final tracer measurements during February 1977, the outside air dampers to floors 4 through 7 were opened and operated in the variable volume mode. The dampers for floors 1 through 3 were not opened because of problems in supplying sufficient heat to these floors at that time. Under these conditions, air exchange rates for the upper floors were higher than for the lower floors, as might be expected. The results are shown on line three of table 3.

The air leakage rates for floors 1 through 3 were 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 lower floors, or (2) the building was operating under slight negative pressure when all the outside air dampers were closed, and opening dampers raised this pressure to where it was more nearly equal to the outside pressure.

Table 3. Results of air exchange measurements in the Norris Cotton Federal Office Building

Date	Floors 1-3 Air changes/hour	Floors 1-3 Dampers	Floors 4-7 Air Changes/hour	Floors 4-7 Dampers	Building Average
1[a]. February 1977	-	-	.72[c]	Closed	-
2[b]. February 1977	1.05[c]	Closed	.54[c]	Closed	.75
3[b]. February 1977	.80[c]	Closed	1.09[c]	VAV[g]	.97
4[b]. February 1979	.75[d]	Closed	.39[e]	Closed	.54
5[b]. February 1979	1.20[f]	Open	.86[f]	VAV[g]	1.01

a). Tracer added to upper floors only
b). Tracer added to whole building
c). Average of two measurements
d). Average of four measurements
e). Average of five measurements
f). Average of three measurements
g). Normal operation in variable air volume mode with minimum outside air dampers open

Weighted average exchange rates for the entire building were calculated assuming that floors 1 through 3 represented three sevenths (3/7) of the building volume and floors 4 through 7 represented four sevenths (4/7).* The results are shown in the right-hand column of table 3. Air exchange rates on the order of 0.7 to 0.8 air change per hour were obtained with complete recirculation, and 0.9 to 1 air change per hour with the upper floors operating in the variable volume mode. These estimates include air exchange rates due to toilet exhausts which are designed for 1.873 m^3/s (3968 cfm). This corresponds to 0.22 air change per hour in a 31,150 m^3 (1,100,000 ft^3) building. There is also a special exhaust to a medical examination room on the fourth floor which can be turned on. This has a rated capacity of 0.7513 m^3/s (1592 cfm) or about 0.09 air change per hour averaged over the entire building when operating.

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 through 3 and 4 through 7, but they were too small to measure quantitatively under the conditions of the experiment. A slightly greater increase in concentration was found in the penthouse near the elevator. This suggests that the elevator shaft is one of the leakage paths. However, the results also suggest that air exchange with the basement is not a major pathway of air leakage in the building.

<u>Tests After Caulking of Building and Damper Modification</u>: During February 1979, 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 occured throughout the day in the operation of certain exhaust fans and dampers but these 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 (VAV) mode. In 1977, this configuration was not used, as mentioned previously, because heating problems prevented opening the dampers to floors 1-3. Therefore, when making comparisons between the 1977 and 1979 results, the first case (dampers closed) is of greater importance since this configuration was the same for both tests. The second case is important for estimating energy use, however, since it is more representative of the way in which the building is actually operated.

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* The volume of the ventilated space was estimated from floor areas and ceiling heights. The floor area of floors 1 through 7 is approximately 1330 m^2 (14,300 ft^2). The floor-to-floor heights are 4.0 m (13 ft), except for the first floor where it is 5.2 m (17 ft). These dimensions correspond to a gross volume of approximately 36,800 m^3 (1,300,000 ft^3). Allowing 15 percent for inside partitions and furnishings results in a rounded estimate of 31,150 m^3 (1,100,000 ft^3).

The results of the 1979 test are shown on lines 4 and 5 of table 3. With the outside air dampers closed, the air exchange rate was 0.75 air change per hour for floors 1-3 and 0.39 for floors 4-7. The weighted average for the building was 0.54 air change per hour which was a decrease of approximately 28 percent from the 1977 value of 0.75. This improvement is considered to be 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.

The average inside volume of the Building has been estimated to be about 31,150 m^3 (1,100,000 ft^3) as explained previously. The average air exchange rate of 0.54 air change per hour (outside air dampers closed) corresponds to about 4.7 m^3/s (9900 cfm). If the number of occupants is assumed to be 280 people (an estimate based on counts made in 1977), the amount of outside air corresponds to 0.017 m^3/s (35 cfm) per person. This can be further broken down for the lower three and the upper four floors where the air exchange rates were different. On floors 1-3, with an average air exchange rate of 0.75 per hour, and an average occupancy of 135, the average ventilation rate per person is about 0.021 m^3/s (45 cfm), while for floors 4-7, with an air exchange rate of 0.39 per hour and an average occupancy of 168, it is about 0.012 m^3/s (25 cfm) per person. The recommended level for office space is 0.007-0.012 m^3/s (15-25 cfm) per person in ASHRAE Standard 62-73 [12], and may be reduced in a subsequent revision. Thus, after retrofit to reduce leaks, the average ventilation rate of the building still meets or exceeds the requirements of the present ASHRAE Standard with outside air dampers closed.

At the time of the 1977 measurements of air exchange rates, measurements were made of the CO_2 concentration within the building. On the two days prior to making the air exchange measurements, February 15 and 16, the main ventilating system to floors 4-7 was shut down while adjustments were being made to the heating system. The system to floors 1 through 3 was operated with outside air dampers closed. This afforded an opportunity to measure carbon dioxide levels in the building under conditions of restricted ventilation. An air sample was collected from each floor and analyzed for CO_2. Sampling points were not selected to be representative of the entire floor but were located in the rooms containing the most people. This was done to obtain approximate maximum levels of CO_2. The results are shown in tables 4 and 5. About 65 percent of the values ranged from 700 to 1200 ppm or roughly two to three times normal ambient levels (400 ppm). The highest concentration of CO_2 observed was 2440 ppm or 5-1/2 times the outdoor level. This concentration was obtained in a room on the fourth floor, where 11 people were taking an examination.

CO_2 measurements were also made on February 17 with the main ventilating fans to floors 4-7 operating. The results are shown in table 6. The change in average CO_2 concentration was small, but there was slightly greater uniformity from floor to floor. also, with 16 people in the fourth floor room, the CO_2 level was less than for the preceding day with 11 people.

Table 4. Carbon dioxide in air samples taken from various floors in the Norris Cotton Federal Office Building, February 15, 1977, 3:00 to 5:00 p.m.[1]

Floor	No. of people on floor	No. of people in room sampled	CO_2 ppm	Ratio of indoor to outdoor CO_2 concentration
1	-	-	-	-
2	48	30	700	1.6
3	32	9	675	1.5
4	17	4	1500	3.4
5	55	15	1250	2.8
6	60	17	1175	2.7
7	26	12	1225	2.8

[1] Main supply and return fans to floors 4-7 shut off. Main supply and return fans to floors 1-3 on with outside air dampers closed.

Table 5. Carbon dioxide in air samples taken from various floors in the Norris Cotton Federal Office Building, February 16, 1977, 10:30 to 12:00 a.m.[1]

Floor	No. of people on floor	No. of people in room sampled	CO_2 ppm	Ratio of indoor to outdoor CO_2 concentration
1	39	20	750	1.7
2	52	26	700	1.6
3	52	12	700	1.6
4	56	11	2240[2]	5.5[2]
5	48	23	990	2.3
6	58	19	1075	2.4
7	34	17	875	2.0

1 Main supply and return fans to floors 4-7 shut off. Main supply and return fans to floors 1-3 running with outside air dampers closed.

2 Sample taken in 40 m^2 (430 ft^2) room while people were taking an examination. Comfort conditions were rather poor due to high temperature and relative humidity.

Table 6. Carbon dioxide in air samples taken from various floors in the Norris Cotton Federal Office Building, February 17, 1977, 1:00 to 2:30 p.m.[1,2]

Floor	No. of people on floor	No. of people in room sampled	CO_2 ppm	Ratio of indoor to outdoor CO_2 concentration
1	36	21	875	2.0
2	55	32	800	1.8
3	36	12	650	1.5
4	51	16	1350	3.1
5	31	22	850	1.9
6	47	16	865	2.0
7	21	12	775	1.8

1 Main supply and return fans to floors 4-7 turned on with outside air dampers cloased.

2 Outside air concentration of CO_2 440 ppm at 5:50 p.m.

Reference [8] includes an analysis showing the relationship between CO_2 concentrations and ventilation rates. The results of the analysis show the levels of CO_2 implicitly tolerated by ASHRAE Standard 62-73 [12]. The minimum outside air of 0.0024 m^3/s (5 cfm) per person which is specified in the standard implicitly allows 2900 ppm CO_2 at an assumed generation rate of 5.9 x 10^6 m^3/s (0.75 ft^3/h) per person [13], while the recommended levels for office space of 0.007 to 0.012 m^3/s (15 to 25 cfm) per person correspond to 900 to 1200 ppm CO_2. Inspection of tables 4 and 5 indicates that most of the measured concentrations fell within the recommended limits even with the main ventilating fans to floors 4-7 off and that all levels were below the maximum allowable value. This analysis based on the CO_2 measurements leads one to conclude that the ventilation rates were not as large as indicated by the air exchange measurements described above. However, this is because the CO_2 samples were taken from rooms of highest occupancy in order to look for areas of inadequate ventilation.

3.4 PERFORMANCE OF THE SOLAR SUB-SYSTEM

Performance of Individual Solar Collector Panels: Solar energy is collected by four rows of roof-mounted flat-plate solar collector panels. Each row has panels of a slightly different design. In order to determine potential collector array performance, NBS had one of each type of collector tested in accordance with ASHRAE Standard 93-77 [14] by a commercial testing laboratory [15,16]. Figures 23 through 26 show a comparison between the collector module performance and the performance as specified in the original request for proposals sent out by GSA. When based on aperture area (as required by the original specifications), the performance of all four collector modules is reasonably close to the requirements for operation at normal incidence. Table 7 includes a list of performance parameters determined from the tests, the area for each row of the array on the building, and the flow rate for the row if the panels in the row were operating at the test flow rate.

Tilt Angle of Collector Array: One unique feature of the collector array designed for this building is that even though fixed in the south-facing orientation, the modules were installed on racks which could be tilted at different angles from the horizontal to better utilize the sun's energy throughout the year. Shortly after the building was put into operation, analyses were conducted to determine optimum tilt angle. Figure 27 shows the results as a function of the time of year. Two different calculation techniques were used. A calculation was first made based solely on being able to obtain an incident angle of 0° at solar noon throughout the year. Secondly, a more refined calculation was done using the recommended computer routines in the 1977 ASHRAE Handbook of Fundamentals [4] to compute the hourly, daily, and monthly incident solar radiation on a south-facing tilted surface. This latter technique accounts for direct, diffuse, and ground reflected solar radiation including the fact that the diffuse radiation from the sky tends to be greater in the summer than the winter. Both techniques produced comparable results and enabled GSA to determine the eight times during the year when the collector tilt should be changed to follow the

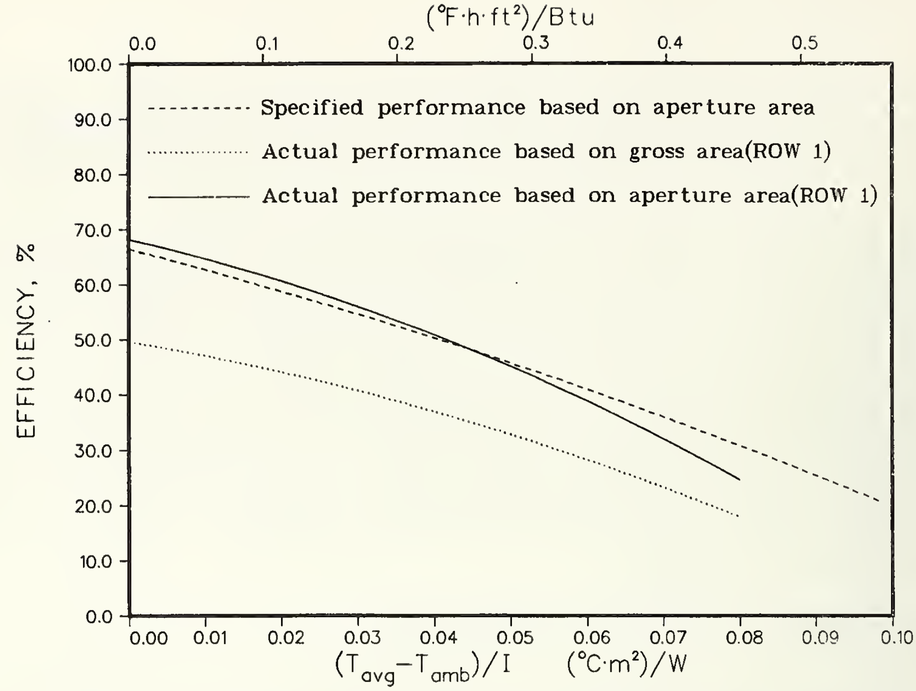

Figure 23. Collector performance for the modules in row 1 at Norris Cotton Federal Office Building as determined by a test of one module in a commercial testing laboratory

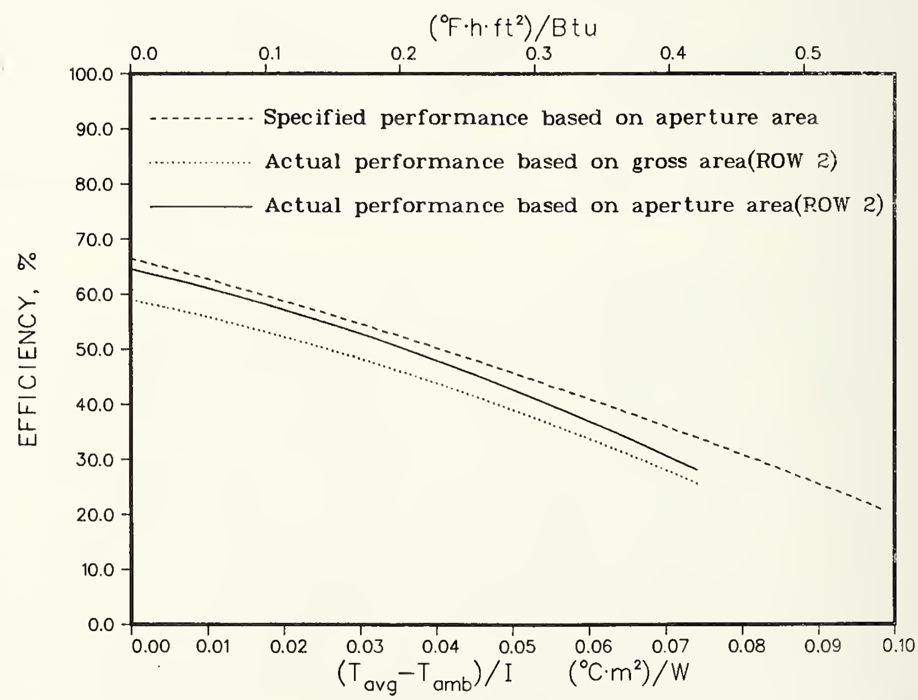

Figure 24. Collector performance for the modules in row 2 at the Norris Cotton Federal Office Building as determined by a test of one module in a commercial testing laboratory

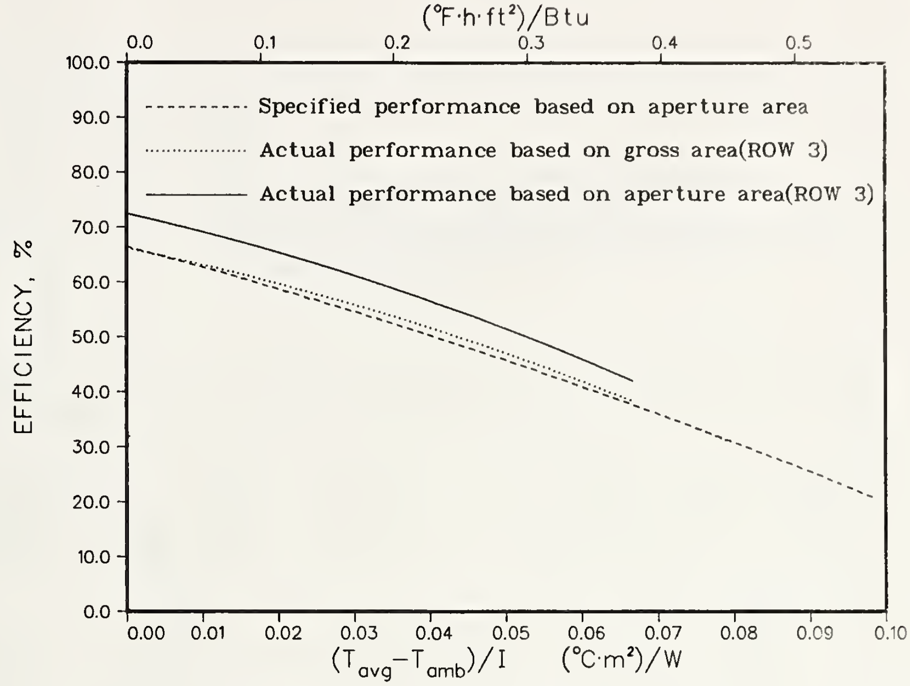

Figure 25. Collector performance for the modules in row 3 at the Norris Cotton Federal Office Building as determined by a test of one module in a commercial testing laboratory

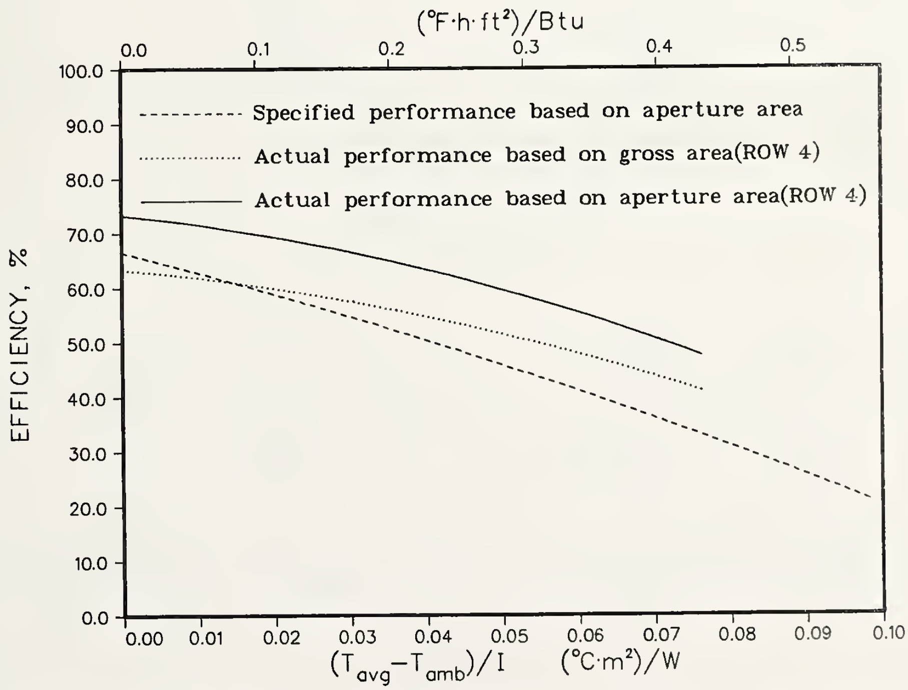

Figure 26. Collector performance for the modules in row 4 at the Norris Cotton Federal Office Building as determined by a test of one module in a commercial testing laboratory

Table 7. Test data for the solar collectors on the Norris Cotton Federal Office Building

Row*	F_R $(\tau\alpha)_{e,n}$	F_R U_L W/(m^2·°C)	b_o	Gross panel area, m^2 (ft^2)	Panel test flow, kg/s·m^2 (lb/(h·ft^2))	Gross row area, m^2 (ft^2)	Flow for array, ℓ/s (gpm)
1	0.487	3.77	0.195	2.61(28.1)	0.407(300)	65.3(703)	0.953(15.1)
2	0.579	4.41	0.160	1.96(21.1)	0.366(270)	117(1260)	2.06(32.6)
3	0.650	4.27	0.122	1.64(17.7)	0.312(230)	73.8(794)	1.31(20.8)
4	0.627	2.90	0.200	3.34(36.0)	0.614(453)	100(1080)	1.72(27.3)
Total	-	-	-	-	-	356.1(3837)	6.04(95.8)

* Row 1: single-glazed, flat-black absorber, plastic convection suppressor
Row 2: single-glazed, flat-black absorber
Row 3: double-glazed, selective surface absorber
Row 4: double-glazed, flat-black absorber

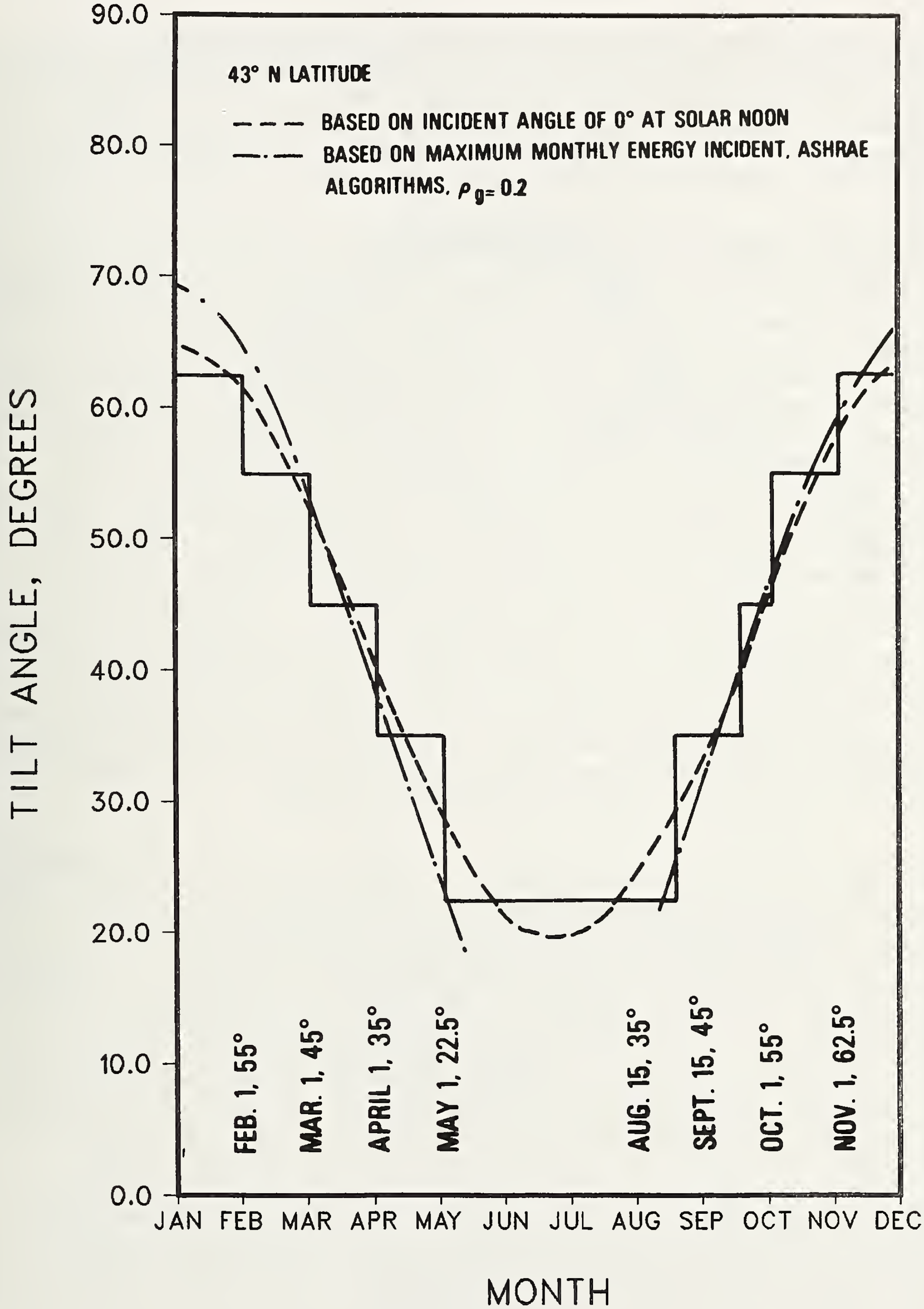

Figure 27. Optimum solar collector tilt angle for the Norris Cotton Federal Office Building as a function of time of year

sun's declination (specified along the bottom of the curve). However, by examining the computer results closely, it was found that simply setting the collector tilt at 60° from October to March and at 20° from April to September resulted in the incident radiation being almost identical to that achieved by the eight changes. This is shown in figure 28 and as a result, NBS staff recommended only two changes in collector tilt per year.

Analysis of Solar Sub-system Operation: The collector array itself has performed adequately when operated. However, major problems have occurred in solar system control and interface of the array with the mechanical systems in the building so that the contribution of solar energy to the building energy use over the first three years of operation has been minimal. This will be explained further below. Figure 29 shows hourly average total collector array efficiency taken from the JC-80 data tapes from October 1979 through January 1980 after the end of the third year of operation. The data were filtered to remove all data points where the solar irradiation was less than 600 W/m^2(190 $Btu/(h \cdot ft^2)$). During the period of data collection shown, the collectors were operated with an ethylene-glycol/water solution moving through the collectors at a total array flow rate of approximately 6.3 ℓ/s (100 gallons/min). Superimposed on the hourly average data points are the efficiency curves for the four solar collectors in the array which were tested in accordance with ASHRAE standard 93-77. The laboratory tests were performed with water at the manufacturer's recommended flow rate and the legend of figure 29 lists the flow rates that the rows in the array would have to be operating at to have the same module flow rate occur. The sum of the laboratory test flow rates is similar to the actual flow rate; however, the existing instrumentation does not allow a determination of whether the rows in the solar array are properly balanced.

The solar energy sub-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 interface problems experienced at the building during the first three years. At the time the solar sub-system was added, much of the architectural and HVAC design was firmly set. Consequently, integration of the collector array with the rest of the system was subject to a number of constraints. For example, collector piping was tied into the main system in such a way that the collector's output can only go to the basement storage tanks. If the temperature of water in the storage tanks is too low, the entire volume of water must be increased in temperature before any useful heat can be extracted. The piping design should have been modified so that the collector array energy could be used directly for meeting building loads.

As already described when discussing the building overall energy consumption, during the first three years the collector array was never able to increase the temperature of any of the storage tanks sufficiently to drive the absorption chiller during summer days. In addition, for space heating the solar collectors were only of use during off-season periods when outdoor air temperatures were relatively mild. This was because during severe weather, it was generally necessary to raise the space heating water loop temperature

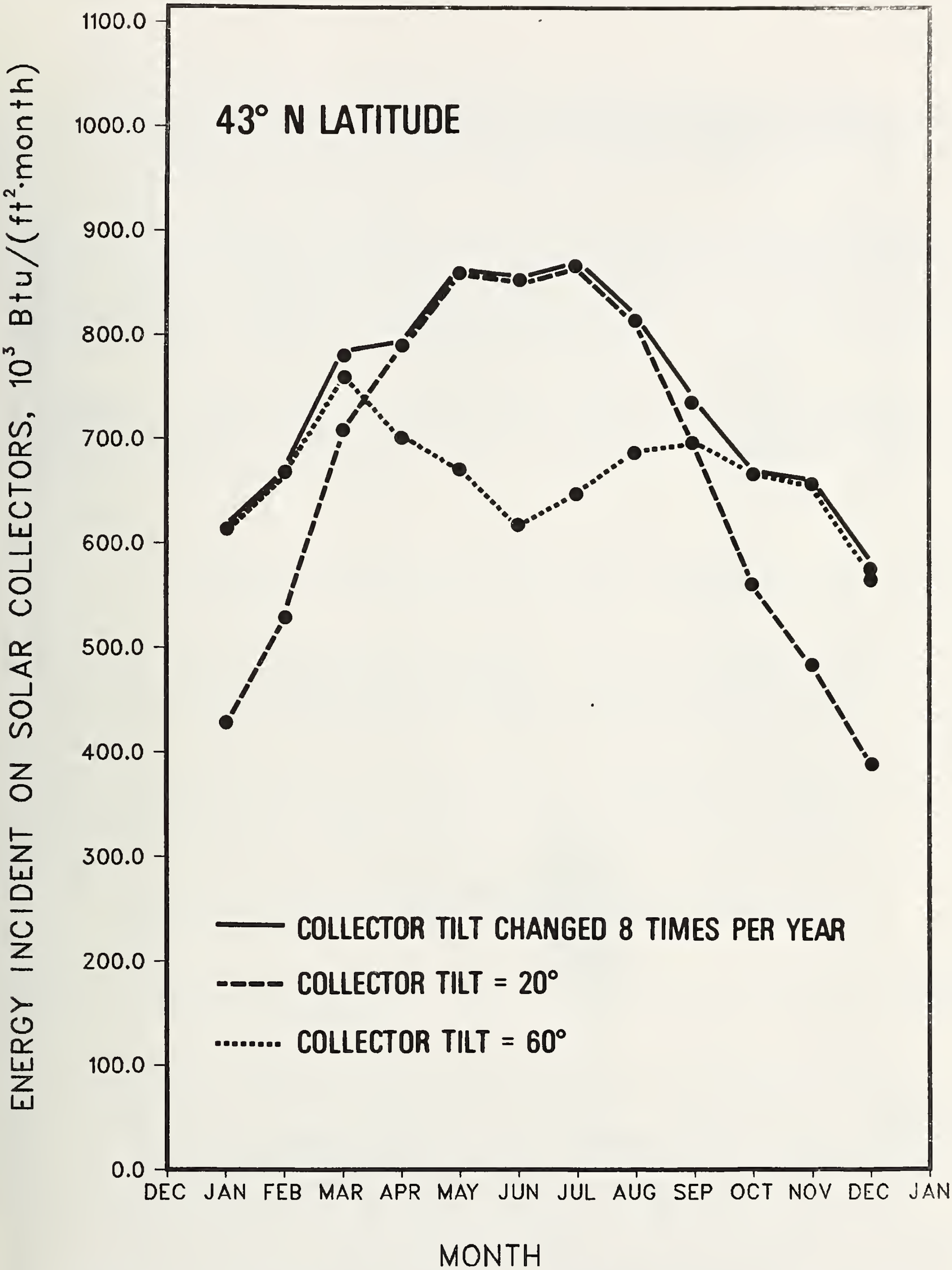

Figure 28. Incident solar energy on the solar collector panels of the Norris Cotton Federal Office Building under clear sky conditions

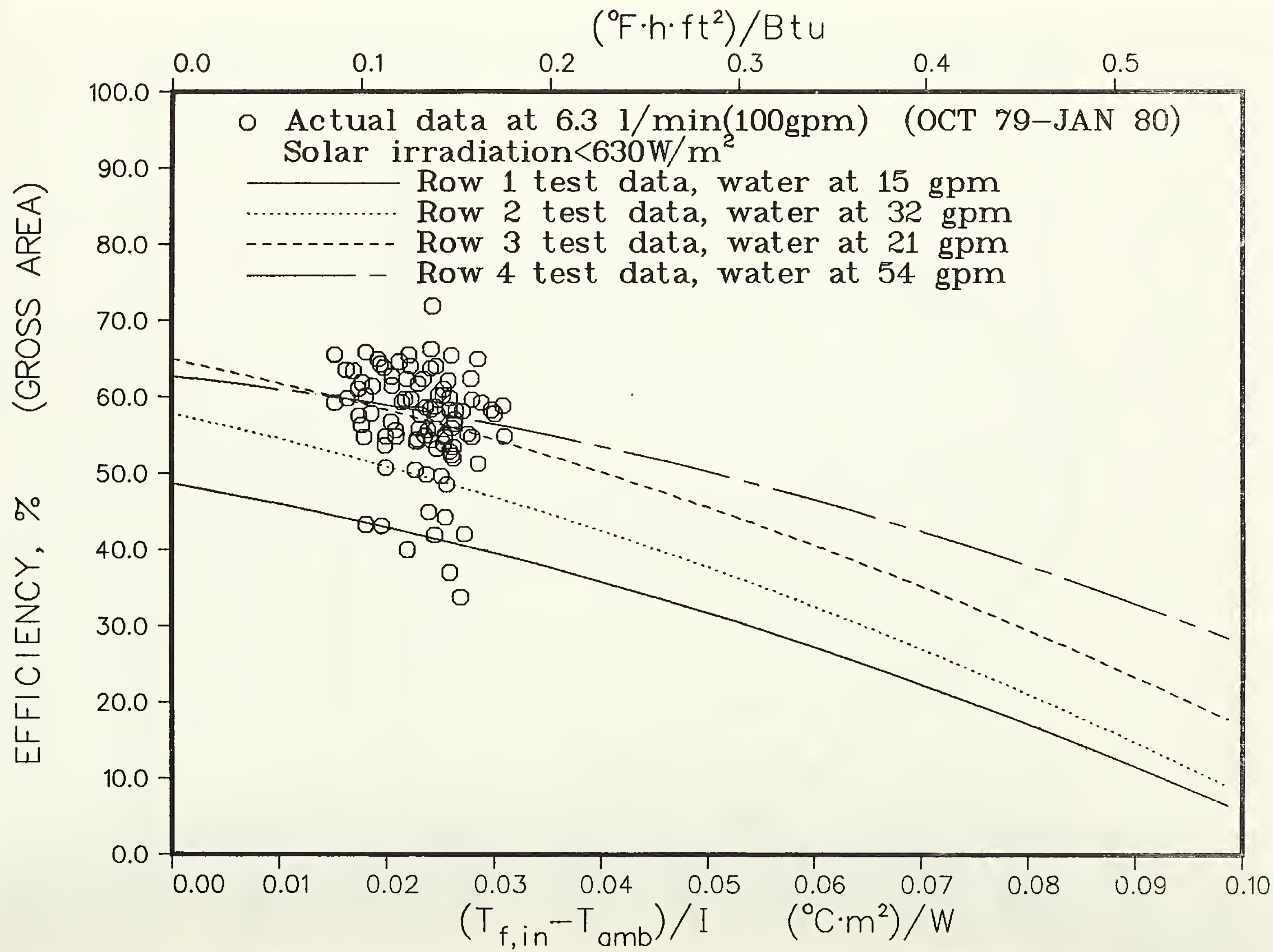

Figure 29. Hourly average solar collector array efficiency values and ASHRAE Standard 93-77 test data for individual rows of the collector array at the Norris Cotton Federal Office Building

to a level above the normal operating range of the collector array. Consequently, the solar collectors were used mainly during spring and fall for space heating and domestic hot water and during summer for domestic hot water only, over the 1½ years of the first 3 years of operation.

Following the end of the third year of building operation when it was fully apparent that the solar collector array was not contributing significantly to the building's energy needs, GSA considered making several modifications to the system. In support of their study, the analysis described below was completed [17]. As of the publication of this report, no final decision has been made on the extent of any changes to be made.

In order to estimate what the total annual output from the existing collector array might be under ideal conditions, calculations were made using the "phibar" method of calculating collector output [18]. Calculations were made under the following assumptions:

1. The collector fluid was assumed to be water.

2. The collector array was balanced so that each row performed as specified by the collector parameters in table 7.

3. The inlet temperature was assumed to be held constant at 21°C (70°F) for supplementing heat pump operation, at 60°C (140°F) (and 43°C (110°F)) for use in the hot water heating system or at 104°C (220°F) for use by the absorption chiller.

4. Weather data used were for Concord, New Hampshire and represented average weather conditions over a long time period. The effects of cloudy days are accounted for in the method.

5. Collectors were tilted at 60 degrees from the horizontal all year and gross collector area was fixed at its present value of 353 m^2 (3800 ft^2).

Table 8 gives the results of the calculations for each row and inlet temperature in GJ (10^6 Btu) per month.

Detailed computer modeling of the building and its systems as operated was also performed and will be discussed in section 3.5. For comparison of collector array output with building requirements, results of the modeling will be cited here. Table 9 lists total energy and thermal energy requirements for the building based on the computer simulation. The building has two major mechanical sub-systems in which solar energy could be used. One, the heat pump system on the first three floors, requires water at 27°C (80°F) or less. The hot water heating system, serving the upper four floors, requires water from 43°C (110°F) to 60°C (140°F), depending on the outside air temperature. If the collector output values in table 8 are compared to the building requirements and the assumption is made that the collectors

Table 8. Predicted collector output for the existing collectors on the Norris Cotton Federal Office Building in GJ (10^6 Btu)/month for a tilt angle of 60°

Row	T_{in},°C (°F)	Jan	Feb	Mar	Apr	May
1	21(70	3.2(3.0)	3.8(3.6)	5.5(5.2)	7.1(6.7)	8.8(8.3)
1	43(110)	1.9(1.8)	2.2(2.1)	3.3(3.1)	4.2(4.0)	5.1(4.8)
1	54(130)	1.3(1.2)	1.6(1.5)	2.3(2.2)	3.0(2.8)	3.6(3.4)
1	104(220)	-	-	-	-	0.5(0.5)
2	21(70)	7.2(6.8)	8.4(8.0)	12.2(11.6)	15.5(14.7)	19.3(18.3)
2	43(110)	4.2(4.0)	5.1(4.8)	7.4(7.0)	9.3(8.8)	11.3(10.7)
2	54(130)	3.0(2.8)	8.6(3.4)	5.3(5.0)	6.6(6.3)	7.9(7.5)
2	104(220)	-	-	-	-	1.3(1.2)
3	21(70)	6.1(5.8)	7.1(6.7)	9.9(9.4)	12.1(11.5)	14.7(13.9)
3	43(110)	3.8(3.6)	4.5(4.3)	6.4(6.1)	7.8(7.4)	9.2(8.7)
3	54(130)	2.8(2.7)	8.5(3.3)	5.0(4.7)	6.0(5.7)	7.0(6.6)
3	104(220)	-	-	-	-	1.6(1.5)
4	21(70)	9.4(8.9)	10.7(10.1)	14.5(13.7)	16.9(16.0)	19.5(18.5)
4	43(110)	7.0(6.6)	8.0(7.6)	10.9(10.3)	12.6(11.9)	14.2(13.5)
4	54(130)	5.8(5.5)	6.6(6.3)	9.1(8.6)	10.6(10.0)	11.9(11.3)
4	104(220)	-	-	-	-	-

Row	T_{in},°C (°F)	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	21(70	-	-	-	9.4(8.9)	7.9(7.5)	3.8(3.6)	2.6(2.5)
1	43(110)	-	-	-	5.8(5.5)	5.0(4.7)	2.2(2.1)	1.5(1.4)
1	54(130)	-	-	-	4.3(4.1)	3.7(3.5)	1.6(1.5)	1.1(1.0)
1	104(220)	0.6(0.6)	0.7(0.7)	0.9(0.9)	-	-	-	-
2	21(70)	-	-	-	20.4(19.3)	17.4(16.5)	8.4(8.0)	5.9(5.6)
2	43(110)	-	-	-	12.8(12.1)	11.0(10.4)	5.0(4.7)	3.4(3.2)
2	54(130)	-	-	-	9.4(8.9)	8.0(7.6)	3.5(3.3)	2.3(2.2)
2	104(220)	1.4(1.3)	1.8(1.7)	2.0(1.9)	-	-	-	-
3	21(70)	-	-	-	15.3(14.5)	13.4(12.7)	6.9(6.5)	5.0(4.7)
3	43(110)	-	-	-	10.2(9.7)	9.0(8.5)	4.2(4.0)	3.1(2.9)
3	54(130)	-	-	-	8.0(7.6)	7.0(6.6)	3.2(3.0)	2.3(2.2)
3	104(220)	1.6(1.5)	2.0(1.9)	2.3(2.2)	-	-	-	-
4	21(70)	-	-	-	19.9(18.9)	18.0(17.1)	9.9(9.4)	7.6(7.2)
4	43(110)	-	-	-	15.3(14.5)	13.8(13.1)	7.2(6.8)	5.5(5.2)
4	54(130)	-	-	-	13.0(12.3)	11.8(11.2)	5.9(5.6)	4.5(4.3)
4	104(220)	4.6(4.4)	5.6(5.3)	6.0(5.7)	-	-	-	-

Table 9. Predicted thermal and total energy requirements for the Norris Cotton Federal Office Building based on computer simulation

Month	Heat pump system thermal requirements, GJ (10^6 Btu)	Hot water system thermal requirements, GJ (10^6 Btu)	Total energy requirements, GJ (10^6 Btu)
Jan	236(224)	127(120)	1001(949)
Feb	224(212)	129(122)	938(889)
Mar	137(130)	76(72)	742(703)
Apr	56(53)	35(33)	497(471)
May	20(19)	15(14)	444(421)
Jun	0(0)	0(0)	476(451)
Jul	0(0)	0(0)	488(463)
Aug	0(0)	0(0)	540(512)
Sep	8(8)	5(5)	388(368)
Oct	44(42)	27(26)	490(464)
Nov	121(115)	68(64)	695(659)
Dec	222(210)	119(113)	954(904)

Table 10. Predicted collector output for 557 m^2 (6000 ft^2) of evacuated tubular collectors located on the Norris Cotton Federal Office Building ($F_R (\tau\alpha)_n = .546, F_R U_L = 2.12$ W/$m^2 \cdot {}^\circ C$, tilt = 60°

Month	Collector output in GJ (10^6 Btu) for inlet temperatures		
	21°C (70°F)	60°C (140°F)	104°C (220°F)
Jan	49.5(46.9)	27.7(26.3)	-
Feb	55.5(52.6)	32.0(30.3)	-
Mar	73.9(70.0)	43.1(40.9)	-
Apr	84.5(80.1)	49.5(46.9)	-
May	96.1(91.1)	55.5(52.6)	19.9(18.9)
Jun	-	-	20.3(19.2)
Jul	-	-	24.1(22.8)
Aug	-	-	26.0(24.6)
Sep	97.8(92.7)	60.1(57.0)	-
Oct	89.5(84.8)	54.9(52.0)	-
Nov	50.3(47.7)	28.1(26.6)	-
Dec	40.0(37.9)	21.7(20.6)	-

operate with an inlet temperature of 21°C (80°F) in the winter and 54°C (130°F) in the spring and fall, it appears that under ideal conditions, the solar collector array could supply, at most, 26 percent of the annual heat pump system thermal energy requirements and 4 percent of the annual hot water heating system thermal energy requirements with a total collector output of 299 GJ (283 x 10^6 Btu) per year. If boiler efficiency is assumed to be 75 percent, then the total savings that the solar sub-system could provide would be 398 GJ (377 x 10^6 Btu) or 5 percent of the total annual energy consumption. It is important to remember that this is a maximum and that operational factors would tend to reduce the solar contribution. Such operational factors include:

1. the use of the ethylene-glycol/water solution in the collectors instead of only water (would reduce the output by approximately 10 percent),

2. control system inadequacies and piping and storage thermal losses, and

3. the collector output and building load requirements are not in phase 100 percent of the time.

Table 8 indicates that the solar collector array should have useful output at an inlet temperature of 104°C (220°F). Actual data from the building during 1978-79 indicated that the absorption chiller energy consumption was only 1 percent of the total energy consumption 63 GJ(60 x 10^6 Btu) of fuel oil). The output indicated in table 8 would provide 47 percent of the absorption chiller thermal requirements or 0.39 percent of the total energy. After taking into account tank and piping losses, load-supply phase problems, and an oversized storage which must be heated to the operating temperature before any solar energy can be used, the benefit from solar assisted cooling appears negligible.

It should be noted that table 8 gives collector output for the array tilted at 60°. A similar prediction for the collectors tilted at 45° resulted in the same percentage of building energy supplied by solar as for the array tilted at 60°. The reason for this is that the 60° array would collect more energy in mid-winter than the 45° array but less in the spring and fall. Changing the collector tilt has proven to be a very difficult and costly operation and this analysis has shown a change in tilt to have little effect when solar energy is not used for cooling purposes.

The heat pump loop was originally designed to operate without any input from the collector array. One of the three storage tanks was intended to serve as a thermal capacitor for the system and a two-way valve was included to route the heat pump loop either through the tank or through an evaporative cooler, depending on the loop temperature. When a solar system was added to the design, the system was modified slightly so that other tanks could be selected for the loop to run into, depending on the temperatures in the tanks and the loop. A separate control tied to another sensor in the heat pump loop brings in boiler-heated water through a modulating valve if the loop temperature falls below a setpoint. If solar-heated water exists in one of the tanks, the two-way valve attempted to route the heat pump loop into one of the tanks. Usually, however, the water in the tank was far above the heat pump loop setpoint and the two-way valve diverted the water in the heat pump loop into the evaporative cooler. In order for solar-heated water to be used in the heat pump loop, a modulating valve would have to be installed to bleed water into the loop from a tank in the same way that boiler-heated water is added to the loop. The controls would have to be carefully studied and modified to bleed solar-heated water into the heat pump loop before bleeding boiler-heated water into the loop.

The control of the solar sub-system actually involves three control systems. A pneumatic control system defines a set of basic operational modes for (1) winter operation with solar, (2) winter operation without solar, (3) summer operation with solar, and (4) summer operation without solar. The mode controls determine where the solar-heated water being collected by the solar system will be sent. Based on the outlet temperature from the array, the system was designed to send the water to one of three storage tanks or bypass all tanks and loop back into the array. The modes, as designed, were beset with problems throughout the 3 years because solar modes (2) and (4) activated the engine-generator set to drive the electric chiller. This engine-chiller arrangement did not work sucessfully as indicated in section 3.1.

A second control system determines the solar system pump speed. This control system senses the temperature difference across the collector array and changes the speed of the variable speed collector pumps to keep the temperature rise across the collectors at 6°C (10°F). On system startup, there is a delay which causes the pumps to run at maximum speed until the system stabilizes. If not enough incident solar energy is available, the controller will run the pumps at a minimum speed. This arrangement caused problems at first but adjustment of the minimum speed allowed the speed control to operate acceptably.

The third control system was intended to determine which of the pneumatic system control modes to select based on the incident irradiation and other factors. The JC-80 minicomputer was supposed to execute this control function but software problems prevented the use of the computer for this function throughout the 3-year period. Actually, the building operators by-passed the JC-80 system and simply turned the collector pumps on and off manually using the JC-80 console or manual controls at the interface panel between the pneumatic system and the JC-80. Changes in the JC-80 software are not easily accomplished and consequently no changes were made to the solar mode selection software during the 3-year period.

Based on the analysis and discussion above, NBS recommended that GSA:

1. continue to use all existing collectors and carefully balance the system so that each row of the collector array will operate at its optimum flow rate,

2. fix the collector array tilt at 60 degrees from the horizontal,

3. add modulating valves and controls to the system so that the solar-heated water can be successfully used in the heat pump system,

4. modify the controls for storage tank selection so that only one or two tanks are used and the set-point temperature of the tanks can be adjusted, and

5. introduce enough automatic control into the solar system so that manual operation will no longer be necessary. This could be implemented by installing a hardware controller at the pneumatic control interface with the mini-computer. The controller would use storage and collector temperature sensors and would be designed specifically for solar system control.

Analysis of Improvements to Solar Sub-system: One option that was considered but not recommended was replacing one or more rows of collectors with new collectors having a higher performance. The information in table 8 was used to predict what effect this might have on the percentage of the load that the solar sub-system could supply. Row 4 collectors appear to have the best performance of the collectors on the array and the entire array could be outfitted with this type. The predicted output of such an array was obtained by scaling the row 4 output in table 8 up to the area of the total array. The result of such calculations was that the array would then be able to provide 30 percent of the heat pump system thermal energy requirements, 7 percent of the hot water heating system thermal energy requirements, and could reduce the total building energy consumption by 7 percent. The additional energy savings over continuing to use the existing collectors would be about 1 percent. Again, actual system performance would be expected to be lower than the calculations indicate.

Another option considered was to replace all of the solar collectors with a larger area of evacuated tubular collectors. This might allow solar cooling to be a reality. The benefits from this were estimated by again using the phibar method. Table 10 lists the predicted output for an array of 557m^2 (6000 ft^2) of evacuated tubular collectors. Using the same assumptions as before, the collector output was determined for inlet temperatures of 21, 60, and 104°C (70, 140, and 220°F). As table 10 shows, the output of the array would increase. However, the output of the collectors at 60°C (140°F) would still not be very large compared to the building loads in table 9. If solar-heated water were used in the heat pump loop as a first priority, as before, the new array could provide 38 percent of the heat pump system requirements, 11 percent of the hot water heating system requirements and would reduce the building energy consumption by a total of 8 percent as a maximum.

If the prediction of collector output at 104°C (220°F) is examined, the output of the collector could supply 86 percent of the total absorption chiller thermal energy requirements for the summer of 1979 under ideal conditions. However, this would involve replacing the existing absorption chiller with one that could accept lower temperature water. This would undoubtedly improve the portion of absorption cooling that solar energy could provide. Again the contribution to the overall building energy needs would be less than 1 percent and therefore such a major modification was not felt to be warranted.

3.5 COMPARISON OF ENERGY USE WITH COMPUTER PREDICTIONS

Even though the building had been modeled during the design phase it was decided to predict the thermal performance of the building using a state-of-the-art hour-by-hour computer program for the following reasons:

1. The original modeling of the building with NBSLD [1,2] predicted the thermal performance of the building based on heating and cooling loads but did not actually simulate the mechanical systems in the building. A simulation of the building using a mechanical system simulation program was felt desirable in order to verify the original design predictions for the building (625 $MJ/m^2 \cdot year$) (55×10^3 $Btu/(ft^2 \cdot year)$).

2. Actual building energy consumption data is available for the building over three years of operation. By comparison of actual data and predicted data from a simulation of the building as it has operated, a contribution could be made to the validation of building simulation computer programs.

3. Assuming that the results of computer modeling could be validated for the original design, a simulation could be used to predict how this building might have performed had the design been different, with less emphasis on energy conservation and as if the building had been designed for commercial use.

4. The model could also be used to examine possible improvements to present building operation and to predict their effect on building energy consumption.

Description of Computer Simulations: The Ross Meriwether Energy System Analysis program* was used for the simulations and was felt to represent the state-of-the-art in building load and mechanical systems modeling. The

* Identification of a proprietary computer program in no case implies a recommendation or endorsement by the National Bureau of Standards.

popular public-domain programs such as DOE-2 [19] and BLAST [20] were not generally available at the time this analysis was begun.

Five different simulation runs were made. The characteristics of the building simulated by each run will be described in the next several paragraphs, followed by a presentation of the simulation results. A complete description of the analysis of the simulation results may be found in reference [21].

The first simulation, the "as-designed" case, was intended to represent the building as it was originally designed. The design plans and specifications for the building were used as input to the program. A solar energy sub-system was not included in the original design and was therefore excluded from the "as-designed" simulation.

The complete building was divided into two sub-buildings for this simulation in order to represent the two main mechanical sub-systems, the heat pump system and the combined central systems. Each of the two sub-buildings was further sub-divided into major zones. The heat pump system sub-building consisted of the first three floors of the building and was divided into a core zone and perimeter zone, each zone spanning three floors. The central system sub-building was divided into four major zones; the fourth floor, the fifth floor, the sixth and seventh floor core, and the six and seventh floor perimeter. In the real building, each major zone utilizes a different type of air-side HVAC and control system and thus each zone had to be simulated differently. As mentioned previously, the fourth floor uses a standard variable air volume system with finned tube radiation to offset transmission losses. The fifth floor uses a variable air volume system with a separate single-duct system to offset transmission losses. The sixth and seventh floors both have variable air volume systems for the core and four-pipe fan coil units for perimeter heating and cooling. Each of the zones was simulated with a design thermostat setting of 20°C (68°F) for heating and 26°C (78°F) for cooling with a winter setback to 16°C (60°F) from 6 pm to 5 am during the week and all day on weekends and holidays. Mechanical equipment simulated included four gas-fired modular boilers used to provide hot water to the heat pump or central systems. Central chilled water was assumed supplied by the electric chiller, always driven by the engine-generator, as called for in the original design. Waste heat from the engine generator was assumed used to drive the absorption chiller in parallel with the electric chiller. Energy storage was available to store excess heat from the engine generator and this storage could supply energy for heating or the absorption chiller if no other sources were available.

The second simulation run used the final building design which included a solar energy sub-system added to the original design. This simulation was basically the same as the "as-designed" simulation with the exception that the central electric chiller was assumed always to run on purchased power rather than power produced by the engine-generator. The "with solar" design called for the solar sub-system to provide thermal energy to run the absorption chiller. With the solar sub-system, the engine-generator was designed to operate and the recovered heat used only if the solar sub-system did not have sufficient output to operate the absorption chiller (on cloudy days, for example). Simulation of this complex control scheme was not possible with the program and therefore engine-generator use was not simulated for this case.

At the time the simulations were run, the program had no provision for direct solar system simulation. The operation of the solar sub-system in the building was approximated by a room with south-facing windows. This room had no space heating capabilities and cooling was provided by an "imaginary" chiller which acted as a "heat" pump to remove solar gain from the room and pump it to storage. This chiller differed from a real chiller in that it required no compressor power. The thermostat setting in the room for cooling was set to 88°C (190°F) during the summer and 37°C (99°F) during the winter to simulate collector temperatures. These settings insured that the simulated collector array would operate at a minimum output temperature for the loads it was required to supply. The design of the solar sub-system called for a storage tank to be heated with solar energy to a specified temperature level before solar energy could be used. Due to limitations in the simulation program it was assumed that energy from the solar system could be used directly. The use of this assumption yielded a slightly higher solar sub-system performance than might be expected from the design.

Prediction of the amount of solar energy entering the room was accomplished by having the program generate a table of solar heat gain values for each hour of the day throughout the year. The regular function of this table is to predict solar heat gain through windows using as input a series of absorptance and transmittance constants. For a solar system, these constants can be given values so that the program simulates the energy arriving at the absorber plate of solar collectors. This gives the same result as applying a transmittance-absorptance product and an incident angle modifier to the energy incident upon the solar panels. Energy loss from the solar collectors by heat transfer to the environment was approximated by the transmission loss through the walls of the solar room. Original design specifications for collector performance were used for the collector simulation.

Following building start-up in September 1976, differences between the design predictions for the building and the actual operational performance became apparent. In many cases, problems with the controls forced building operators to resort to manual operation of systems. Because of the differences between the actual operation of the building and what was assumed during the design phase a simulation was felt to be required that would predict the energy consumption of the building "as-operated." Some of the most important differences between the assumptions made at the time of design and what has occurred with the actual building were incorporated in the "as-operated" simulation and are as follows:

1. Different air infiltration rates. In the "as-designed" simulation, 0.5 air change per hour were used. As has already been described, average rates of 0.75 air change per hour were measured initially after occupancy of the building. After recaulking of the building exterior, lower rates were measured (0.75 air change per hour on the first three floors and 0.39 on the upper four floors or an average of 0.54 air change per hour for the building). The lower rates were used in the "as-operated" simulation. In the "as-designed" case, infiltration was assumed to be constant on the first three floors and exist only on the upper four floors when the fans were off (a pressurized building). The air exchange measurements showed that there is constant infiltration throughout the building even when fans are operating. Consequently the infiltration rate for the "as-operated" case was input as constant.

2. Two manually controlled oil-fired boilers were added. Originally, these boilers were only intended as back-up equipment in the event of an interruption of natural gas but have been used routinely during winter operation in sequence with the gas boilers to meet higher than expected heating loads. The oil-fired boilers have also been used in the summer as the source of hot water for the absorption chiller as has been described. Gas is not used to heat water for the chiller because retrofit piping was only added between the chiller and the oil boilers to avoid modifications to gas boiler controls.

3. For the "as-operated" simulation, the operation of the gas-fired boilers was limited to the months of October through April for heating and the operation of the chillers was limited to the months of May through September.

4. The building operators increased the hot water heating system temperature from the design value of 41°C (105°F) to 60°C (140°F) during mid-winter to improve comfort conditions and meet peak heating loads in the building.

5. Recovered heat from the engine generator has never successfully driven the absorption chiller. The electric chiller is always driven by purchased power since the waste heat produced by the engine generator cannot be put to any use. The absorption chiller is driven by water heated in the oil-fired boilers. Also, the two other heat recovery options for the electric chiller (double-bundle condenser and false loading) have never been used successfully. No heat recovery from the engine generator or electric chiller was simulated in the "as-operated" case.

6. In the actual building, the solar array output is used only during the spring and fall to provide energy for the hot water heating system. During mid-winter, the heating water system temperature

is raised to 60°C (140°F) and at this temperature the efficiency of the existing solar array is too low for any usable energy to be collected. In the summer, the solar array has been unable to produce usable energy for the absorption chiller. To simulate this situation, the "as-operated" simulation allowed the solar array to provide energy for the hot water heating system only during the months of April, May, September, and October (when heating water temperatures are lowered). The only other system in which solar energy was assumed used in the simulation was the service hot water system (used all year).

7. Thermostat settings were changed to 18°C (65°F) for occupied heating and to 13°C (55°F) for unoccupied setback.

8. In the "as-operated" simulation the lighting loads were raised slightly and redistributed to more accurately reflect the electrical energy requirements of the various agency tenants.

A fourth simulation of the building was made to predict what the effect would be of several easily implemented changes to the current operation of the building. The "as-operated" simulation was taken as a baseline and several changes were made to the input data. The changes consisted of the following:

1. The heat pump fans were cycled by room thermostats with the heating or cooling load. As presently operated, the heat pump fans operate continuously during occupied hours.

2. The variable air volume air handling unit cooling coil discharge temperature was raised from 13°C (55°F) to 16°C (60°F).

3. The water loop temperature for the heat pump system was operated at the maximum temperature consistent with the safety of the heat pump units.

4. The temperature of the central chiller condenser water was lowered to the minimum consistent with chiller safety and cooling tower capability (The use of (40°C) 105°F condenser water was required only to allow heat recovery and has reduced chiller efficiency). Also in the simulation, the absorption chiller was sequenced to run after the electric chiller was at full load rather than in parallel.

The fifth and final simulation run was intended to be a prediction of how a design alternative to the building might have performed, had it been built instead of the existing building. The design of the alternative chosen did not stress energy conservation as much as the actual building and represented what was felt to be typical design practice for an ordinary commercial building during the early 1970's. Basically, the "design alternative" had the same configuration as the "as-designed" building, with the same shape, occupancy, layout and floor area. The differences were in the thermal quality of the building envelope and the types of mechanical systems used. In addition, the alternative building had none of the demonstration character of the existing building. The major differences between the "as-designed" and the "design alternative" building were as follows:

1. The alternative used approximately twice as much electricity for lighting per unit of floor area and had higher total internal gains.

2. The alternative had no solar or heat recovery systems.

3. The overall wall U-value including the effect of windows was changed from 0.57 to 1.59 W/(m^2·°C)(0.10 to 0.28 Btu/(h·ft^2·°F)).

4. The window area was changed from 6 percent to 29 percent of the total wall area and windows were used on the north wall. A shading coefficient of 0.5 was used to calculate solar gain.

5. The wall and roof U-value was changed from 0.34 to 0.85 W/(m^2·°C) (0.06 to 0.15 Btu/(h·ft^2·°F)).

6. The design alternative used a hot water system for heating with a central boiler and hot water coils on the perimeter.

7. The design alternative used through-the-wall air conditioning units on the perimeter and packaged air conditioning units in the core for cooling.

8. A pressurized building was assumed and infiltration rates were those with fans off.

<u>Predicted Overall Energy Consumption</u>: Each of the simulation runs resulted in a prediction of the consumption of various fuels and the building overall energy consumption, on a monthly and annual basis. The following paragraphs will describe the simulation results.

Total energy consumption predicted in each of the five simulation runs is shown in figure 30 for each month of the year. The total consumption is the sum of the maximum energy contents of electricity and all forms of fuel as they pass through the building boundary. It is important to remember that while different buildings may use the same amounts of energy at the boundary, the cost of the energy will differ between buildings using different fuels and having different demand characteristics. The basic shape of the energy consumption curves is the same for all runs and shows that for an office building in this climatic region, the predominant energy use is for heating rather than for cooling. Differences between the individual curves are the

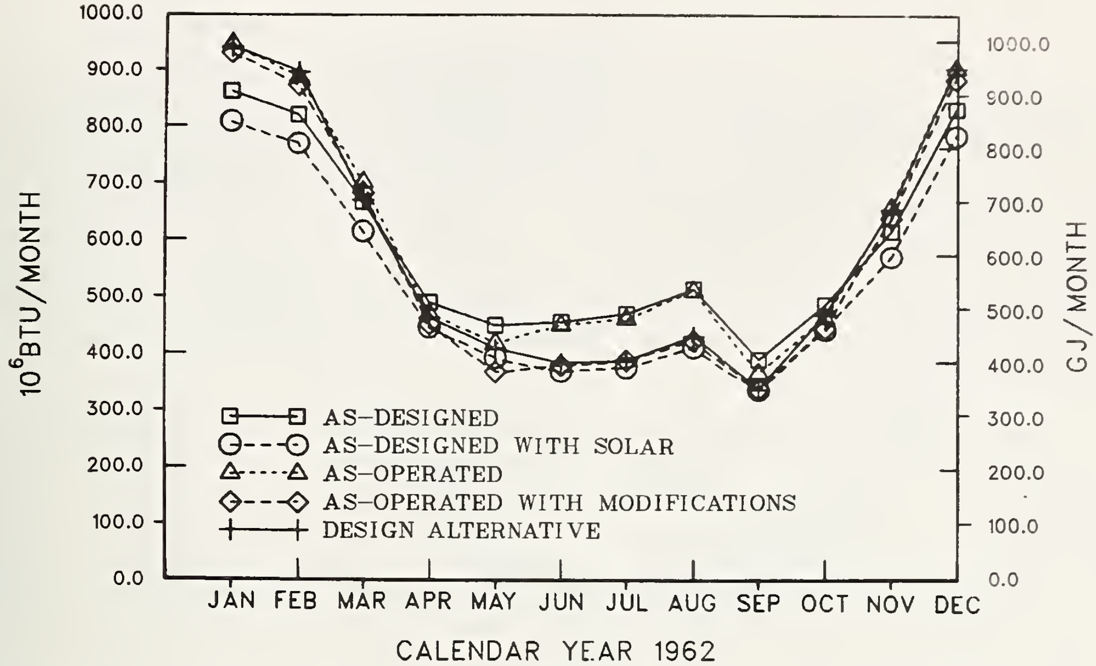

Figure 30. Total energy consumption at the Norris Cotton Federal Office Building as predicted by simulation

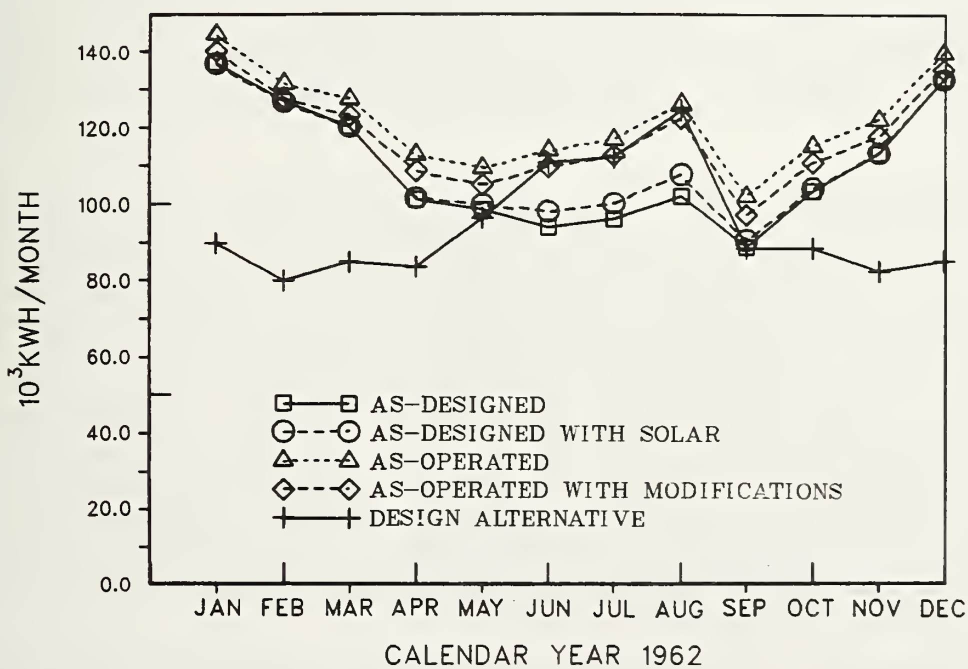

Figure 31. Electric energy consumption at the Norris Cotton Federal Office Building as predicted by simulation

result of a number of factors. The "as-designed with solar" consumption is slightly lower than in the "as-designed" case since some of the solar energy collected replaces purchased energy. The energy consumption for the "as-operated" case is higher in winter than for the "as-designed" case due to factors such as higher heating loads. The effect of the modifications to the building in the "as-operated with modifications" case is a slight overall decrease in the energy consumption. A surprising result is that the "design alternative" case, energy consumption levels are predicted to be similar to those in the "as-operated" case. The reasons for this result will be examined in later paragraphs.

The electric energy consumption per month predicted for the building is shown in figure 31. For the "as-designed" case, electric energy is used for lights, receptacles, the mini-computer, miscellaneous, pumps, fans, and for heat pumps all year. The greater electrical use in winter can be attributed to the heat pump system which must meet the heating load for the first three floors. The addition of the solar sub-system has little effect on the electric energy consumption compared to the "as-designed" case except in the summer months. The increase in the summer is the result of running the electric chiller on purchased power and never with the engine generator. The electric energy consumption for the "as-operated" case is significantly higher than for the "as-designed" case due to higher heating and cooling loads, greater energy use by pumps, fans, controls, lighting, and the operation of the electric chiller solely on purchased power. The slight reduction in electric consumption for the "as-operated with modifications" case is due to savings in fan energy and heat pump electric consumption, and more efficient electric chiller operation. A noticeable difference exists between the electrical consumption for the "design alternative" and the other cases. The "design alternative" does not use heat pumps for heating, but does utilize electricity for cooling. Therefore this results in a lower curve during the winter and a higher one in the summer.

Predicted natural gas consumption is shown in figure 32. The "as-designed" curve shows a large winter usage of gas (used in boilers for heating) and a smaller but significant use of gas in summer (to operate the engine-generator to drive the electric chiller). The "as-designed with solar" gas consumption is lower all year reflecting the replacement of boiler generated thermal energy with solar thermal energy. Some gas consumption exists in the summer even though this simulation case did not allow use of the engine-generator. Gas is used to heat water to fire the absorption chiller when the solar sub-system can not supply all of the absorption chiller requirements. In the original design with solar the engine-generator was supposed to be used when solar energy was not available and therefore the gas boilers were not permitted to fire the absorption chiller. Thus, the summer gas use in figure 32 only approximates gas use in the engine-generator as called for in the original design with solar.

In the "as-operated" case, the engine-generator is never used and the electric chiller operates on purchased power while the absorption chiller is fired by

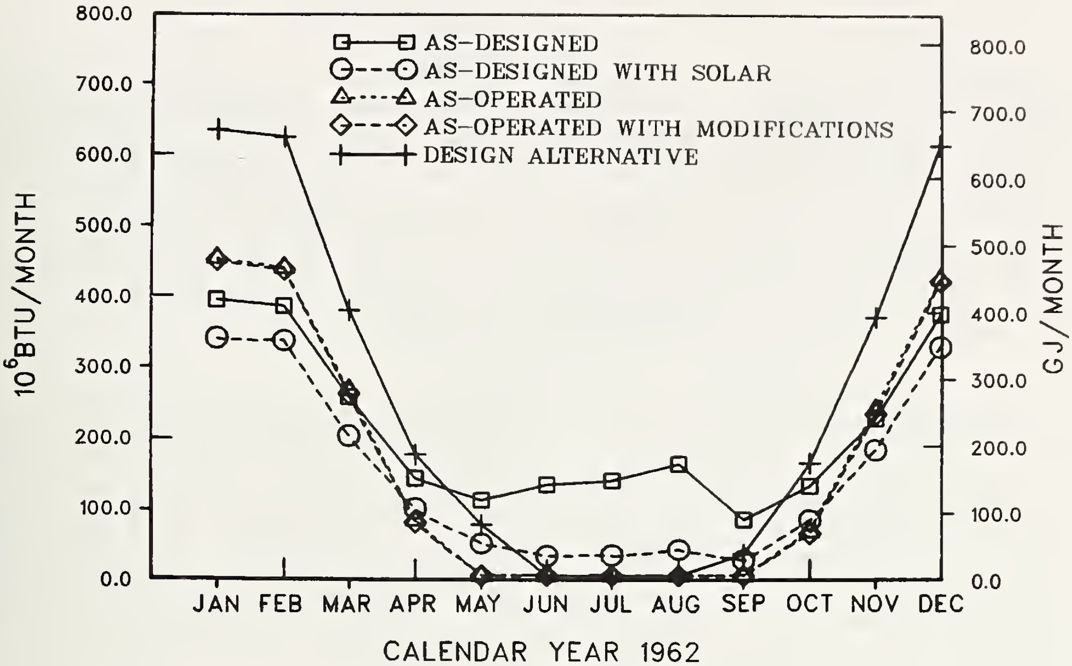

Figure 32. Natural gas consumption at the Norris Cotton Federal Office Building as predicted by simulation

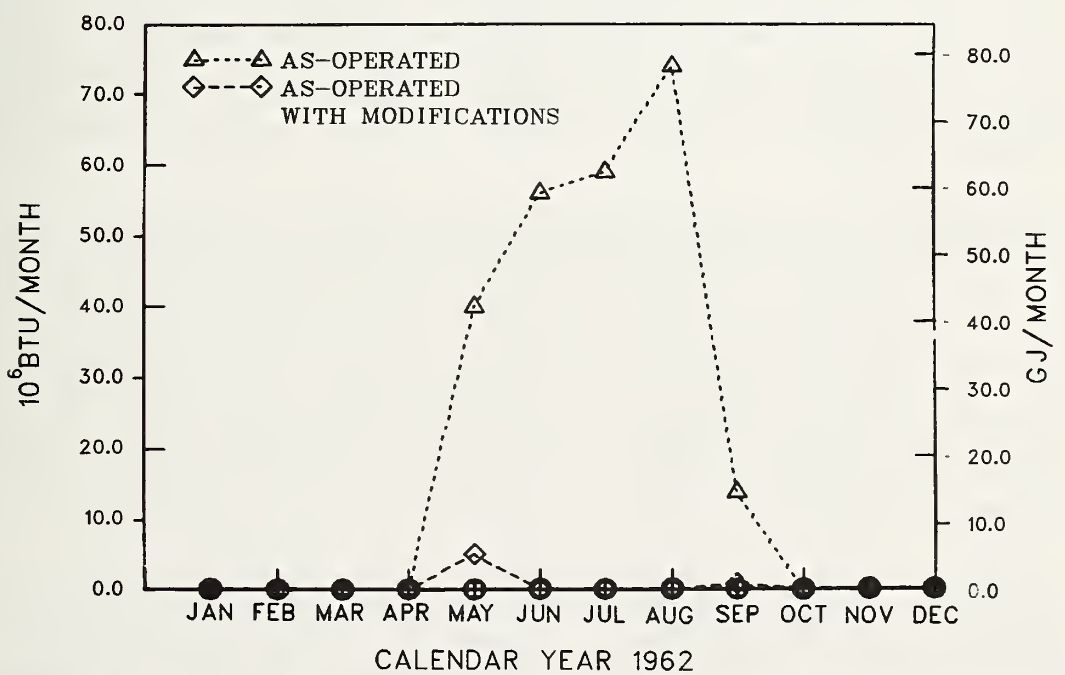

Figure 33. Fuel oil consumption at the Norris Cotton Federal Office Building as predicted by simulation

water heated in the oil boilers. Thus there is no natural gas use in the summer for this case. The winter natural gas consumption is higher than for the "as-designed" case because of higher heating loads. The modifications to the "as-operated" case are not of the type which would save boiler energy and therefore there is no change in the gas consumption for the "with modifications" case. The gas consumption for the "design alternative" case is significantly higher than for the other cases but it must be kept in mind that the "design alternative" does not use heat pumps and all of the energy for heating is supplied by natural gas boilers.

No fuel-oil-fired equipment was included in the original design and therefore no consumption is predicted for the first two simulation cases. Fuel oil boilers were added to the actual building as supplementary boilers and in the "as-operated" case and the "as-operated with modifications" case oil boiler capacity was included. In the winter, the oil boilers have been used when the demand on the boiler system exceeded the gas boiler capacity. In simulating the complex control scheme of the building more gas boiler capacity had to be included in the simulation than the building actually has. The "as-operated" simulations predicted that the extra gas boiler capacity was exceeded and that fuel oil would have been used in the winter. This agrees with the actual operation of the building where the fuel oil boilers were used during the winter.

Figure 33 depicts use of fuel oil in the summer predicted by the simulation cases. Piping was added to the building so that the oil boilers could be used to heat water to fire the absorption chiller. Figure 33 shows a large use of oil for the absorption chiller and a reduced usage for the "as-operated with modifications" case. The lower usage after the "modifications" results from a reduction in absorption chiller operating hours due to use of the absorption machine in sequence with the electric chiller rather than in parallel with it.

Comparison of Actual and Predicted Overall Energy Consumption: The simulation runs were all made using weather data for Concord, New Hampshire for the calendar year 1962. In comparing actual energy consumption data with the results of the simulations it is important to consider that the actual weather has been different from the 1962 weather assumed in the simulations. Although it would have been desirable to use input weather tapes from the period during which the actual building has been operating, detailed hourly weather tapes were not obtainable. Figure 1 is a plot of the average monthly ambient dry-bulb temperature in Concord for 1962 and for the 3 years that the building has been in operation.

A comparison of the building overall energy consumption for the "as-operated" case and the actual consumption for the three years of building operation is shown in figure 34. The energy consumption for the first 2 years of operation was quite variable and much higher than predicted by the simulation. The first two years represent the long period required to "debug" the building as operators attempted to make the mechanical systems perform as called for

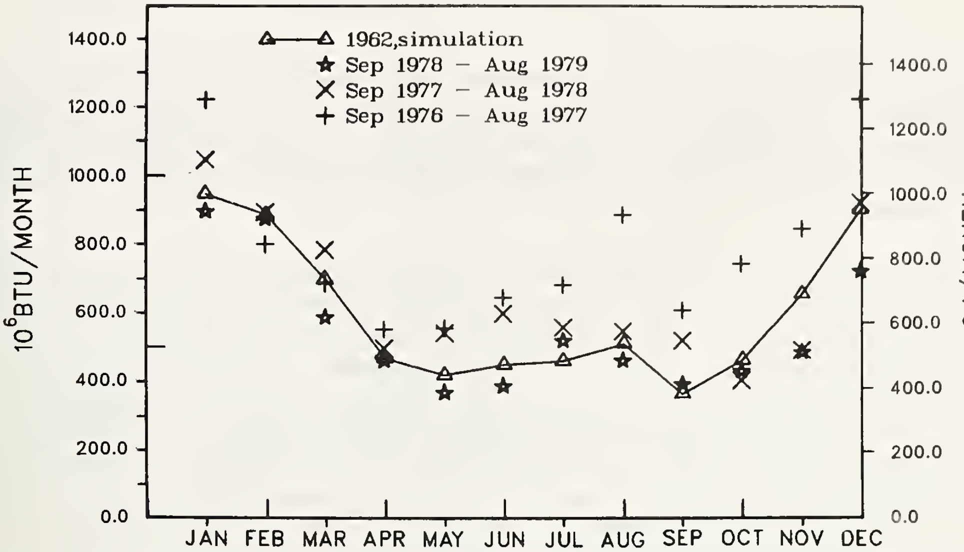

Figure 34. Total energy consumption at the Norris Cotton Federal Office Building as predicted by the "as-operated" simulation compared with actual consumption for three years

Table 11. Norris Cotton Federal Office Building annual energy consumption

SIMULATION CASES (1962 weather data)	Energy consumption in MJ/(m^{2*}·yr) (kBtu/(ft^{2*}·yr))			
	Total	Gas	Electric	Oil
Design Goal	625(55.0)	---	---	---
"As-designed"	686(60.2)	251(22.0)	436(38.2)	---
"As-designed with solar"	616(54.0)	174(15.3)	441(38.7)	---
"As-operated"	705(61.8)	197(17.2)	442(38.8)	24(2.1)
"As-operated with modifications"	662(58.1)	194(17.0)	468(41.0)	1(0.1)
"Design alternative"	676(59.3)	303(26.5)	373(32.8)	---
ACTUAL DATA				
September 1976-August 1977	919(80.6)	280(24.6)	563(49.4)	76(6.6)
January 1977-December 1977	813(71.3)	237(20.9)	514(45.1)	61(5.3)
September 1977-August 1978	758(66.5)	225(19.7)	498(43.7)	35(3.1)
January 1978-December 1978	730(64.0)	208(18.3)	495(43.4)	27(2.3)
September 1978-August 1979	641(56.2)	153(13.4)	459(40.3)	28(2.5)
January 1979-December 1979	619(54.3)	141(12.3)	459(40.3)	19(1.7)

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*equivalent gross floor area = 10,900 m^2 (117334 ft^2)

in the original design. During the third year of operation, the building was finally operated in the best way possible given the shortcomings of the installed systems and equipment. The agreement between the actual energy consumption and the "as-operated" simulation results is fairly close for the third year.

The expression of overall building energy consumption on a per unit area basis has been used to make comparisons between buildings and to establish energy consumption design goals. In making such comparisons, it is important that all buildings involved in the comparison have their areas calculated in a consistent manner and that all references to a single building use the same area. The GSA Public Buildings Service (PBS) uses two methods of computing floor area. The "equivalent gross floor area" (EGFA) method of calculating building area is used as a basis for energy consumption goals [22]. This method identifies three types of building area: office space, mechanical equipment space, and garage areas. Since garage and mechanical areas use energy for lighting, elevator service, and ventilation, GSA/PBS felt that it was important to include such areas in the total but not "weight" them as fully as conditioned office areas. Equivalent gross floor area as defined by GSA/PBS is one quarter of the mechanical and garage areas plus the total office area. A different area, the total gross floor area, is used for reporting of building performance. This area includes all areas of the building.

In order to be consistent with the GSA/PBS conventions, an EGFA of 10,900 m^2 (117,334 ft^2) is used here. This includes 9072 m^2 (97,648 ft^2) of office space, 643 m^2 (6,925 ft^2) of mechanical space, and 6672 m^2 (71,818 ft^2) of garage. The total area of the building is 16,387 m^2 (176,304 ft^2). During the design stage GSA established an energy consumption goal of 625 MJ/(m^2×year) (55 x 10^3 Btu/(ft^2×year)) for this building and for other energy conserving buildings to follow.

Table 11 lists the annual energy consumption per unit equivalent gross floor area predicted for the building as a result of the five computer simulations. Also listed are the values of actual energy consumption of the building since occupancy in September 1976. The "as-designed" simulation prediction exceeds the GSA goal by nine percent. However, when the solar sub-system is added, the simulation prediction is 2 percent less than the goal. The "as-operated" simulation prediction is 12 percent higher than the goal. The "design alternative" simulation results in a value which is eight percent above the GSA goal.

The "as-operated" simulation was intended to represent the actual operation of the building during the recent past. At the time that the simulations were performed, the operation of the building during the third calendar year (1979) was used as a basis for selecting "as-operated" case inputs. It is important to remember that the "as-operated" simulation could not exactly simulate the actual building operation because some manual control has been used by the operator during the three years of operation, and various operational schemes have been used for time periods shorter than a year. It is impossible to accurately simulate a mechanical system when human judgement has been used to control the operation of the equipment. Including the qualifications given, the simulation predicted a total energy consumption 14 percent greater than the third calendar year consumption.

The modifications to the "as-operated" simulation resulted in an annual reduction in energy consumption of about 6 percent. A summary of the major modifications causing the energy reduction are given in table 12.

Heating and Cooling Energy Requirements: The monthly heating and cooling energy requirements, or the energy delivered to or removed from the air side of the mechanical systems, were available from the simulation output. Monthly heating energy requirements per unit area for the "as-operated" case are shown in figure 35. In the figure, the results for the core and perimeter have been combined. The most apparent characteristic of this plot is that the requirements for the first three floors are much larger than the requirements for the other floors. This is due to a higher infiltration rate on these three floors compared to the other floors. Since the thermal design of the building facade is of high quality, loads due to infiltration tend to dominate. Also the heating capacity of the heat pump system on the lower three floors is higher than for the central system on the other floors. Higher capacity results in less time in which the air-side system cannot satisfy the load. Since in the simulation it was found that the air-side systems were not able to meet the load on many occasions, the lower capacity of the equipment on the upper four floors results in less energy delivered to the upper four floors by the air-side systems than if all loads had been satisfied. The figure shows the effect of an increase in air infiltration rate from 0.75 to 1.0 air change per hour. The higher rate represents the value measured in the air exchange tests made on the first three floors before the building facade was caulked. The dotted line representing the requirements for the higher air change rate is approximately 25 percent higher than for the lower air change rate (solid line). In the "as-operated" case the lower three floors have higher energy requirements than the upper floors. The greater requirements result from a higher rate of constant infiltration. Higher infiltration rates flush more heat out of the building during moderate weather thus reducing cooling requirements.

The effect of infiltration rate on the cooling energy requirements for the "as-operated" case can be observed in figure 36. For the lower floor zones, the increase in infiltration rate lowers the cooling requirements. In this figure, the fifth floor stands above the other floors. This is a result of the redistribution of the lighting loads to reflect the tenant requirements. The fifth floor in the simulation has a higher internal gain from lighting than the fourth floor, which is otherwise similar.

Heating and cooling energy requirements for the "design alternative" case are shown in figures 37 and 38. In this case there are only three major zones. One zone represents an area on the first floor occupied 24 hours

Table 12. Summary of effects of modifications made to the "as-operated" simulation

MODIFICATIONS	EFFECT	PERCENT REDUCTION IN TOTAL ENERGY CONSUMPTION
1. Cycle heat pump fans	Save 45,000 kWh	1.3%
2. Raise cooling coil discharge temperature of VAV	Reduce cooling requirements 18 percent	1.2%
3. Raise heat pump loop temperature	Save 5000 kWh	0.3%
4. Lower central chiller condenser water temperature and sequence chillers; electric chiller first, absorption last	Save 54,415 kWh absorption chiller seldom used	2.5%

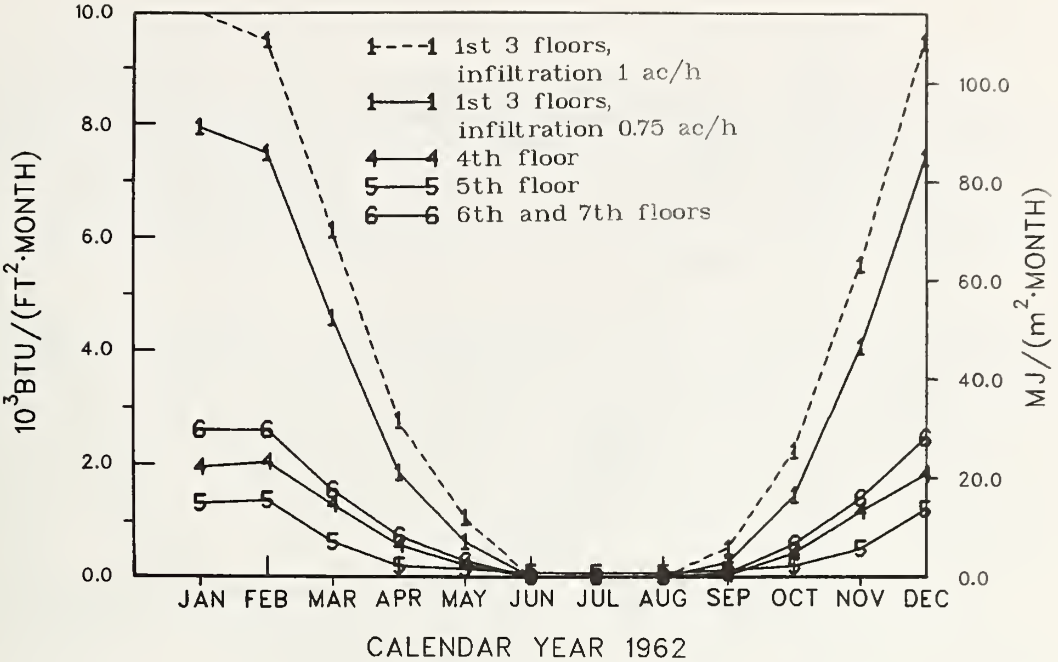

Figure 35. Monthly total heating requirements per unit area for the Norris Cotton Federal Office Building as predicted by the "as-operated" simulation

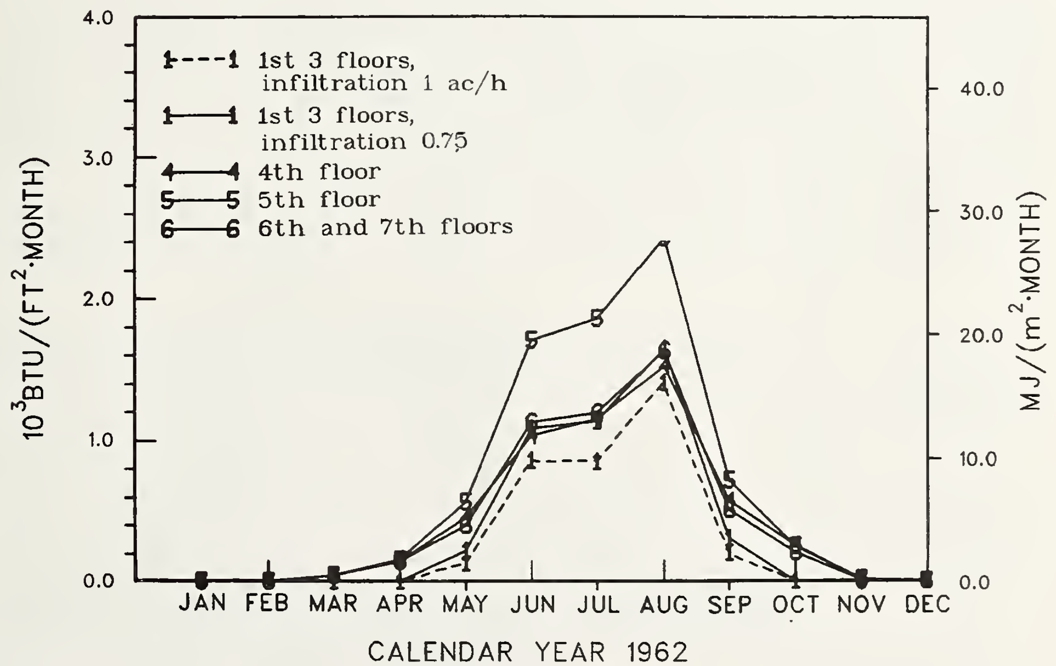

Figure 36. Monthly total cooling requirements per unit area for the Norris Cotton Federal Office Building as predicted by the "as-operated" simulation

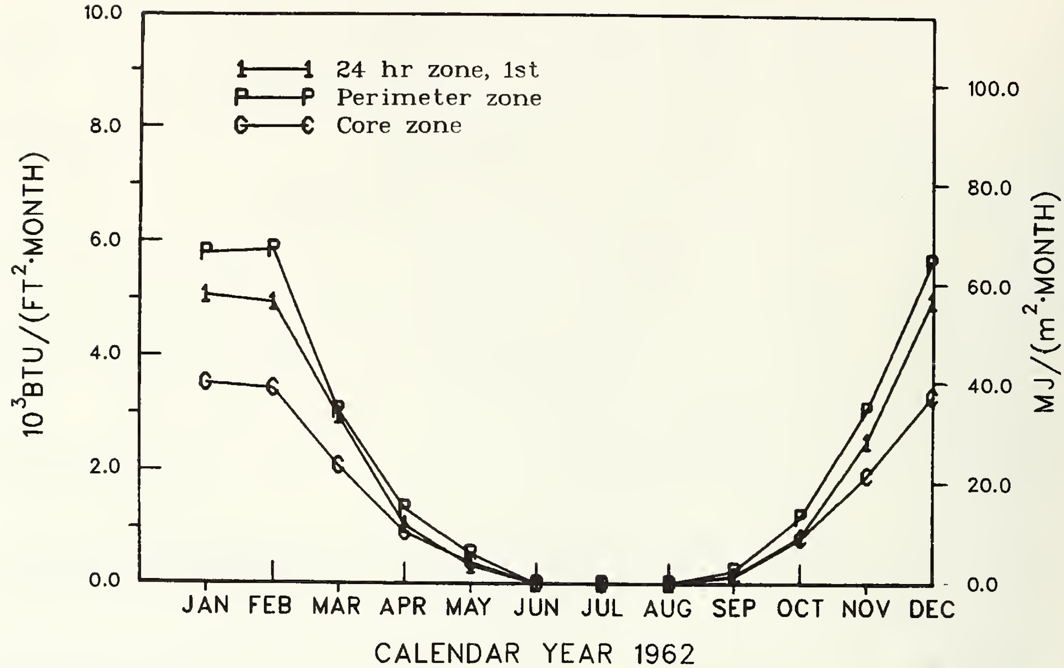

Figure 37. Monthly total heating requirements per unit area for the Norris Cotton Federal Office Building as predicted by the "design alternative" simulation

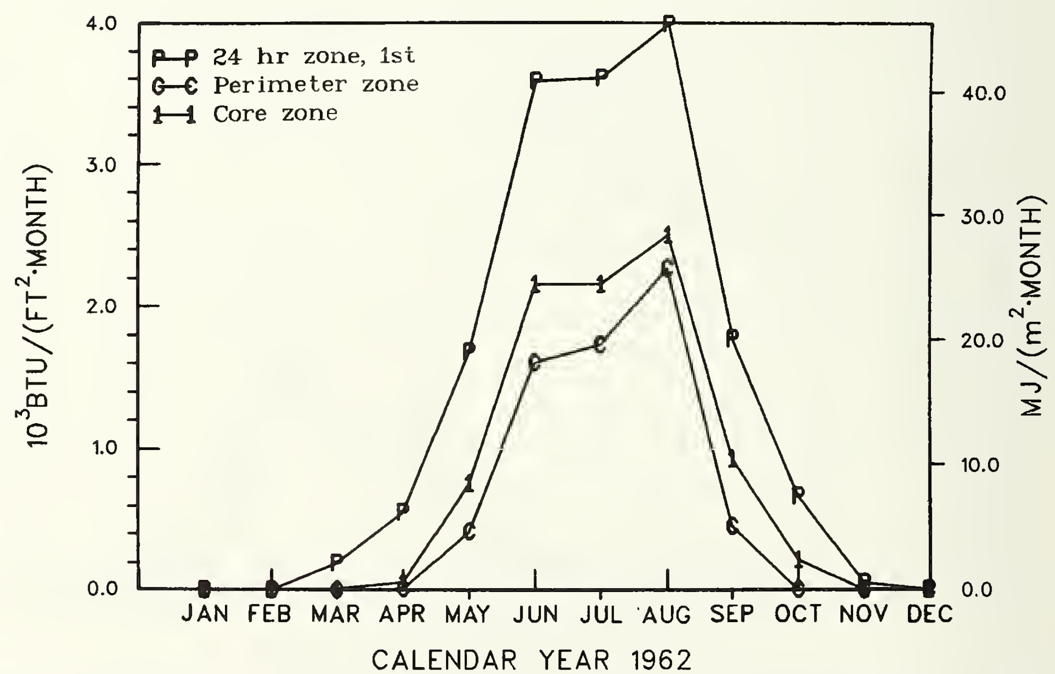

Figure 38. Monthly total cooling requirements per unit area for the Norris Cotton Federal Office Building as predicted by the "design alternative" simulation

per day as a guard office. The heating requirements are slightly higher and the cooling requirements are definitely higher than in the other cases. The higher cooling requirements result from greater internal gains and from solar gain. The high cooling requirements in the perimeter zone relative to the core zone result from solar gains. For comparison, the total monthly heating and cooling energy requirements for all cases are shown in figure 39.

Load Components: One type of output data available from the ERE program is a summation of load components such as transmission losses and internal gains. The information is output as a yearly total. This means that the summation of, for example, transmission losses, includes losses during the summer as well as the winter. This limits the value of the data but it is still possible to gain insight into the building performance by looking at these components. Figure 40 shows the components for all cases in bar chart form. Infiltration and transmission gains are not shown since these are very small relative to the corresponding type of losses. The figure shows that the heating energy requirements for all cases are very similar although the cooling energy requirements differ. All of the simulation cases result in approximately the same infiltration losses. The internal gains differ somewhat, the gains being higher in the "design alternative" case and lower in the "as-designed" case. However, the most striking difference is for transmission losses where the "design alternative" values are much larger than for the other cases. It might seem that this would cause the "design alternative" to have higher heating energy requirements. However, examination of the solar gain data shows a much higher solar gain in the "design alternative" than in the other cases (where gain is zero because of the very small window area). This solar gain, together with the higher internal gains, is the cause of the higher cooling requirements in the "design alternative" case. However, the higher solar and internal gains offset the larger transmission losses in the "design alternative" so that for all the cases, the heating requirements are approximately the same. The conclusion is that smaller window areas in the actual building do decrease transmission losses but also reduce beneficial winter solar gain. In general, the solar gain, transmission loss, and internal gains should be carefully balanced in any design to minimize energy usage or cost.

Fuel Energy Use for Meeting Heating and Cooling Requirements: In order to meet heating and cooling energy requirements, fuel must be used. Besides oil and gas, fuel is also considered to include the electric energy used by compressors in the heat pumps and chillers. Total fuel use can be plotted versus the ambient temperature. The value of such a plot is that actual fuel consumption data are available for the building and a comparison with the simulation results can be made. For the actual data, fan energy cannot be separated from the fuel use. Figure 41 shows the fuel plus fan energy versus monthly average ambient temperature for all the simulation cases and actual data. The lines shown represent a third order (cubic) fit of the data. Residual standard deviations (standard deviation between values predicted by the fitted curve and the original data) for the simulation data range from 16 to 21 GJ (15 to 20 x 10^6 Btu) and for the actual data the residual standard deviation is 51 GJ (48 x 10^6 Btu). The fit is approximately

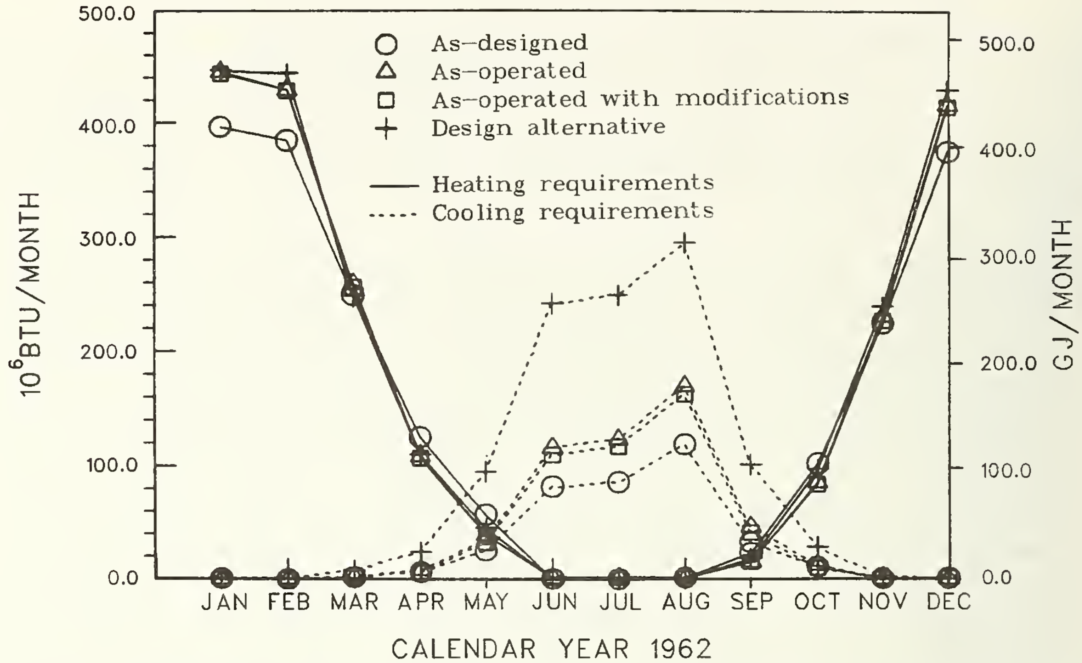

Figure 39. Monthly total heating and cooling requirements for the Norris Cotton Federal Office Building as predicted by all simulations

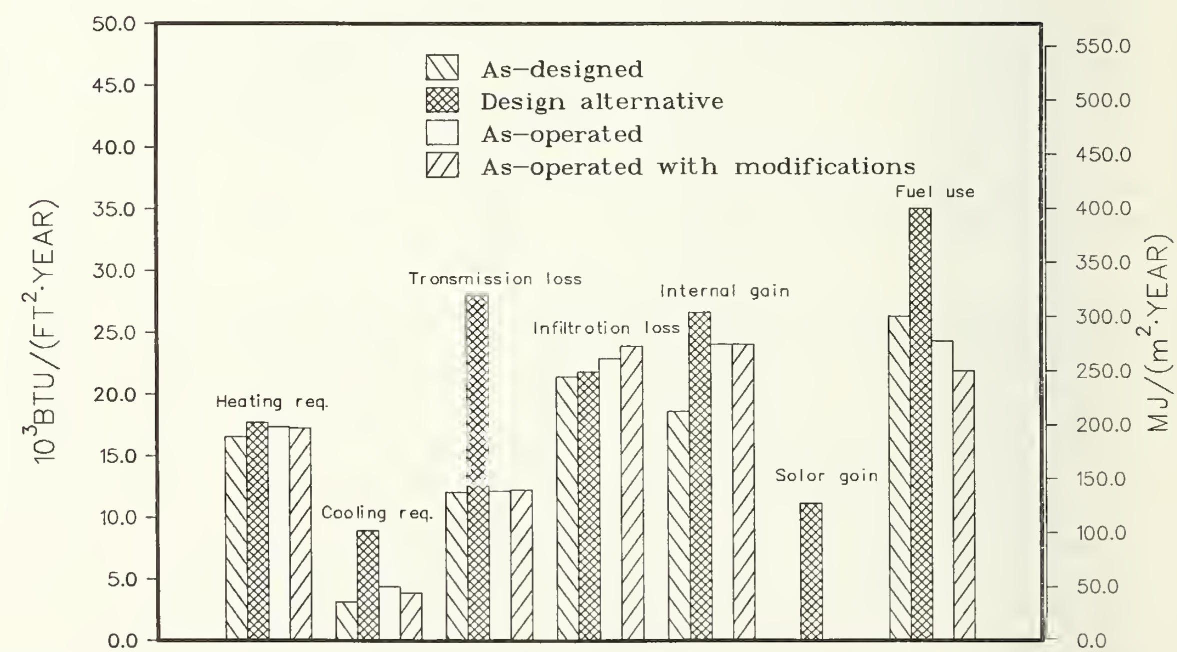

Figure 40. Comparison of heating and cooling requirement components for the Norris Cotton Federal Office Building as predicted by simulation

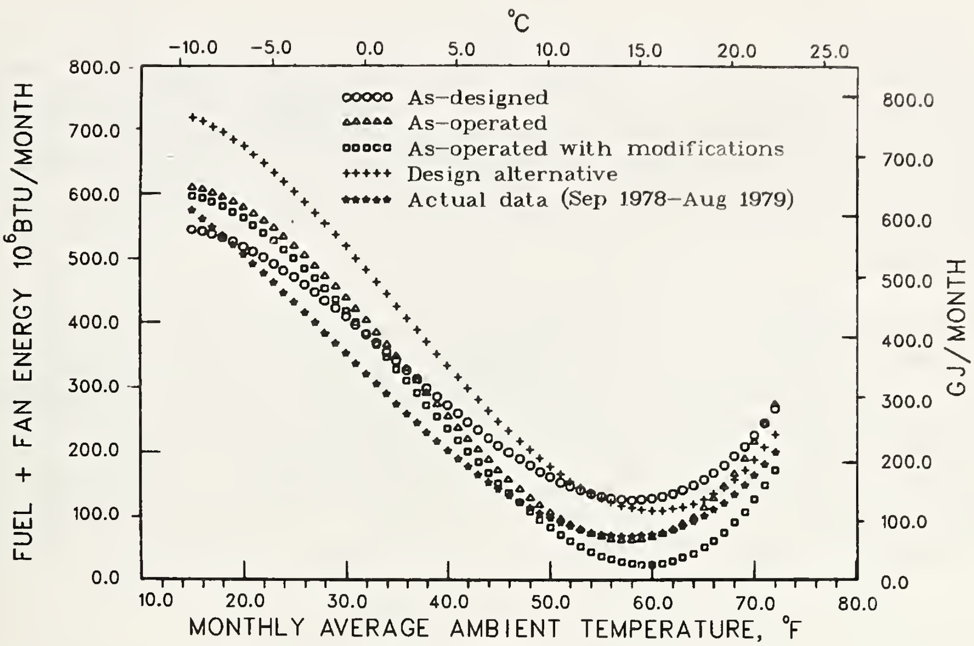

Figure 41. Third order least squares fit of predicted and actual fuel use plus fan energy for the Norris Cotton Federal Office Building versus monthly average ambient temperature

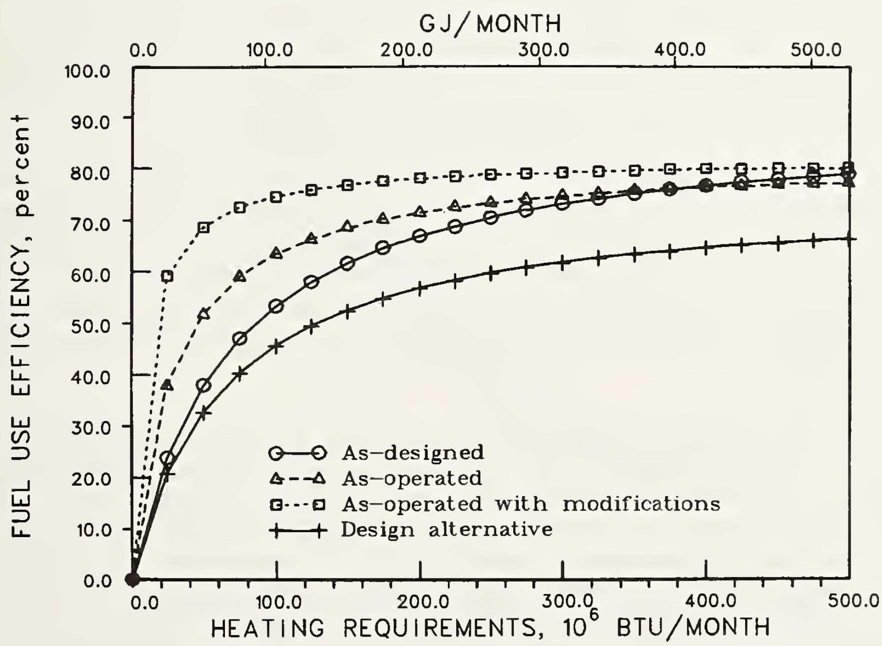

Figure 42. Fuel use efficiency for the Norris Cotton Federal Office Building as predicted by simulations

a "U" shaped curve with a minimum at an ambient temperature of approximately 16°C (60°F). Energy use to the left of the minimum is predominantly for heating; to the right is predominantly for cooling. The actual data compare well with the simulation data although the actual data are somewhat lower than the "as-operated" simulation data. This figure also shows that fuel use for heating is higher for the "design alternative" case than for the other simulation cases.

The figures presented to this point have described overall building performance. The performance of the mechanical equipment may be represented by the ratio of heating and cooling requirements to the fuel (plus fan) energy consumed for each month. For heating, such a ratio may be termed the fuel use efficiency. Least squares fits of the monthly calculated fuel use efficiency for heating are plotted versus heating requirements in figure 42. The energy necessary to meet the requirements was observed to be roughly a linear function of the requirements and thus the efficiency curves are of the form:

$$e = R/(AR + B)$$

where A and B are constants, R is heating (or cooling) requirements, and e is efficiency. Residual standard deviations for the fits are less than nine percentage points of efficiency. In general the efficiency decreases with decreasing load on the mechanical equipment and approaches a full load efficiency at high loads. The "as-designed," "as-operated," and "as-operated with modifications" curves approach efficiencies of 79 percent. At low requirements the "as-operated with modifications" curve is higher because fan energy is reduced in this case. The "design alternative" curve is lower than the other curves, approaching only 66 percent efficiency.

For cooling, the ratio of cooling requirements to fuel plus fan energy may be termed the cooling performance factor. Figure 43 shows least squares fits of cooling performance factor versus requirements. Residual standard deviations range from 1 to 15 percentage points. The "as-operated with modifications" case shows the highest performance factors and the "as-designed" case the lowest. The low "as-designed" curve is due to the use of natural gas as the primary cooling fuel for the central system.

Figures 41 through 43 used fuel consumption as the major dependent variable. In any building, equipment is used to heat and cool the building space and to supply required ventilation. Such equipment, which includes pumps, controls, and fans, requires energy to operate. Such energy usage may be termed energy distribution energy or operating energy. It is important to consider both the operating energy and the fuel energy use in designing and analyzing the performance of large buildings. Figure 44 is similar to figure 41 except that total HVAC energy (fuel and operating energy) is plotted versus the ambient temperature. This plot is also a third order fit of the data and residual standard deviations are 18 to 22 GJ (17 to 21 x 10^6 Btu) for the simulation data and 67.5 GJ (64 x 10^6 Btu) for the actual measured data.

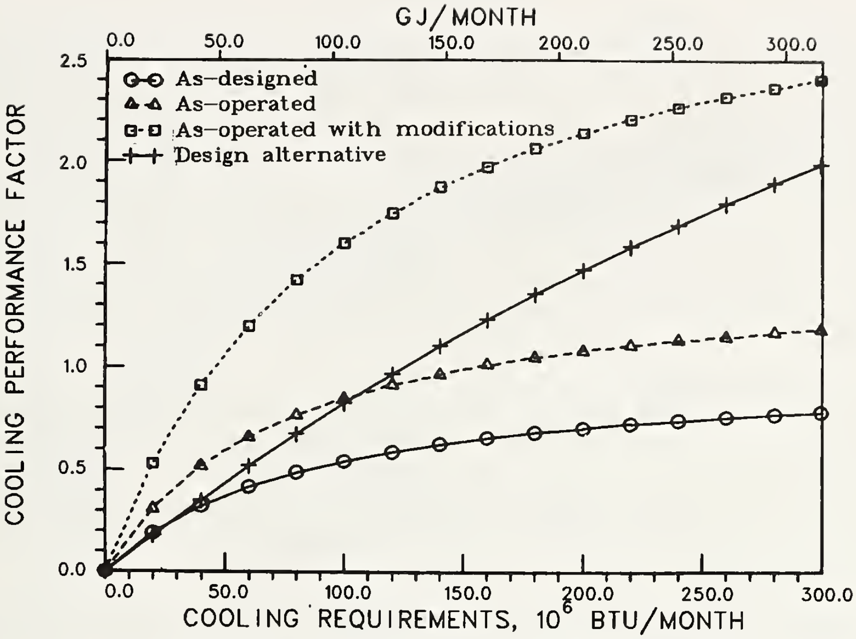

Figure 43. Cooling performance factor for the Norris Cotton Federal Office building as predicted by simulations

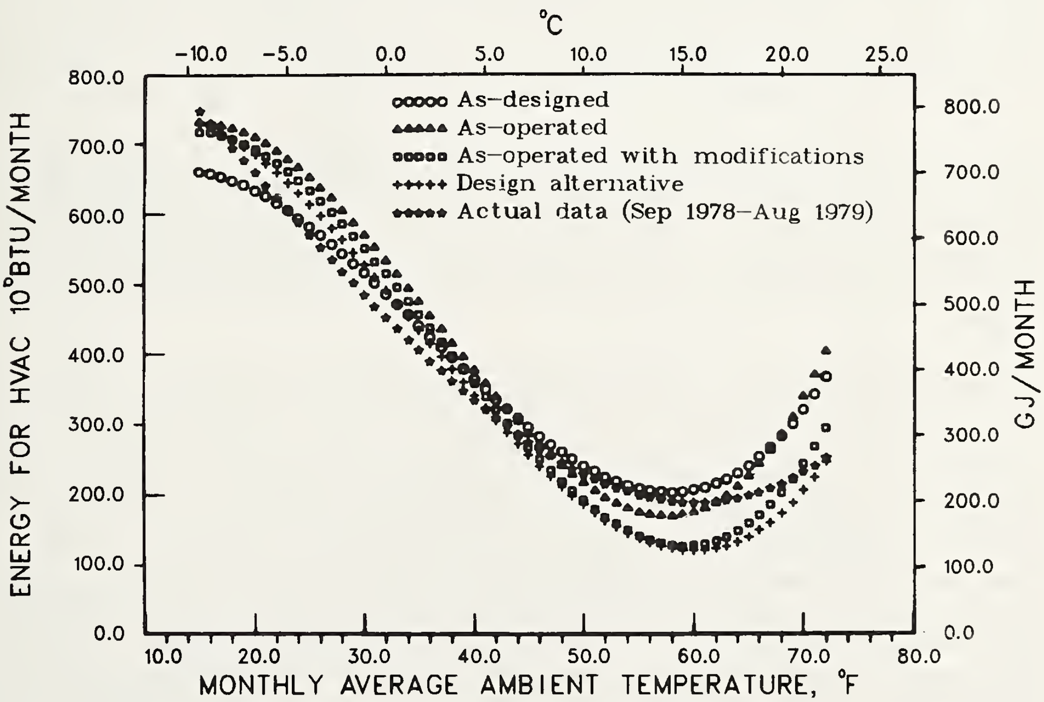

Figure 44. Third order least squares fit of predicted and actual total energy used for HVAC at the Norris Cotton Federal Office building

The curves in figure 44 lie closer together than the curves in figure 41 and the actual data curve is in better agreement with the "as-operated" simulation data curve than in figure 41. There is a distinct difference between the simulation and the actual data curves for cooling, the actual being lower than the predicted. This discrepancy is due to differences in the operation of the building cooling systems in actual practice compared to what was assumed in the simulations. For example, the strategy of flushing the building with outside air in the early morning by manual control was used during the third year of operation but not simulated in any of the cases.

In figure 44, the position of the "design alternative" curve relative to the other curves in the figure is different than the corresponding position in figure 41. In figure 44, the "design alternative" curve is in roughly the same position for heating as the other curves. In the plot of figure 41, the "design alternative" curve is distinctly above the other curves. This indicates that the operating energy is lower for the "design alternative" compared to the other cases.

A total heating efficiency may be defined as the heating requirements divided by the total energy for heating (fuel plus operating energy). Figure 45 is a plot of least squares fitted curves of total heating efficiency versus heating requirements. Residual standard deviations are all low, less than two percentage points. At high loads all curves approach 64 percent efficiency. The "design alternative" curve is in the same region of the plot as the other curves while in the fuel use efficiency plot, figure 42, it was lower. This is due to the addition of the operating energy to fuel energy.

Least squares fits of calculated total cooling factors (cooling requirements divided by the sum of operating and fuel energy for cooling) are plotted in figure 46. Residual standard deviations are less than 14 percentage points. Due to the inclusion of operating energy in the total cooling factor the "design alternative" cooling factors are higher than for the other simulation cases.

Plotting HVAC energy versus energy requirements from the various simulation cases allows a comparison to be made of the two major systems in this building, the heat pump and central systems. A plot of the total heating energy (fuel and operating) versus the heating requirement is shown in figure 47 with a different symbol for each of the two systems. It appears that the central system uses a slightly larger amount of energy to meet a given load than does the heat pump system, but there are not enough points for a strong preference for either of the systems. Data for the cooling season is shown in figure 48 and again the central system appears to use a slight amount more energy than the heat pump system. A complete comparison of the systems should use a life cycle cost analysis (as in Chapter 6) including effects of fuel and equipment cost.

Components of Fuel Energy Use at the Building: The output data from the simulation program allow the amount of energy being used by the major pieces

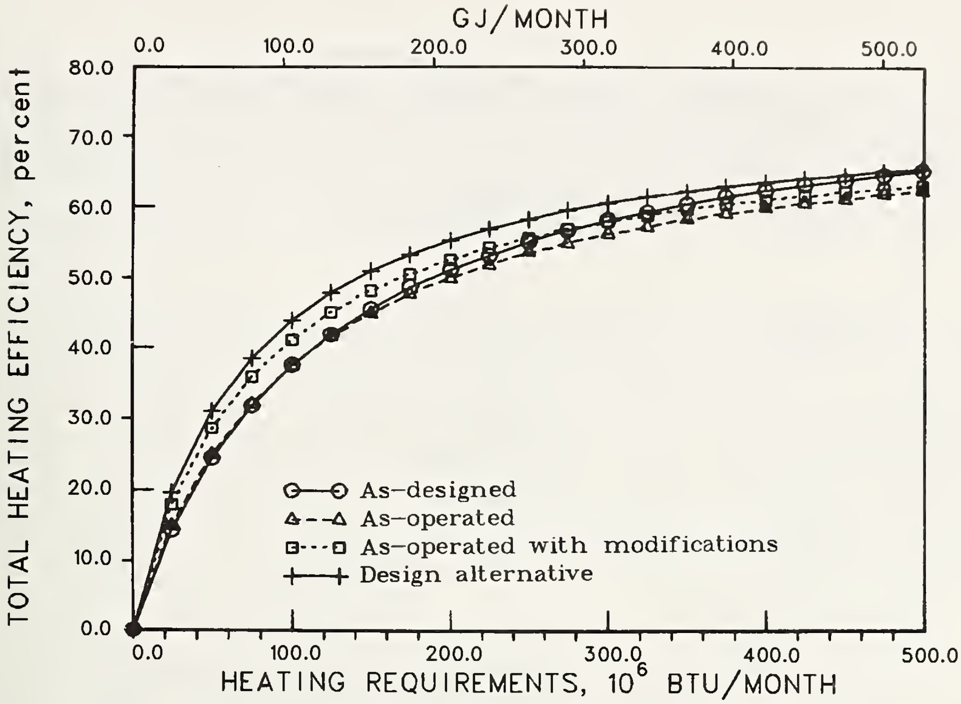

Figure 45. Total heating efficiency for the Norris Cotton Federal Office Building as predicted by simulations

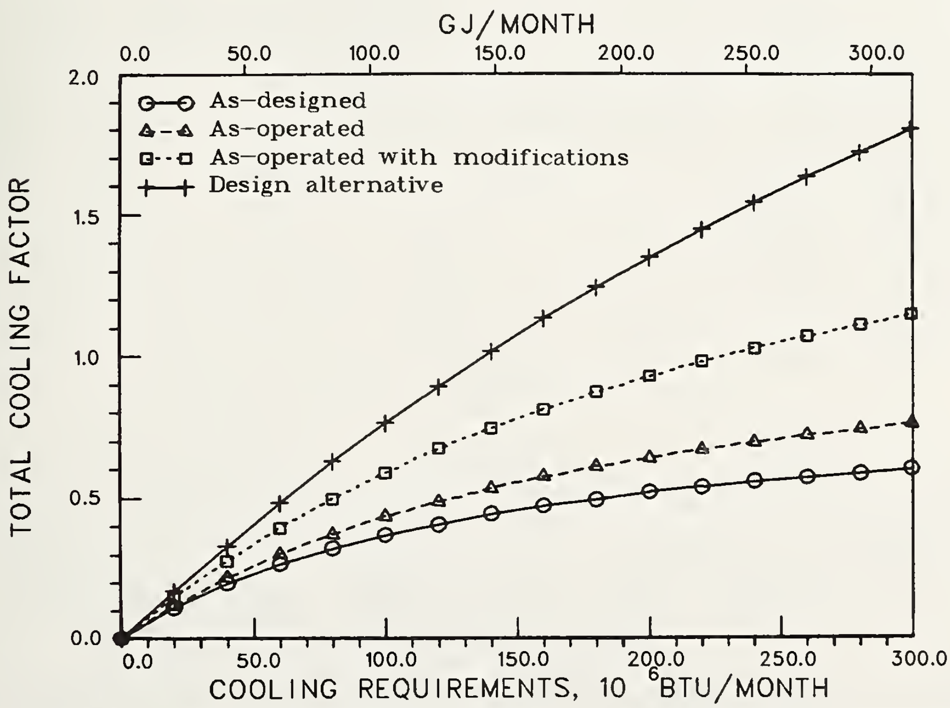

Figure 46. Total cooling factor for the Norris Cotton Federal Office Building as predicted by simulations

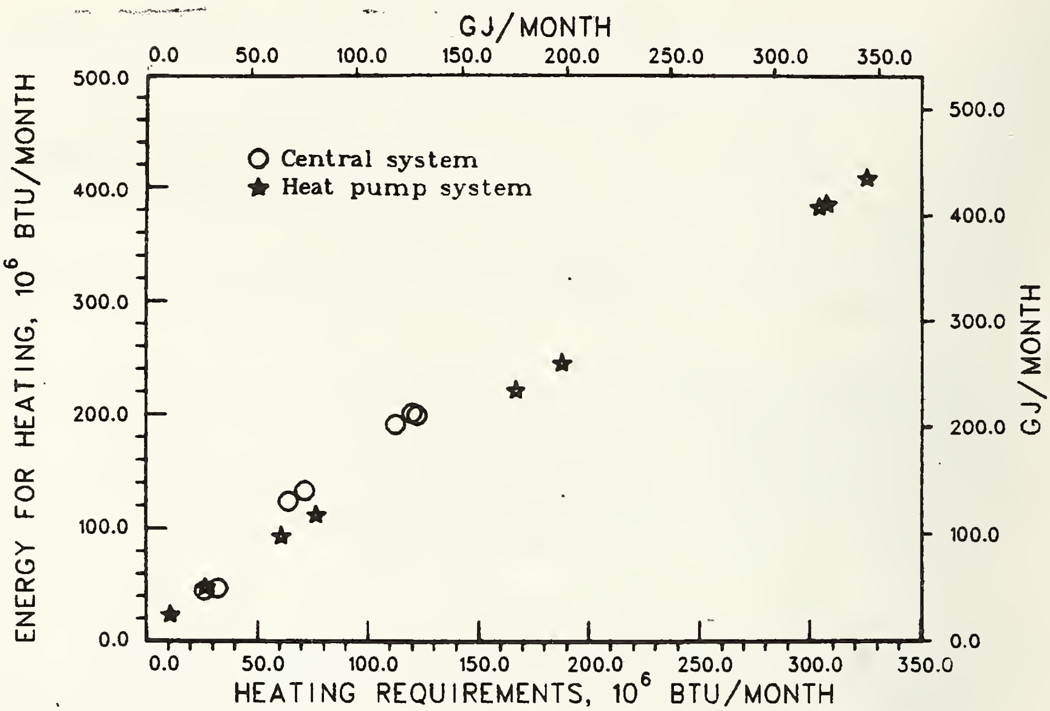

Figure 47. Total energy for heating versus heating requirements for the central and heat pump mechanical subsystems at the Norris Cotton Federal Office Building as predicted by the "as-operated" simulation

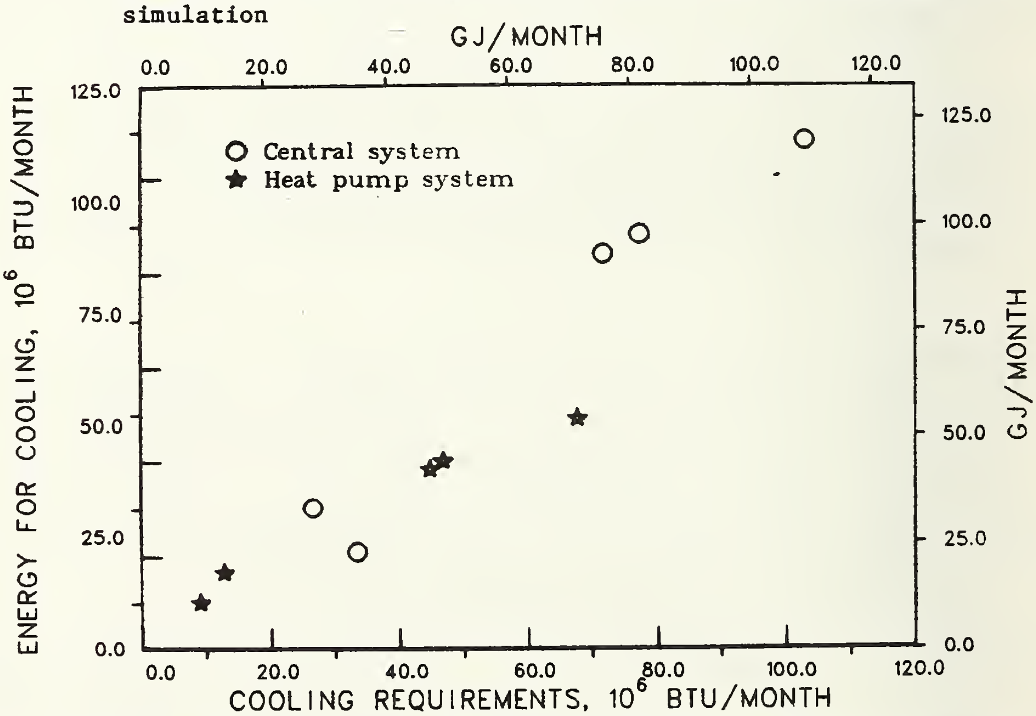

Figure 48. Total energy for cooling versus cooling requirements for the central and heat pump mechanical subsystems at the Norris Cotton Federal Office Building as predicted by the "as-operated" simulation

of equipment such as the boilers, chillers, heat pumps, and engine-generator to be determined, as well as the amount of energy delivered to areas with heating loads and extracted from area with cooling loads. This does not include auxiliary energy to operate the major pieces of equipment and to operate pumps, fans, controls, and other devices used to transport fluids throughout the building.

Actual measured energy data collected at the building was available for comparison with the simulation energy data. The actual data consists of fuel input to boilers, fuel input to the domestic hot water heater, electric input to heat pumps, fuel input to the boilers used to heat water for the absorption chiller, and electric chiller input. No actual energy requirements or load data was available and therefore nothing can be said about the actual energy conversion efficiency of the equipment. It is possible to compare the actual fuel energy data with the analogous simulation data and this is done in figures 49, 50, and 51. There are differences between the "as-operated" simulation data and the actual data.

Figure 49 compares measured boiler input (gas and oil) and simulation predicted boiler input. The actual input to the boilers is lower than the simulated input at low ambient temperatures. Figure 50 shows the comparison for heat pump electric input and service hot water heating (purchased energy only). The actual data for the heat pumps include fans in the heat pump units, while the simulated data are for compressor input only (total heat pump system fan input in the simulation is one the order of 22 GJ/month (20 x 10^6 Btu/month). The actual electric input to the heat pumps in winter is lower than in the simulation, especially when fan energy is added to the simulation data. However, the actual summer heat pump electric consumption is slightly higher even when fan energy is added to the simulation data. The simulated and actual service hot water heater inputs are similar although in the actual case all requirements for service water heating are met by solar energy during summer months. A comparison of actual and simulation data for the chillers is given in figure 51. Actual input to the electric chiller is slightly lower than predicted. Figure 51 also shows that the pattern of use for the absorption chiller that is simulated is very different from the actual use pattern. The simulation is based on parallel operation of the chillers. In actuality, the absorption chiller can be and was used independently of the electric chiller via manual control.

Components of Total Energy Use at the Building: Total energy use can be divided into two broad categories, lighting-miscellaneous and HVAC. HVAC energy is used to provide all heating, cooling, ventilation and service hot water. Lighting-miscellaneous energy is used to provide all other functions of the building such as lights, elevators, and electric receptacles for operating typewriters, copiers, and other equipment. HVAC energy can be further broken down into fuel and operating energy.

Operating energy can be subdivided into energy to operate fans and energy to operate pumps, controls, and miscellaneous HVAC equipment. Table 13

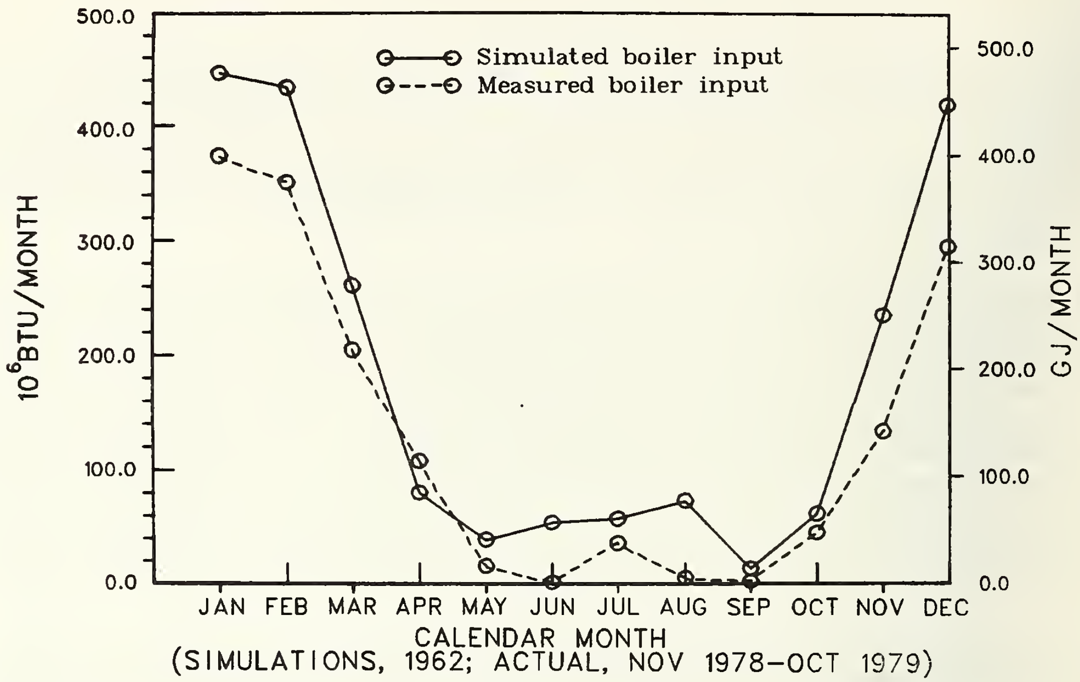

Figure 49. Comparison of actual and predicted boiler fuel input at the Norris Cotton Federal Office Building using "as-operated" simulation data

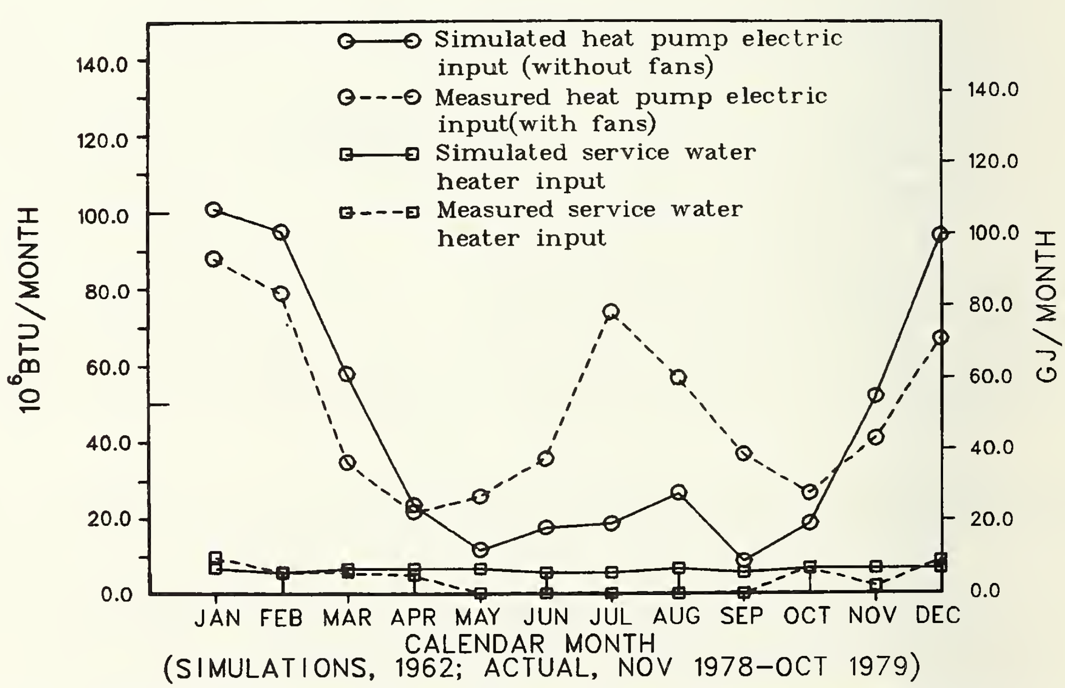

Figure 50. Comparison of actual and predicted heat pump and service hot water input at the Norris Cotton Federal Office Building using "as-operated" simulation data

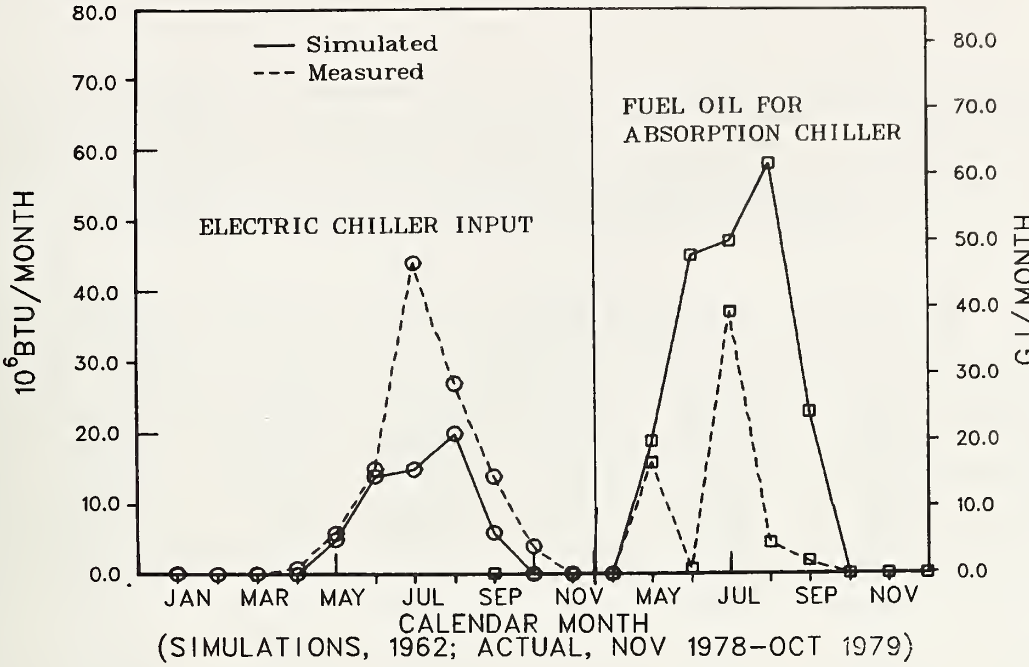

Figure 51. Comparison of actual and predicted energy to central chillers at the Norris Cotton Federal Office Building using "as-operated" simulation data

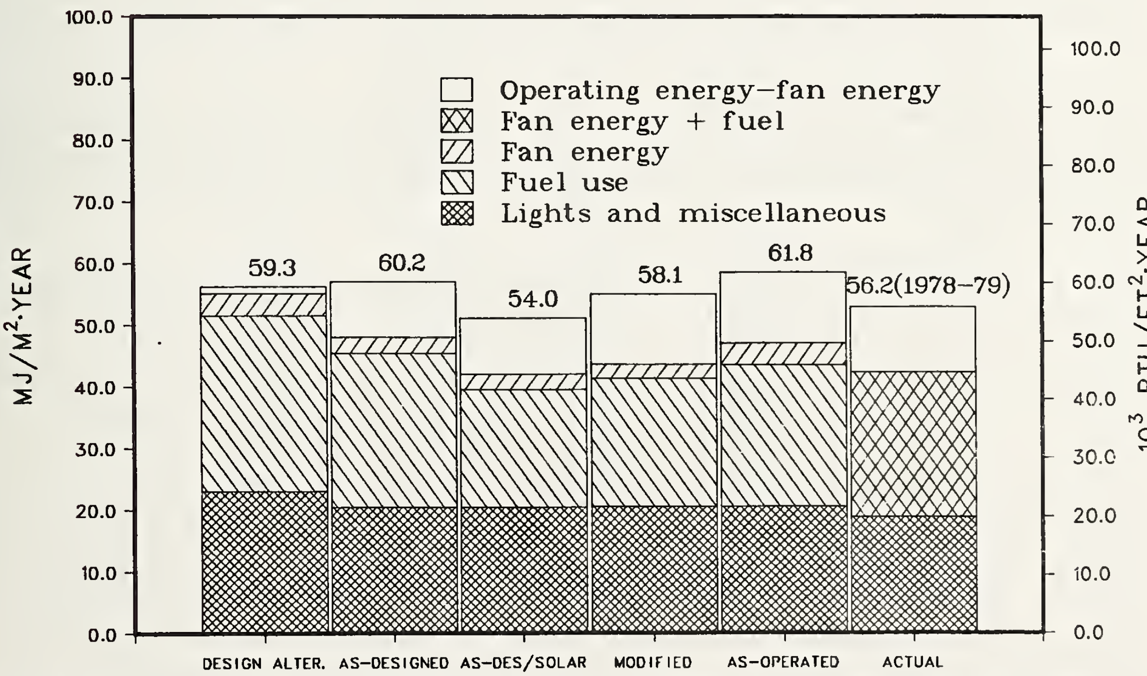

Figure 52. Energy use components and total energy use per year at the Norris Cotton Federal Office Building using simulation results and measured data from September 1978 to August 1979

contains data on a monthly basis for the "as-operated" simulation results. At the bottom of the table are annual totals and the percentage of the total for each category. The table shows that lighting-miscellaneous energy accounts for 35 percent of the total usage. Fuel energy makes up 39 percent while operating energy consumes a surprisingly large fraction of the total, 26 percent.

Actual measured data from the building for the period from November 1978 to October 1979 is given in table 14 and is broken down into categories similar to those used in the table for the simulation results. In order to compare the results on an annual basis for the simulations and the actual data, figure 52 has been prepared in bar chart form with the quantity of energy for each end use shown as different regions of the bars. Using the actual data, the energy for fuel and energy to operate fans cannot be separated due to the fact that the heat pump units do not have separate meters for the compressors and the integral fans. Thus, for the actual data, fan and fuel energy have been combined.

In the "as-operated" case, while the energy predicted for lights and miscellaneous was the same relative to the "as-designed" case, fuel use decreases and operating energy goes up to approximately 26 percent of the total. The operating energy is larger in the "as-operated" case because several pumps in the actual building operate around the clock but were assumed to operate only when heating or cooling loads existed in the "as-designed" case. Also, some equipment was added to the building after the original design, most notably an air conditioner for the elevator machine room to cool the solid state controls.

The "as-operated with modifications" case shows a reduction in HVAC energy, both in the fuel and the operating energy categories. Operating energy for this case is approximately 25 percent of the total and HVAC energy makes up 63 percent.

The energy use profile for the "design alternative" looks very different from the uses for the other cases. The lighting-miscellaneous increases to about 41 percent of the total and fuel use increases to 51 percent of the total. However, the operating energy is much less than in other cases, accounting for only 8 percent of the total energy usage. The energy to operate fans is 4 to 6 percent of the total in all cases. If the fan energy is subtracted from the operating energy for the "design alternative", the remainder is 2 percent for pumps, controls and other HVAC equipment compared to 16 to 21 percent of the total in the other simulation cases. Much of the equipment used in the "design alternative" is more distributed throughout the building and less efficient than the equipment in the actual building but requires less supporting equipment and less operating energy. The fact that the Norris Cotton Building is an experimental building also has an effect on operating energy. The multiple systems in the building require much more operating energy than if a single type of mechanical system were used.

Table 13. Energy use components for the "as-operated" simulation

Month (1962)	Lights + misc. kWh	HVAC kWh	Direct fuel kWh	Operating energy kWh	Fans kWh	Pumps, controls + misc. kWh	Total
1	64138	213986	162945	51041	11676	39365	278124
2	56585	203955	156895	47060	10749	36311	260540
3	62592	143437	95618	47819	10924	36895	206029
4	61620	76416	32489	43927	9597	34330	138036
5	64138	59245	18753	40492	9886	30606	123383
6	61620	70555	27562	42993	10186	32807	132175
7	62592	73100	28992	44108	10414	33692	135695
8	65685	84367	37656	46712	10856	35856	150052
9	58530	49320	10263	39057	9205	29852	107850
10	64138	71847	26328	45519	9864	35655	135985
11	61620	131514	86413	45101	10157	34944	193134
12	61046	203890	152804	51086	11610	39476	264936
Annual	744308	1381632	836718	544915	125124	419791	2125940
% of total energy	35	65	39	26	6	20	

Table 14. Energy use components from actual data

Month (1978-79)	Total energy kWh	Lights + misc. kWh	HVAC kWh	Direct fuel and fans kWh	Pumps, controls + misc. kWh
1	262943	60149	202794	162002	40793
2	256124	53576	202548	169060	33488
3	172472	62367	110105	82476	27630
4	135282	57227	78055	51995	26060
5	108612	55405	53207	23454	29753
6	113981	55450	58531	25543	32988
7	151981	58840	93141	58684	34457
8	135853	60074	75779	36373	39405
9	108498	56012	52486	26305	26181
10	120062	59150	60912	33670	27242
11	142696	53981	88715	60884	27831
12	212201	53197	159004	120383	38621
Annual	1920705	685428	1235277	850828	384449
% of total energy	100	36	64	44	20

The "as-operated" case shows an operating energy use 9 percent greater than the actual building data indicates, a lighting-miscellaneous 9 percent greater than actual, and a fuel plus fan energy use which is 12 percent greater than the actual. Fuel plus fan energy for the simulation and measured data were compared on a monthly basis in figure 41. After plotting the fuel data versus ambient temperature, the "as-operated" curve fitted through the data was higher than the measured data curve. Some of the difference may be due to weather differences. The lights plus miscellaneous energy and operating energy may be compared on a monthly basis in figure 53. The lights plus miscellaneous energy is higher for the simulation than for the measured data and the difference is approximately constant through the year. However, the difference between predicted and measured operating energy varies as a function of the month. The actual operating energy dips to lower values during spring and fall compared to the "as-operated" simulation results.

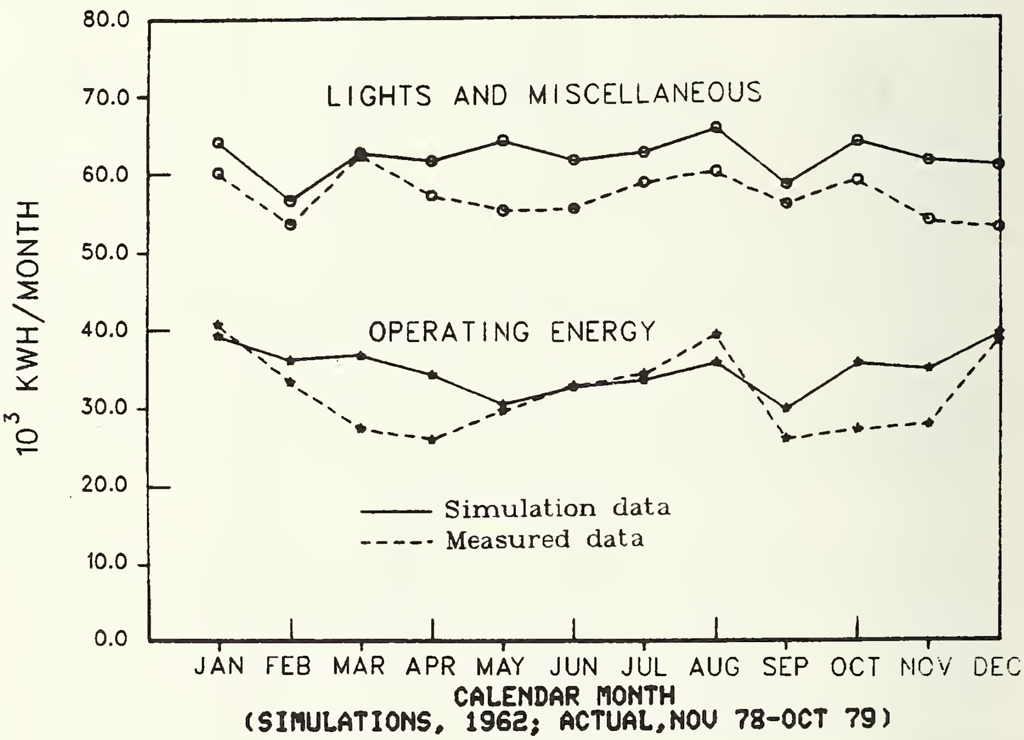

Figure 53. Comparison of actual and predicted lighting-miscellaneous and operating energy at the Norris Cotton Federal Office Building using "as-operated" simulation data.

Facing page:

Lobby of the fourth floor at the Norris Cotton Federal Office Building. Sodium vapor lighting is used on this floor.

4. PERFORMANCE OF THE LIGHTING SYSTEMS

Measurements of the performance characteristics of the lighting systems at the Norris Cotton Federal Office building were made during the first 3 years of operation.

4.1 LIGHTING SYSTEMS

The Norris Cotton Federal Office Building has six different illumination systems, all having approximately the same connected electric power per unit floor area. The luminaires installed in the building are listed in table 15. Note that for all floors with fluorescent lighting systems, the lamp distribution is four lamps per 9.3 m^2 (100 ft^2). All lamps with single lamp luminaires are in two-lamp series circuits. Therefore, the connected power densities for all floors with the fluorescent lighting systems are 19.8 W/m^2 (1.84 W/ft^2). On the fourth floor, the power density for the high pressure sodium lamps is 18.3 W/m^2 (1.7 W/ft^2). The power density for the fifth floor is not fixed, but is dependent on the density of the work modules. At the time of measurements of lighting characteristics made at the building, the power density for the fifth floor was obtained by actual count of the number of working modules in the space and found to be 26.2 W/m^2 (2.43 W/ft^2).

The first and third floors have identical luminaires, but differ in the type of installed lenses. The first floor has prismatic lenses and the third polarized lenses. The second and sixth floors have identical lighting systems, but differ in the amount of fenestration, and therefore the amount of potential contribution from daylight. The window area on the second floor, comprising 12 percent of the east, west and south facades, is approximately 2½ times larger than on the other floors. All windows are double glazed with a venetian blind between the two glazings. The slats of the blinds were in s horizontal position when measurements of lighting performance were being made.

4.2 EVALUATION PROCEDURE

A basic quantitative performance measure of a lighting system is the amount of light it directs toward the task, that is, the illuminance, denoted by E and in units of lumens per unit area. However, the effectiveness of the illumination for visual task performance will vary depending on the geometry of the light flux reaching the task surface. A common method used to assess the geometric effectiveness of a lighting system is to compare its performance to that of a reference lighting system by means of the contrast rendition factor, (CRF), defined as:

$$CRF = C_t/C_r \qquad (1)$$

where C is contrast and the subscripts t and r refer to test and reference lighting systems, respectively. Contrast is defined as:

$$C = (L_b - L_d)/L_b \qquad (2)$$

where L_b is the luminance (in lumens) of the background and L_d is the luminance of the task detail.

Effective Illuminance, E_{ef}, can be defined as

$$E_{ef} = CRF \times E \qquad (3)$$

Table 15. Lighting systems installed in the Norris Cotton Federal Office Building

Floor	Light distribution	Luminaire lense	Luminaires per 9.3m^2(100 ft^2)	Lamps per luminaire
1	Direct	Prismatic	2	2
2	Direct	Twin beam	4	1
3	Direct	Polarized	2	2
4	Direct	Prismatic	1	1
5	Indirect	Task-lit systems furniture		1
	Direct			2
6	Direct	Twin beam	4	1
7	Direct	Prismatic	1	4

Floor	Lamps per 9.3m^2(100 ft^2)	Lamp Type	Watts	Power density W/m^2(W/ft^2) (inc. ballast)
1	4	Fluorescent	40	19.8 (1.84)
2	4	Fluorescent	40	19.8 (1.84)
3	4	Fluorescent	40	19.8 (1.84)
4	1	High-pressure sodium	150	18.3 (1.70)
5		Metal Halide	250	*
		Fluorescent	20	
6	4	Fluorescent	40	19.8 (1.84)
7	4	Fluorescent	40	19.8 (1.84)

* depends on furniture density.

where E is the illuminance at the task surface. That is, the luminous flux falling on the task surface is weighted by a factor, CRF, that "weights" the luminous flux in terms of how well it makes the task detail stand out from the background.

In terms of energy usage and system effectiveness, the most relevant performance measure was felt to be one relating the "amount of useful light" to the input power density. Luminous efficacy (of a system) is defined as:

$$\text{luminous efficacy} = E_{ef}/P_A \quad (4)$$

where P_A is the input power per unit area.

Equivalent sphere illumination (ESI) is often used in the literature as a measure of system effectiveness. Briefly, ESI assigns different weights to the same CRF, depending on the absolute luminance level. As indicated in Equation (3), the treatment of system efficiency used in this study did not weight the CRF differentially for luminance levels. Since the contrast is the same regardless of the luminance level, and since efficiency is determined by the geometry of the flux distribution, no rationale could be justified for differential weighting of the luminance levels.

In order to complete the measurements and determine luminous efficacy for each of the lighting systems in accordance with Equation (4), a reference lighting system and a reference task had to be used.

4.3 REFERENCE LIGHTING SYSTEM

A reference lighting system is a system in which light flux is incident on the task equally from all directions. The reference lighting system used for this study was designed and constructed at NBS as is shown schematically in figure 54. The projector, P, produced a homogeneous beam over the entire face of the diffusing plastic, D. The light was diffused while passing through the plastic plate and fell on the hemisphere wall, H. The hemisphere was coated with halon and thus light incident on the hemisphere was diffusely reflected. That portion of the light incident on the plastic after reflection from the hemisphere wall was either transmitted to the outside or was diffusely reflected back to the hemisphere, since the inner surface of the plastic had a finely ground finish. The target holder, C, was placed in the center of the plate, D. The target was viewed through an aperture, A, located at $\equiv_v = 25$ degrees from the center of the hemisphere.

Calibration of the hemisphere was accomplished by inserting a small acceptance angle fiber optic in the center of the target holder with the fiber aperture near the target plane. The fiber optic was aimed toward the hemisphere wall and luminance readings taken. Readings were taken every 15 degrees along the polar axis and at four azimuth angles. The readings are given in table 16. As table 16 indicates, the flux reflected from the hemisphere wall which fell on the task was homogeneous to within plus or minus 2 percent.

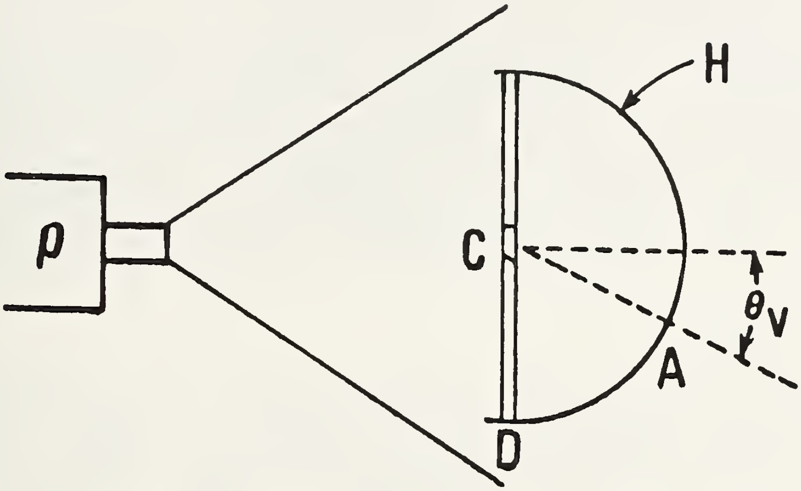

Figure 54. Reference hemispherical lighting system used in lighting measurements for the Norris Cotton Federal Office Building

Table 16. Luminance (cd/m^2) of hemisphere wall with center of task area as the viewing point

Polar angle	Azimuth angle 0	90	180	270
0	65	65	65	65
15	66	66	66	65
30 45	64	65	65	65
60	65	65	65	64
75	65	65	65	64

The Illumination Engineering Society (IES) recommends that body shadow be excluded from the hemispherical contribution to task lighting. In the measurements to be reported in this study, this exclusion was not observed. A body shadow inclusion is relevant, in that the body occludes all flux directed to the task from behind the body. But due to variation in the reflectance of the clothing worn by the worker, the light flux reflected off the clothing and directed toward the task surface cannot be easily determined. It could be substantial for a worker wearing a white shirt, but insignificant for a worker wearing dark clothing. Since the reference lighting system was an arbitrary one chosen primarily for its simple and consistent geometric properties, the inclusion of a body shadow with its size and reflectance variabilities and the resulting complexities were not felt warranted. The primary requirement was that consistent conditions be utilized.

4.4 REFERENCE TASK

The reference task used was a thin line drawn with a no. 2 pencil on bond paper. The contrast under hemispherical lighting was 0.426. The task used in evaluating the CRF is an important variable. It is theoretically possible to have CRF = 1.0 for all lighting systems, by using a reference task in which both the detail and background are complete diffusers. At the other extreme, it is possible to have a task with a mirror finish (highly specular) such that CRF is influenced only by rays near the specular angle, i.e., incident angle equals the observing angle and viewing direction is 180° from the incident direction. The above considerations played an important role in the choice of the task used in the set of measurements made.

4.5 MEASUREMENT LOCATIONS

Since the aspect of the lighting system effectiveness that was being evaluated in this study was the geometric properties of the installed luminaires and reflectance characteristics of the spaces, the location where the measurements were taken was an important variable. There were infinitely many locations in the spaces that could have been used. For simplicity, measurement locations were restricted to two broad categories, beneath and between luminaires, as shown in figure 55. For the three types of luminaire spacing in the building, continuous rows (R), symmetrical (S), and checkerboard (C), the two categories are indicated in figure 55 as 1 for beneath the luminaires and 2-3 for between the luminaires.

The quantity of interest in contrast rendition is the luminous flux reaching the eye after being reflected off the task surface. Therefore, at a specific location, the direction of view and viewing angle had to be considered. The viewing angle, θ, was fixed at 25 degrees (see figure 56). That is, the angle between the line of sight of the photometer, P, and the normal to the task plane, T, was fixed at 25 degrees. For a specific task location, there were four primary directions pointing toward the task that could be represented by the four compass points: north, east, south, and west. Each of these

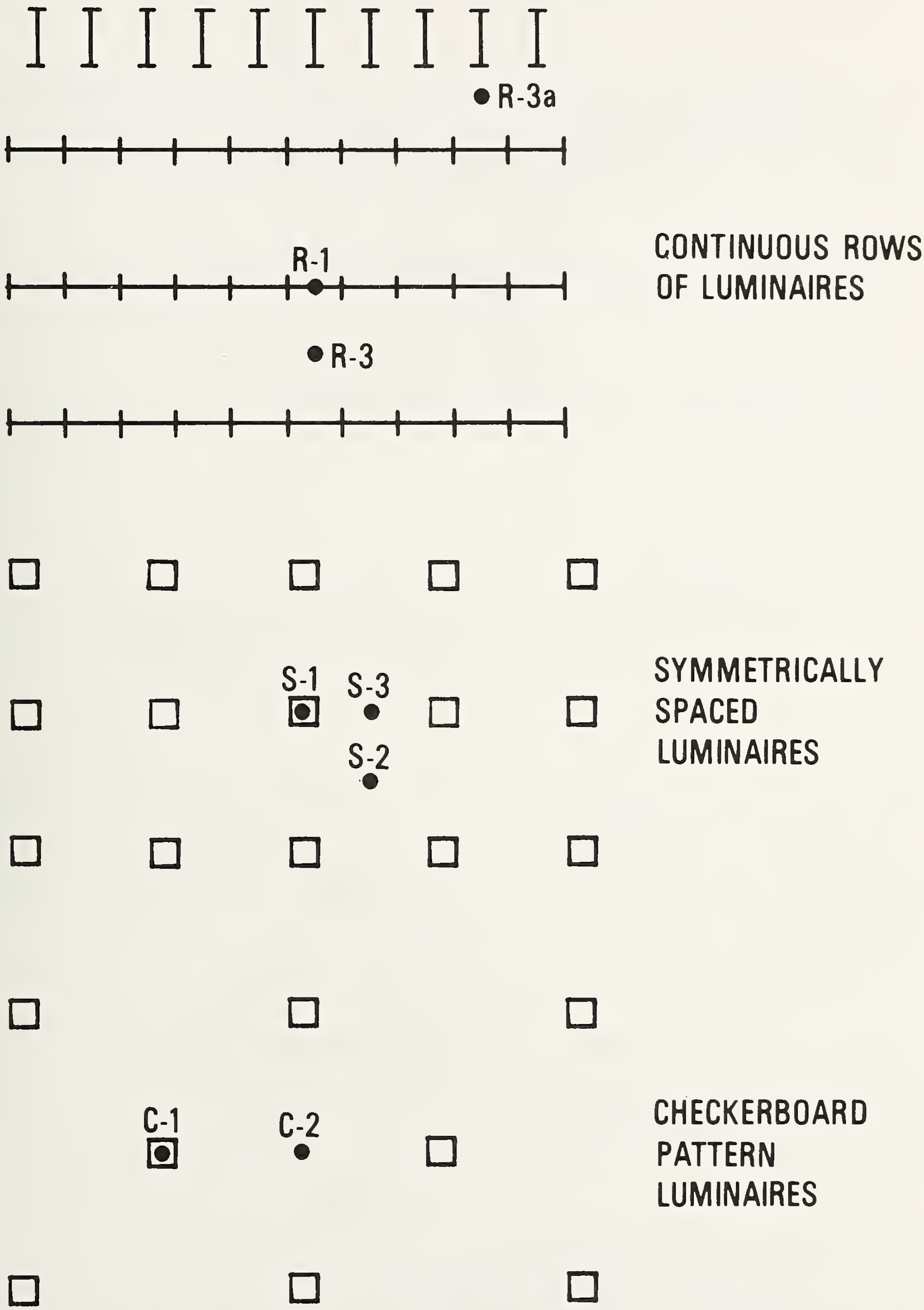

Figure 55. Lighting system test measurement locations shown relative to luminaire orientation and location in the Norris Cotton Federal Office Building

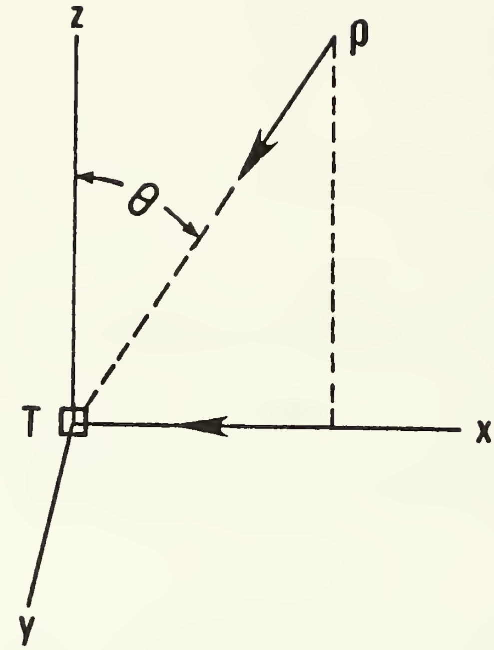

Figure 56. Viewing angle for contrast measurements at the Norris Cotton Federal Office Building

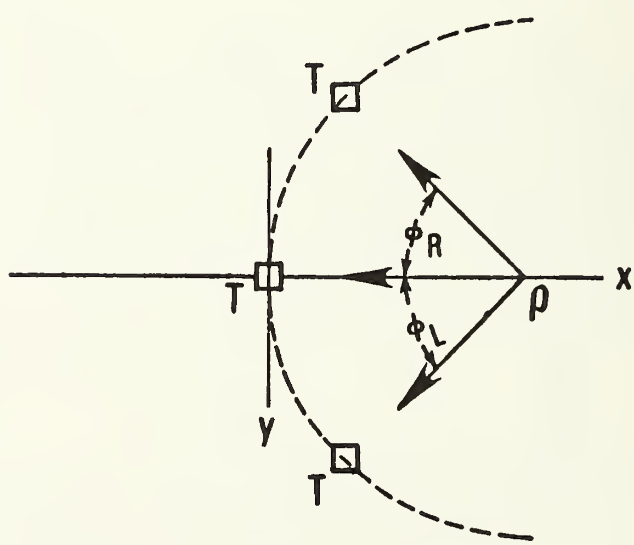

Figure 57. Diagram showing the three measurement directions for the same observing spot when making contrast measurements in the Norris Cotton Federal Office Building

compass points was appropriate for evaluating lighting system effectiveness for the condition where the task was directly in front of the worker. Measurements were made at two additional directions for each compass point. These directions were intended to represent the conditions where the worker turned his head to look at a task located off center.

For these conditions, the task was moved 45 degrees to the left, Ξ_L, or right, Ξ_R, on an arc formed with the center of curvature at the location of the photometer, P (see figure 57). Therefore at a given task location, measurements were made in 4 x 3 = 12 directions of view.

For the special case of the task-lit furniture on floor 5, the direction of view was fixed. Therefore, for this case, measurements were made at only one compass point with its right and left viewing directions, giving 1 x 3 = 3 measurements.

4.6 RESULTS

The illuminance values were obtained with a color-and-cosine-corrected illuminometer, calibrated against a 500 W, T-20 inside-frosted 2856 K working standard, and were measured with the photometer in place for contrast measurements. The results are given in table 17 and figure 58. The N and D in the location column refer to night and day, respectively. The rest of the alphanumeric code describes the location relative to the luminaires as shown in figure 55.

The bars in figure 58 give an indication of the variability of illuminances as a function of the direction of view at a given location. The numbers at the top of the columns designate the floor in the building. The ends of the vertical bars give the extreme range of illuminances. The rectangular area filled with diagonal lines includes the range for the middle 50 percent, i.e., with the highest and lowest 25 percent of the values excluded. Therefore, the vertical lines connecting the rectangular areas and the upper and lower horizontal bars give the range of the upper and lower 25 percent illuminance values. Figure 58 shows that the variation in the level of illuminance was largest for the fourth floor.

The illuminances for the first and fourth floors were much higher than those measured for the remaining floors. Day and night readings were taken at the same locations on the second floor. The day readings for floor 2 were generally higher than those obtained at night, the difference indicating the effect of the larger window area on the second floor.

The results of the contrast rendition factor measurements are given in table 18 and figure 59. Each value is the arithmetic average of 3 measurements. The importance of direction of view in making contrast measurements is indicated by the range of CRF's found at the same location. For example, on the fourth floor at location N3, when facing south with the task located to the left, the CRF was 1.057. At this same location when the task was straight

Table 17. Illuminance (dekalux) at task surface with contrast measuring instruments in place at the Norris Cotton Federal Office Building

Floor	Location	North R	North O	North L	East R	East O	East L	South R	South O	South L	West R	West O	West L
1	NC2	99.2	90.1	98.6	97.5	90.2	98.2	95.4	87.7	97.4	96.8	87.7	96.3
	NC1	88.2	95.2	88.8	102	115	102	87.2	112	102	87.2	93.6	86.6
	NC1	98.0	105	96.8	96.8	105	97.9	96.8	104	96.8	97.1	105	97.9
	NC2	93.5	85.0	94.5	94.8	86.2	93.8	94.8	86.9	94.3	94.8	86.1	93.6
2	DR1	66.3	68.9	67.8	60.6	64.8	69.7	66.0	60.5	65.1	72.6	66.6	62.3
	DR3	73.8	71.3	74.8	74.8	81.0	73.2	76.2	71.6	75.1	73.2	81.5	75.6
	DR3	77.7	73.5	79.2	76.3	80.7	77.1	80.2	74.8	75.5	79.1	86.5	78.8
	NR1	47.7	49.8	48.4	41.0	46.3	52.3	44.8	38.7	45.0	53.2	46.6	42.1
	NR2	58.7	56.5	58.3	57.7	65.1	58.9	58.6	54.6	59.4	58.6	65.2	58.3
	NR3	70.6	66.7	72.6	68.3	76.4	71.0	71.1	66.6	68.4	68.3	77.6	70.0
3	NC2	55.6	47.6	54.0	56.1	48.4	55.3	56.0	49.6	56.0	55.3	48.5	55.0
	NC1	55.3	59.6	55.3	56.1	62.0	56.5	55.0	59.8	56.4	55.6	59.2	55.3
	NC1	53.8	59.7	53.8	54.2	60.5	55.1	54.7	58.6	54.2	53.6	59.2	53.5
	NC2	53.6	45.5	52.5	53.8	45.8	52.7	53.7	46.2	53.3	53.5	46.1	53.4
4	NS3	97.4	96.8	96.8	94.2	57.6	92.0	95.8	96.3	96.8	93.1	59.2	90.9
	NS1	112	112	110	115	114	112	113	118	114	110	114	114
	NS2	76.4	91.7	75.4	77.4	91.4	75.4	75.3	90.7	76.8	75.3	92.4	75.4
	NS3	116	68.6	121	127	126	126	126	77.5	121	128	131	132
5	D1				57.8	63.2	64.7						
	D2	65.1	62.0	61.9									
	D3	64.9	57.9	52.1									
	D4				67.1	60.0	62.3						
6	DR1	54.0	53.8	53.4	46.2	49.6	56.2	50.4	45.4	48.9	56.8	50.6	46.7
	DR3	67.8	63.9	68.0	62.6	73.9	68.2	68.2	61.7	65.6	67.8	75.2	64.7
	DR3a	67.7	61.4	65.6	69.8	72.4	69.1	74.2	74.2	74.4	67.8	74.6	71.8
7	NS2	49.5	59.3	48.1	46.3	58.1	48.5	46.9	57.9	46.7	47.1	57.1	46.4
	NS1	78.5	79.3	78.2	77.0	79.1	78.7	76.4	79.0	78.7	76.6	80.4	78.0

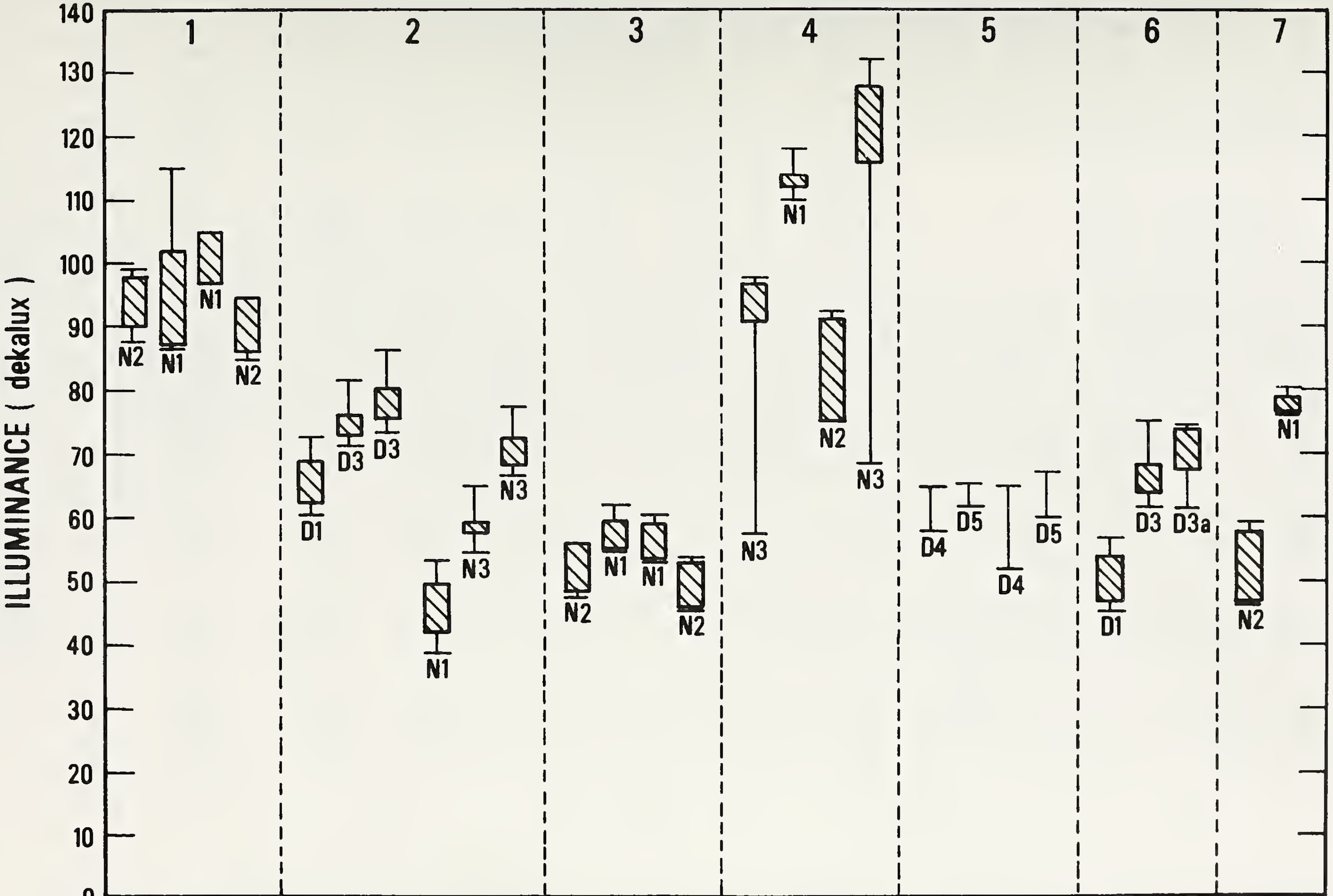

Figure 58. Illuminance at the task surface with contrast rendering instrumentation in place at the Norris Cotton Federal Office Building

Table 18. Contrast rendition factors obtained with photometric techniques at the Norris Cotton Federal Office Building

Floor	Location	North R	North O	North L	East R	East O	East L	South R	South O	South L	West R	West O	West L
1	NC2	.929	.816	.913	.954	.815	.907	.992	.882	.986	.975	.894	.976
	NC1	.951	.970	.859	.919	.948	.892	.908	.957	.867	.881	.959	.884
	NC1	.897	.982	.961	.946	.988	.925	.946	.952	.925	.940	.971	.997
	NC2	.986	.886	1.012	1.008	.929	.994	.980	.918	1.026	.998	.917	.965
2	DR1	1.010	.987	1.052	1.044	1.033	1.048	1.002	1.037	1.038	1.021	1.045	1.031
	DR3	.981	.890	.954	.955	1.029	.972	1.000	.879	.992	.954	1.015	.920
	DR3	.959	.921	1.053	.970	1.047	.984	.962	.915	.946	.969	.996	.961
	NR1	.970	.878	.924	1.009	1.007	.959	.954	1.066	.986	.906	.946	.923
	NR3	.889	.890	.821	.865	.974	1.010	.875	.837	.887	.891	.858	.845
	NR3	.921	.827	.917	.877	1.034	.889	.912	.816	.909	.886	.981	.868
3	NC2	1.043	.979	1.051	1.088	.967	1.051	1.027	.987	1.055	1.119	.965	1.033
	NC1	.934	.940	.930	1.019	.935	.940	.918	1.076	.954	.899	.967	.957
	NC1	.939	.911	.922	.939	.948	.943	.947	.968	.919	.969	.911	.928
	NC2	1.011	.976	1.084	1.076	.919	1.070	1.043	.944	1.018	.999	.955	.968
4	NS3	.984	1.004	.968	.999	.641	.914	.937	.983	.984	.991	.641	1.057
	NS1	.901	.875	.866	.874	.845	.880	.916	.852	.885	.959	.867	.937
	NS2	1.004	1.066	1.013	.988	1.059	.983	.993	1.130	.943	.985	1.038	.962
	NS3	1.018	.659	.990	.906	1.002	1.112	.995	.510	1.057	.982	.987	.977
5	D1				.941	.924	.872						
	D2	.899	.976	.645									
	D3	.924	.957	1.023									
	D4				.762	.904	.973						
6	DR1	1.007	.939	1.017	1.045	.995	.995	1.109	1.146	.977	1.021	.961	1.000
	DR3	.935	.856	.952	.921	1.069	.934	.959	.850	.923	.899	1.050	.937
	DR3a	.975	1.010	1.027	.871	1.012	1.009	1.069	.886	.972	1.069	.999	.946
7	NS2	.996	1.106	.944	1.020	1.036	.970	1.016	1.046	.980	.999	1.042	1.022
	NS1	.894	.839	.858	.914	.881	.867	.896	.859	.889	.892	.974	.862

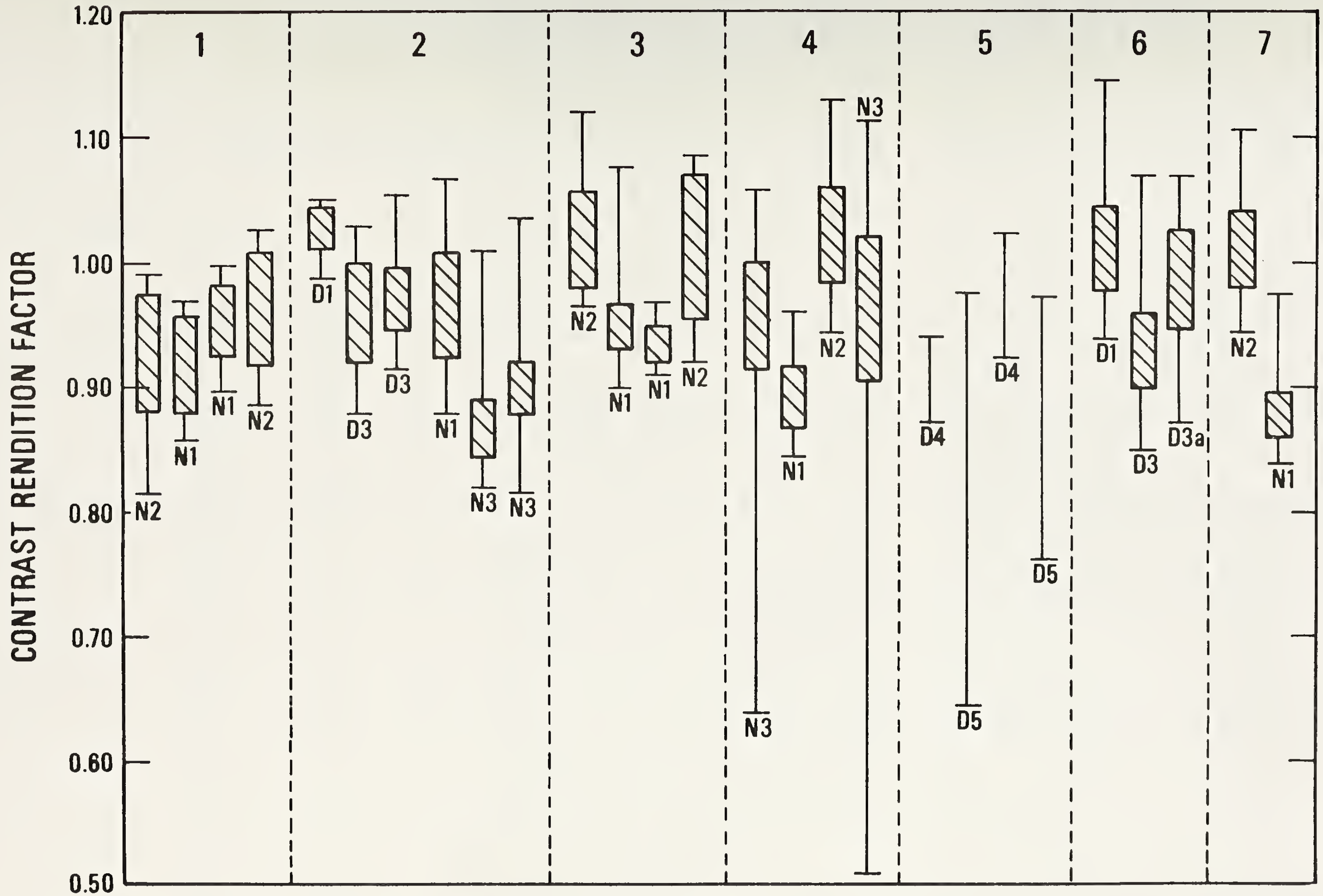

Figure 29. Contrast rendition factors obtained by a photometric technique at the Norris Cotton Federal Office Building

ahead, the CRF was 0.510. In other words, when facing left the task contrast was better than that under hemispherical lighting, but when sitting in the same position and facing straight ahead, the task contrast was considerably lower than under hemispherical lighting. There was no obvious difference in CRF values between floors. CRF's on floor 3 were slightly higher and on floor 5 slightly lower than the average, but the differences were not marked.

The effective illuminance per unit power input density or luminous efficacy values are given in table 19 and figure 60. The results indicate that some systems were definitely more effective that others. As can be seen, the visual performance and efficiency of the fourth floor system was high. However, other factors resulted in this system being unsatisfactory to a large number of workers. This will be discussed in Chapter 5. Excluding the fourth floor system, the system on the first floor had higher luminous efficacy values than the systems on the other floors.

Figure 61 shows measurement results to indicate the effect of daylighting. Measurements were made on the second floor during a sunny day (2D) and also at the same locations at night (2N). As can be seen, the illuminance values were consistently higher during the day. Measurements were made on the sixth floor only during the day; however, a comparison of illuminance values between 2N and 6D indicate small but consistently higher illuminances during the day. The effect of the larger glazed area on the second floor can be seen by comparing results 2D and 6D. Both measurements were made during the day and the results show a larger difference than between results 2N and 6D. For location 1, the contribution of daylighting was sufficient to bring the illuminance level from below the design level, 54 dekalux, to above it. The CRF values that were obtained on the second floor under daylight conditions (2D) were also generally higher than during the night (2N). Obviously, if illuminance and CRF values were higher during the day, then the product of these two, effective lumens per watt, was also higher as shown at the bottom of the figure.

Table 19. Effective lumens per watt obtained with photometric techniques at the Norris Cotton Federal Office Building

Floor	Location	North R	North O	North L	East R	East O	East L	South R	South O	South L	West R	West O	West L
1	NC2	46.6	37.1	45.5	47.0	37.1	45.0	47.8	39.1	48.5	47.7	39.6	47.5
	NC1	42.4	46.7	38.5	47.4	55.1	46.1	40.0	54.1	44.8	38.8	45.3	38.7
	NC1	44.4	52.2	47.0	46.3	52.6	45.7	46.3	50.2	45.2	46.1	51.7	49.3
	NC2	46.6	38.0	48.3	48.3	40.4	47.1	46.9	40.3	48.8	47.8	39.9	45.6
2	DR1	33.8	34.3	36.0	31.9	33.8	36.9	33.4	31.7	34.1	37.5	35.2	32.4
	DR3	36.6	32.1	36.0	36.1	42.1	35.9	38.5	31.8	37.6	35.3	41.8	35.2
	DR3	37.6	34.2	42.1	37.4	42.7	38.3	39.0	34.6	36.1	38.7	43.5	38.2
	NR1	23.4	22.1	22.6	20.9	23.5	25.3	21.6	20.9	22.4	24.3	22.3	19.6
	NR3	26.4	25.4	24.2	25.2	32.0	30.0	25.9	23.1	26.6	26.4	28.3	24.9
	NR3	32.8	27.9	33.6	30.3	39.9	31.9	32.8	27.5	31.4	30.6	38.4	30.7
3	NC2	29.3	23.5	28.7	30.8	23.6	29.4	29.0	24.7	29.8	31.3	23.7	28.7
	NC1	26.1	28.3	26.0	28.9	29.3	26.8	25.5	32.5	27.2	25.3	28.9	26.7
	NC1	25.5	27.5	25.1	25.7	29.0	26.2	26.1	28.7	25.2	26.2	27.2	25.1
	NC2	27.4	22.4	28.7	29.2	21.3	28.5	28.3	22.0	27.4	27.0	22.2	26.1
4	NS3	52.4	53.2	51.2	51.4	20.2	46.0	49.1	51.8	52.1	50.4	20.7	52.5
	NS1	55.1	53.5	52.0	55.0	52.7	53.8	56.6	55.1	55.2	57.5	54.1	58.4
	NS2	41.9	53.4	41.8	41.8	52.9	40.5	40.9	56.0	39.6	40.6	52.4	39.7
	NS3	64.7	24.7	65.2	62.9	69.0	76.5	68.5	21.6	69.6	68.7	70.8	70.7
5	D1				20.8	22.3	21.5						
	D2	22.4	23.2	15.3									
	D3	23.0	21.2	20.4									
	D4				19.6	20.7	23.2						
6	DR1	27.5	25.5	27.4	24.4	24.9	28.2	28.2	26.3	24.1	29.3	24.5	23.6
	DR3	32.0	27.6	32.7	29.1	39.9	32.2	33.0	26.5	30.6	30.8	39.9	30.6
	DR3a	33.3	31.3	34.0	30.7	37.0	35.2	40.1	33.2	36.5	36.6	37.6	34.3
7	NS2	24.9	33.1	22.9	23.8	30.4	23.8	24.1	30.6	23.1	23.8	30.1	23.9
	NS1	35.5	33.6	33.9	35.6	35.2	34.4	34.6	34.3	35.3	34.5	39.5	34.0

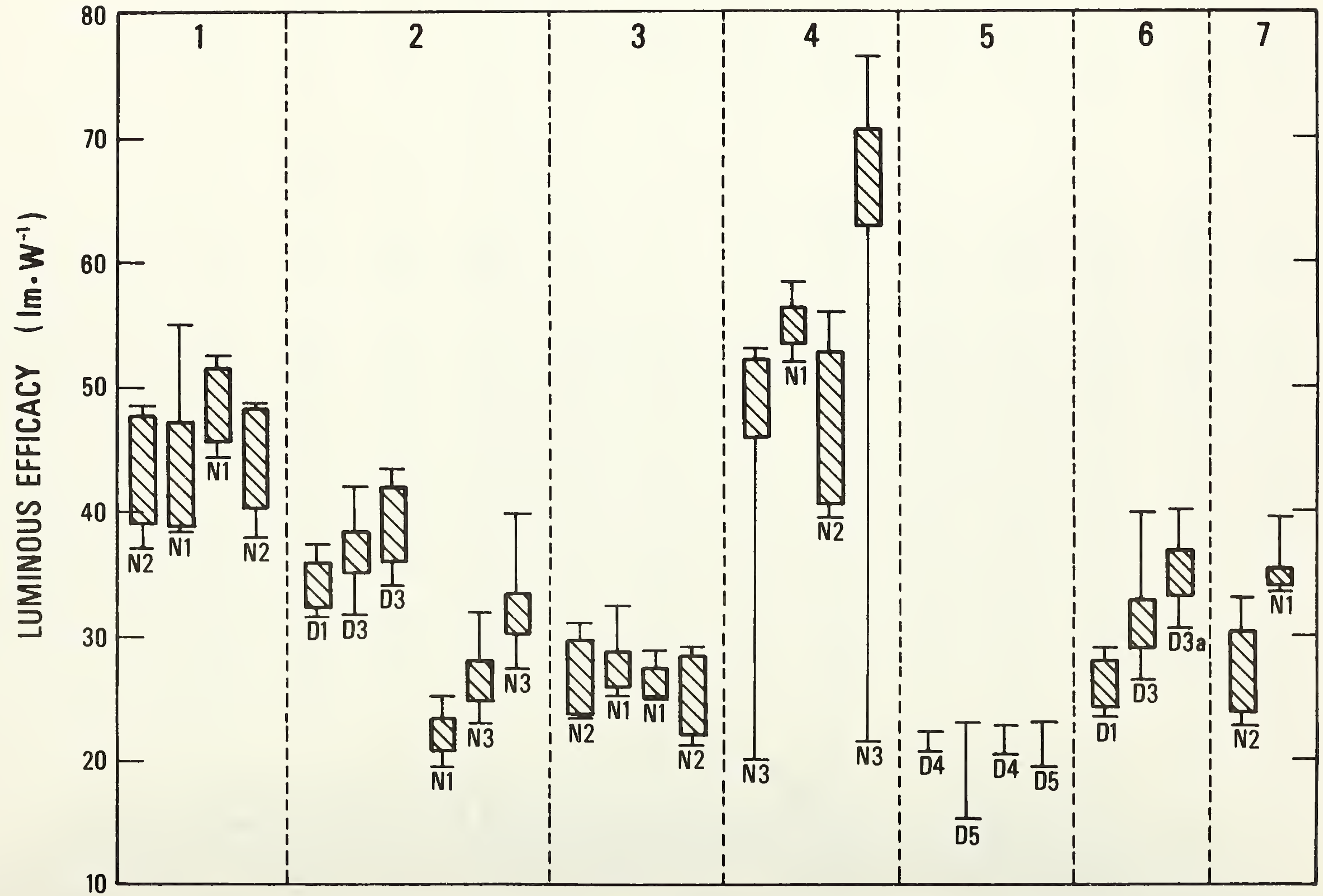

Figure 60. Luminous efficacy values obtained by a photometric technique at the Norris Cotton Federal Office Building

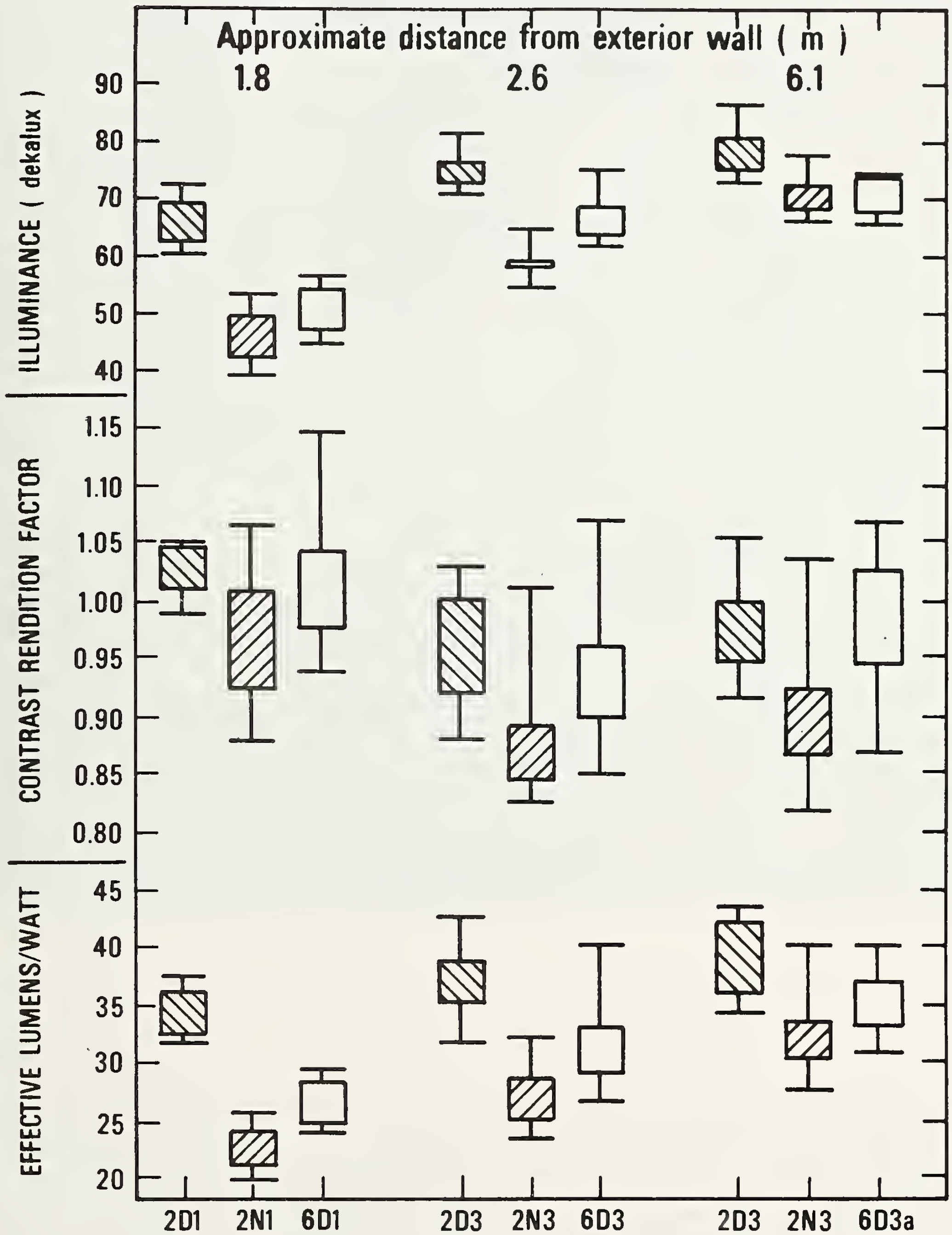

Figure 61. The effect of daylight on luminance, contrast rendition factor and luminous efficacy in the Norris Cotton Federal Office Building

Facing page:

View of open plan office on second floor of Norris Cotton Building showing the different window style on this floor.

5. OCCUPANT RESPONSE

Occupant response to the Norris Cotton Building was assessed in two ways. First, observations were made and personal interviews conducted in various government agencies prior to their relocation to the Norris Cotton Building. Second, two questionnaires -- one six months after occupancy, the other eight months later -- were distributed to all occupants of the building. This chapter will summarize the results of that work. Reference [23] includes an in-depth analysis of the occupant response study including its relationship to similar studies conducted in other buildings.

5.1 INTERIOR SPACE OCCUPANCY AND DESIGN

Most of the energy conserving features of the building that would be expected to affect occupant response have been described in other chapters of this report. These include the lighting systems, windows, and heating, ventilating, and air conditioning systems. An additional feature that will be described here is the interior space occupancy and design.

The building is occupied by various Federal agencies with a total of approximately 400 employees. The first floor is occupied by the Social Security Administration with approximately 25 employees; the second and third floors by the Veterans Administration (VA) with a total of about 90 employees; the fourth floor by the Armed Forces Examining Station (AFES) with about 40 employees; the fifth floor by the Department of Housing and Urban Development (HUD) with about 70 employees; the sixth floor by the Internal Revenue Service (IRS) with about 60 employees; and finally the seventh floor has two senators' offices, a congressional representative's office, and several agencies with a small number of employees.

Most areas in the building consist of open-plan offices with a minimum number of ceiling-high partitions. An exception is the fourth floor, occupied by AFES, which has been subdivided into medical examination rooms, laboratory space, testing rooms, private offices, and conference rooms. The seventh floor also has been subdivided since several groups are located there.

5.2 RESEARCH APPROACH -- INTERVIEWS AND QUESTIONNAIRES

Interviews were conducted in August 1976 in three agencies (IRS, VA, and AFES) prior to their relocation to the Norris Cotton Building. The interviews covered employee reaction to their then current environment, impressions about the Norris Cotton Building, and attitudes toward the upcoming move (see Reference [23] for a discussion of the results of these interviews). The insights gained in this phase served as a reference for the interpretation of the responses to the Norris Cotton Building.

In March 1977, a questionnaire was distributed to every employee in the Norris Cotton Building. By March, the employees had been in the building 6 months and had experienced a winter in their new offices. Of 390 questionnaires distributed, 292 completed questionnaires were returned, a return rate of 75 percent.

The questionnaire had 47 questions and required between 10 and 20 minutes to complete. It began with questions concerning the occupants' general impressions of the building. For example: "Is there anything you particularly like about the Norris Cotton Federal Office Building?" "Would you like to change your present office in any way? If yes, how?" These early questions tended to be open-ended and general in order to elicit opinions from the occupants without drawing attention to specific environmental attributes. Questions were then asked about more specific topics such as the lighting;

noise, particularly as it related to the open-plan offices; the thermal environment; and the windows, especially their size and the view from them. The questionnaire concluded with information such as floor number, sex, age category, and general job category.

After the employees has occupied the building for a little over a year and had experienced both winter and summer operating conditions, the questionnaire was readministered. The second questionnaire was distributed to the employees in mid-November 1977. This questionnaire was essentially the same as the first. A few questions were eliminated, for example, those asking the employees to compare the Norris Cotton Building with their previous office, and some questions were consolidated. As a result of response to the open-ended questions on the first questionnaire, a question was added about satisfaction with parking, elevators, eating facilities, and exterior appearance. Sixty percent (230) of questionnaires were returned.

5.3 QUESTIONNAIRE RESULTS

General Response to the Norris Cotton Building: Table 20 presents a summary of the major employee "likes" in the building. As table 20 shows, the results of the two questionnaires were essentially the same. Approximately two-thirds of the occupants named at least one aspect of the building that they liked. Location ranked first, being cited as "convenient," "downtown," and "central." Appearance and related aspects such as "newness" and "cleanness" were other positive attributes.

The major "dislikes" are summarized in table 21. On the first questionnaire, 83 percent named at least one aspect of the building they disliked and on the second questionnaire, 79 percent named at least one. The main problems identified by the building's occupants were:

- The temperature was considered to be too cold and too variable.
- The elevators were too slow and unreliable.
- The amount of parking space available was inadequate.
- The windows were too small, there were too few of them, and they could not be opened.
- The amount of ventilation was excessive during the heating season and inadequate during the cooling season.
- The building had no cafeteria.
- The front entrance doors were too difficult to open, particularly for the handicapped and elderly people who often visited the Social Security Administration offices in the building.
- The lighting on the fourth floor distorted colors, caused annoying glare, and provided illumination levels which were perceived to be too low.

Most respondents said they would like to change one or more aspects of their offices. On both questionnaires, the most often mentioned desired changes were better temperature regulation, more privacy (especially on the second

Table 20. Summary of occupant "likes" in the Norris Cotton Federal Office Building

First questionnaire (N = 265)	Number	%	Second questionnaire (N = 213)	Number	%
Location	55	21	Location	60	28
Appearance	38	14	Appearance	29	14
Newness	24	9	Newness	16	8
Cleanness	18	7	Lighting	15	7
Atmosphere	17	6	Atmosphere	13	6
Design	11	4	Cleanness	12	6

Table 21. Summary of occupant "dislikes" in the Norris Cotton Federal Office Building

First questionnaire (N = 265)	Number	%	Second questionnaire (N = 213)	Number	%
Temperature	85	32	Temperature	105	49
Elevators	70	26	Elevators	39	18
Parking	48	18	Parking	37	17
Windows	47	18	Ventilation	31	14
Ventilation	45	17	Windows	26	12
Lack of cafeteria	35	13	Lighting	23	11
Heavy front doors	30	11	Lack of cafeteria	21	10
Lighting	29	11	Heavy front doors	16	7

and fifth floors), and greater window area. Other changes desired were better lighting (on the fourth floor), more space, and less noise. "Comfortable temperature" and "good light" were felt to be the two most important physical features that determine the quality of the office environment. All other features named, such as privacy and window area, were considered much less important.

Response to Specific Design Features: Response to six features -- lighting, noise, odor, ventilation, temperature, and windows -- was examined in detail. The results are described in this section.

On both questionnaires, lighting was the most satisfactory design feature in the building. In addition, there was a statistically significant increase in the number of persons who were satisfied* with the lighting on the second questionnaire (73 percent) as compared with the number satisfied on the first questionnaire given eight months earlier (62 percent). Follow-up questions on light levels, color rendition, and glare also yielded generally favorable opinions on both questionnaires, with no statistically significant shifts in response over the eight-month interval between the questionnaires. There was, however, an obvious lack of satisfaction with the high pressure sodium lighting system as it was installed on the fourth floor. Despite the fact that the illumination levels on the fourth floor were among the highest in the building, most persons there felt they had "too little light" to work by. By contrast, occupants of other floors where the illumination levels were generally much lower perceived the amount of light as "about right." Many people also felt that the high pressure sodium system distorted colors and caused annoying glare. There were some unusually low contrast rendition factors measured on the fourth floor, which could be expected to produce complaints of poor task visibility if the placement of work stations was not carefully considered. More fourth floor occupants complained of headaches and eyestrain than did occupants of other floors.

Response to the first and second floor lighting systems was consistently quite positive. On both questionnaries over 80 percent of the respondents on these two floors were satisfied with the lighting. Both floors have uniformly spaced fluorescent lighting, with added daylight on the second floor.

The fifth floor has task lighting built into each work station, thereby concentrating light in those areas where it is needed. Despite the fact that this system is quite different from those installed on the other

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* A five-point rating scale was used to assess satisfaction: very satisfied, somewhat satisfied, indifferent, somewhat dissatisfied, and very dissatisfied. "Percent satisfied" is the percent of respondents who were either "very satisfied" or "somewhat satisfied" with the particular design feature.

floors, user satisfaction with the lighting was neither unusually high nor low compared with the other systems in the building.

Two other comparisons between systems were made. The second and the sixth floors have identical lighting systems, with the exception that on the second floor horizontal windows near the ceiling provide more daylight. Statistical analyses revealed that on both questionnaires the second floor system was significantly more satisfactory (about 90 percent satisfied) than the sixth floor system (about 60 percent satisfied).

The first and third floors have identical luminaires but different lenses (originally prismatic on the first floor, polarized on the third). In June 1977, the lenses were interchanged in order to determine whether the polarized lenses had been responsible for the lower level of satisfaction initially observed on the third floor. On the second questionnaire, administered in November 1977, satisfaction increased substantially on both the first and third floors. Thus no conclusions can be made about the relative acceptability of the prismatic and polarized lenses based on these data.

With respect to noise, 50 percent of the respondents on the first questionnaire were satisfied with the noise level in their offices, and 42 percent were dissatisfied. On the second questionnaire, 53 percent were satisfied and 35 percent were dissatisfied. On both questionnaires more than 60 percent said their offices were never too noisy to work in, although 39 percent thought there was more noise in their present office than in others they had worked in, while only 26 percent thought there was less. Voices were the most "noticeable" type of noise and the most "bothersome." Telephones and office machines ranked second and third.

A comparison of the noise climate in the open-plan and partitioned offices revealed statistically significant differences in user response in terms of both the level of noise and its distractiveness. On the first questionnaire, employees in open-plan offices were more dissatisfied with the noise level and had experienced more difficulty in working because of noise. Although there was not a statistically significant difference in satisfaction with the noise level on the second questionnaire, the difference in the extent of work disruption due to noise persisted.

In contrast to most of the floors, the sixth floor response to noise was very negative. On both questionnaires, less than 20 percent of the sixth floor occupants were satisfied with the noise level. Nearly 90 percent said their current office was noisier than the last one they had; no one found it quieter. Employees stated that the source of the noise problem was "white noise" or "ventilation system noise."

On two floors there was a statistically significant change in satisfaction with noise level between the first and second questionnaires. On the fifth floor, it increased from 29 percent to 53 percent; on the second floor, it decreased from 64 percent to 45 percent. The reasons for these shifts are not clear, but may be related to the fact that white noise generators were initially installed on both of these floors, as on the sixth floor, but were turned off on all but the east side of the second floor because of complaints by the occupants.

The response to odor was characterized by both satisfaction and indifference. While slightly more than half of the employees were "very" or "somewhat" satisfied with the odor in their offices, about one-third were "indifferent." Only 10 percent on the first questionnaire were dissatisfied, and 15 percent on the second. On the second questionnaire, there was an increase in the number of persons who "often" or "sometimes" noticed unpleasant odors in their offices; however, odor remained a relatively minor problem.

On both questionnaires, there was a statistically significant difference between floors 1 through 3, outfitted with heat pump HVAC systems, and floors 4 through 7, serviced by central equipment systems, in terms of satisfaction with odor. In both instances, respondents on floors 1 through 3 reported relatively more "very satisfied" and "somewhat satisfied" responses and fewer "indifferent" responses. Satisfaction was particularly low on the sixth and seventh floors. These findings are explainable in light of the physical measurements of air leakage in the building made in February 1977, which showed that the rate at which air (and hence odor) was expelled from the building and replaced by fresh air from the outside was much higher on floors 1 through 3 than on floors 4 through 7.

On the first questionnaire, response to ventilation was mixed, with nearly equal amounts of positive and negative sentiment (41 percent satisfied, 43 percent dissatisfied). Following the summer months, however, there was a general decline in satisfaction (34 percent satisfied, 53 percent dissatisfied), and an increase in the number of persons who "often" felt "uncomfortably stuffy" from 22 percent to 32 percent. The decrease in satisfaction on the second questionnaire was found in varying degrees on all floors. Some individuals mentioned that there was poor air circulation in the building during the summer. Many respondents were also bothered by cold drafts from the ventilation system, particularly during the winter months on the second and third floors.

A statistical comparison of the response on floors 1 through 3 with the response on floors 4 through 7 revealed no difference in satisfaction with ventilation on either questionnaire. On the second questionnaire, however, after summer conditions had been experienced, feelings of stuffiness were significantly more common on floors 4 through 7 than on floors 1 through 3. These data, like the odor data, are in agreement with the physical data on air leakage.

Occupant response to temperature in the building was extremely negative on both questionnaires and on all floors. On the first questionnaire, 75 percent were dissatisfied with the temperature of their offices; on the second questionnaire, 83 percent. The main reason for this widespread dissatisfaction appears to be that temperatures were felt to be too cold. This particular complaint was almost twice as common as any other concerning the temperature. Over 80 percent on both questionnaires reported that they were "often" or "sometimes" uncomfortably cold. (At the time of the first survey in March 1977, Federal guidelines were in effect which specified that thermostat settings not exceed 20°C (68°F).) Persons on floors 1 through 3 were more often bothered by cold temperatures than persons on floors 4 through 7. This was especially a problem for occupants on the second and third floors. Overheating was also a problem, particularly during the summer on the fourth through the seventh floors. Some persons were bothered by fluctuations in temperature during the course of the day, while others noted variations depending on the location within an office. The latter complaint was most common on the first three floors, where cold drafts near windows were a problem. These results are consistent with the results of the thermographic measurements of the building, which showed more cold surfaces on the first three floors than on the other floors, particularly on the east and west exterior walls.

The windows were also a very negatively perceived building feature. Only 12 percent of the respondents on the first questionnaire and 17 percent on the second were satisfied with the size of their windows. More than 80 percent thought the 0.4 m x 1.6 m (1.2 ft x 5.3 ft) windows were too small and that they offered an insufficient view of the outside world. The windows were perceived as being "poorly proportioned," "narrow," and "irregular." Cold drafts near windows were "often" a problem for 30 percent of the respondents on the first questionnaire and 25 percent on the second. Very few people had experienced problems with glare, overheating, or outside noise from their windows.

From a design standpoint, a comparison of the response on the second floor with that on the others is of interest, in order to assess the effect of its larger window area (12 percent of the east, west, and south exterior walls, as compared with six percent on the other floors) on user satisfaction. Satisfaction with the size of the windows on the second floor was greater than the average for the other six floors but was exceeded by the first floor on the first questionnaire and the fourth floor on the second one. Floor-by-floor analysis of related questions on both questionnaires showed that the second floor ranked highest by a slight margin on providing a good view of the outside world and on having windows that are "about right" in size. Despite the slightly higher level of satisfaction with the windows on the second floor, however, the majority of persons on that floor still considered the windows to be inadequate.

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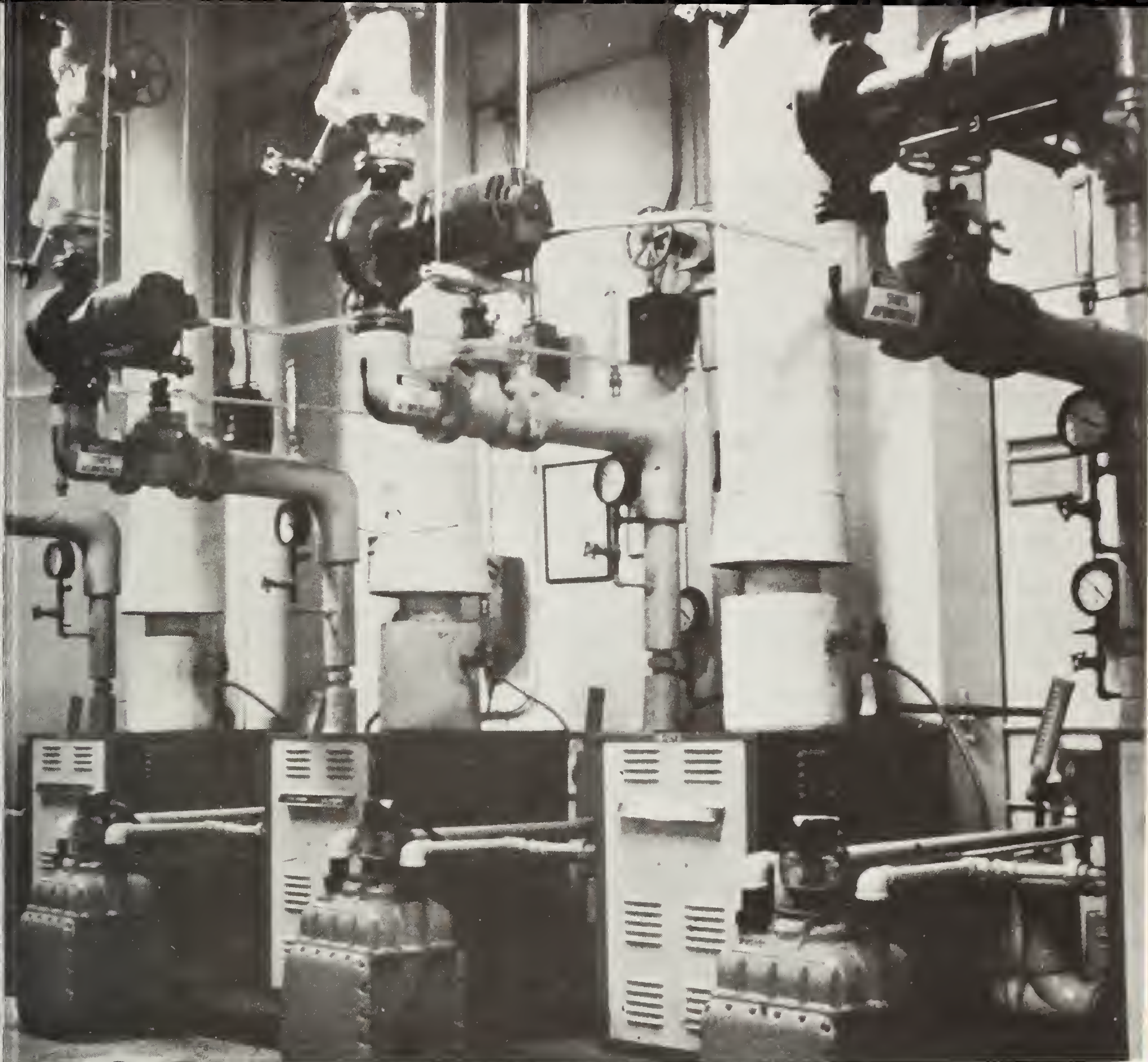
Four natural gas modular boilers in the mechanical penthouse provide heating at the Norris Cotton Building



6. COST ANALYSIS

The purpose of this chapter is to present an example of life-cycle cost analysis of the investments made in the energy conserving techniques used at the Norris Cotton Federal Office Building in Manchester, New Hampshire. This analysis addresses the question of whether additional construction costs incurred in order to reduce the energy consumption of the building are adequately offset by the value of the resulting annual energy savings. An example is also given of analysis involving two buildings which offer different quality of construction.

In this chapter, the construction costs of the Norris Cotton Federal Office Building (NCFOB), an Equivalent Conventional Building (ECB) and a Design Alternative Building (DAB) are combined with the corresponsing annual energy consumption in a present value format for a maximum lifespan of 30 years. The ECB design represented what might have been built by the government if energy conservation had not been stressed and its size and shape, quality of material and construction, and occupancy requirements were approximately equal to those of the NCFOB. The DAB selected was intended to represent an ordinary commercial speculative office building of similar size to the NCFOB but not constructed to Government specifications or standards required for a building such as a corporate headquarters. The life-cycle costs resulting from initial construction and annual energy use are calculated for the three buildings and serve as the basis for the economic evaluation.

The actual energy consumption data for the year spanning from September 1978 to August 1979 are used in conjunction with the actual construction cost of the NCFOB to compute the life-cycle cost of the building as a whole. The building construction costs for the ECB are estimated in accordance with the GSA Design Handbook of 1969, and energy consumption is calculated by simulation [2, 25]. The building represented by the DAB is the same as the "design alternative" simulation case described in section 3.5.

Since no meaningful data on operation and maintenance costs (except energy cost) are available to be included in the economic analysis at this time, this report includes only the building construction costs and yearly energy costs of the NCFOB, ECB and DAB in the economic evaluation. A complete evaluation would take into account equipment repair and replacement costs and manpower requirements for building operation. In addition, the effect of local and Federal income taxes on the building owner would have to be included.

6.1 BUILDING CONSTRUCTION COSTS

The construction costs developed for the NCFOB, ECB, and DAB do not include the following cost items: Site acquisition cost; architecture and engineering design fees; furniture and furnishing cost; and relocation cost. These cost items are excluded from the economic comparison because they are considered to be equal for the three buildings and therefore will not affect the outcome of the cost comparison of these buildings.

The NCFOB construction cost represents the original contract price given in the spring of 1974 to be fully paid for in the fall of 1976. All contract change orders made during the construction period were adjusted so that the resulting figures represent the dollar values as of the start of construction. The sum of the original contract price and the adjusted change order prices is used here as the total NCFOB construction cost incurred at the end of 1976.

The ECB construction cost was estimated and component costs given in a previous report [25]. The DAB construction cost was obtained by modifying the estimates of electrical, lighting, and air conditioning costs for the construction of the ECB. The construction costs assumed for all three buildings are shown in table 22.

6.2 ANNUAL ENERGY CONSUMPTION

Annual energy consumption data for the NCFOB, ECB, and DAB are summarized in tables 23 and 24. The NCFOB and DAB simulation estimates were obtained by a system computer simulation as described in section 3.5. The energy consumption estimates for the ECB were obtained by a load prediction computer program [2, 25].

6.3 LIFE-CYCLE COST MODEL

There are several methods to express the combined cost of an initial investment and associated recurring costs for energy consumption, operation, and maintenance associated with a building. One method is to transform the initial investment cost into an equivalent yearly uniform capital recovery payment over the life and then combine this yearly payment with the corresponding recurring costs associated with operation, maintenance and energy consumption

Table 22. Building construction costs in 1976 dollars

	BUILDINGS		
Building	NCFOB	ECB	DAB
Architectural/Structural	$6,147,122	$5,706,361	$5,706,361
Mechanical	1,195,731	944,028	907,028
Electrical	576,181	698,698	642,698
Subtotal	7,919,034	7,349,087	7,256,087
GC Overhead/Profit	601,847	558,531	551,463
TOTAL	8,520,881	7,907,620	7,807,550
Less Extras for non-building items[a]	-285,765	None	None
Comparable cost	$8,235,116	$7,907,620	$7,807,550

[a] This figure represents the "Demonstration" items as explained in Appendix A of reference [25].

Table 23. Annual energy consumption in 10^6 Btu

Energy type	NCFOB 1979* Actual	NCFOB 1962 Simulated	ECB 1962 Simulated	DAB 1962 Simulated
Electricity	4,810	4,986	7,277	3,846
Fuel oil	292	242	0	0
Natural gas	1,578	2,022	4,983	3,115
TOTAL	6,680	7,250	12,250	6,961

Table 24. Cost of annual energy consumption in 1979 dollars

Energy type	NCFOB 1979 Actual	NCFOB 1962 Simulated	ECB 1962 Simulated	DAB 1962 Simulated
Electricity	77,973	80,973	117,955	62,323
Fuel oil	853	707	0	0
Natural gas	7,417	9,503	23,420	14,641
TOTAL	86,243	91,003	141,375	76,964

* September 1978 - August 1979

over the life of the building. Another method is to transform both the initial building investment cost and the recurring costs to a single capital recovery amount occurring at the end of the lifespan. The third method is to bring the stream of recurring costs back to the same period in which the initial building investment was made and then combine these transformed recurring costs with the initial investment to arrive at the present value cost of owning and operating a building throughout its life. This present value cost method will be used for the economic evaluation of both buildings. Equation (5) is the general expression used to obtain present value costs over a building lifetime.

$$PVC = C + \sum_{i=1}^{L} (1+D)^{-i}(E_i+M_i) - (1+D)^{-L} \cdot S \,, \tag{5}$$

where

PVC = Present value cost
C = Construction cost
D = Discount rate
E_i = Annual energy cost in period i
M_i = Annual operation and maintenance cost (excluding energy cost)
L = Lifespan of the building in years
S = Salvage value at the end of lifespan.

With the exception of energy cost, no meaningful physical and cost data for building operation and maintenance are available. Until operation and maintenance data become available, it is assumed that these costs would be similar for the three buildings. The most significant difference between the non-energy costs for these buildings would be for equipment service and replacement costs, especially because the DAB uses mechanical equipment with a shorter expected lifetime. Since equipment service lives are not available this time, the replacement costs due to aging for the DAB are not included in this study. Also, for all practical purposes the salvage values for the three buildings are considered equal and negligible, given the relatively long expected life of a building.

Therefore, equation (5) can be simplified to

$$PVC = C + \sum_{i=1}^{L} (1+D)^{-i} \cdot E_i \tag{6}$$

Equation (6) will be used for the calculation of present value costs of the NCFOB, ECB, and DAB. In equation (6), D is assumed to be 10 percent and E_i is obtained by multiplying the annual energy costs with the following corresponding escalating rates [26] shown in table 25.

Table 25

Annual percentage change of energy escalating rate

Year	Electricity	Natural gas	Distilate
1980-1985	2.51	-4.39	1.32
1986-1990	-1.28	3.42	3.39
1991-beyond	-0.45	1.95	2.46

The results of calculating present value costs for all years from 1976 through 2006 for the three buildings are presented in table 26. The present value costs and present value savings for the NCFOB over the other alternatives are summarized for three building lifespans in table 27.

Several noteworthy conclusions can be drawn from an examination of tables 26 and 27. Most importantly, the present value savings for the NCFOB over the ECB are $46,000 in 15 years and $141,000 in 30 years. These positive present value savings indicate that the additional investment in energy conservation when the NCFOB is built rather than a building such as the ECB is more than compensated by the value of the energy savings over the 30 year and 15 year lifespans assumed. In other words, the NCFOB is economically more attractive than the ECB for all lifespans over 12 years. In addition to the present value saving, it is possible to calculate the discounted payback period for the additional investment made on the energy conserving features of the NCFOB. The discounted payback period is defined as the number of years required for the additional investment in a building to be fully paid for with the present value savings produced by the energy conservation features, taking into account the time value of money. A discounted payback period of 11.8 years is illustrated in figure 62 for the energy conservation investment made in the NCFOB compared with the ECB. The present value savings of the NCFOB over the ECB for all given lifetimes of up to 30 years can also be determined by measuring the distance between the two curves shown on figure 62.

Based on the 1979 actual energy consumption for the NCFOB, the present value cost for the period ending in 1991, a 15 year lifespan, is $8,882,000 as compared to $8,916,000 when the simulation predicted energy consumption for the NCFOB with 1962 weather is used for same lifespan. The difference of $34,000 represents only a 0.4% decrease of the present value cost based on 1962 weather condition. Similarly, at the 30 year lifespan, the difference of $44,000 in present value cost represents only a 0.5% decrease based on the simulation using 1962 weather.

Table 26

Present value cost at year ending ($1000) for three buildings for the period ending in a given year

Ending year of period	NCFOB 1979 Actual	NCFOB 1962 Simulated	ECB 1962 Simulated	DAB 1962 Simulated
1976	8235	8235	7908	7808
1977	8290	8294	8004	7861
1978	8348	8355	8098	7912
1979	8413	8423	8204	7970
1980	8473	8487	8302	8023
1981	8528	8545	8392	8072
1982	8580	8599	8476	8117
1983	8628	8650	8552	8158
1984	8672	8696	8623	8197
1985	8712	8738	8688	8232
1986	8748	8776	8745	8263
1987	8781	8810	8798	8292
1988	8810	8841	8845	8317
1989	8836	8868	8888	8340
1990	8860	8894	8926	8362
1991	8882	8916	8962	8381
1992	8901	8937	8994	8398
1993	8919	8956	9023	8414
1994	8935	8973	9049	8428
1995	8950	8988	9073	8441
1996	8963	9002	9095	8453
1997	8975	9015	9115	8464
1998	8986	9027	9133	8474
1999	8996	9037	9149	8483
2000	9005	9047	9164	8491
2001	9013	9055	9177	8498
2002	9021	9063	9190	8505
2003	9027	9070	9201	8511
2004	9034	9077	9211	8517
2005	9039	9083	9220	8522
2006	9044	9088	9229	8526

Table 27

Present value costs and calculation of present value savings[a] ($1000)

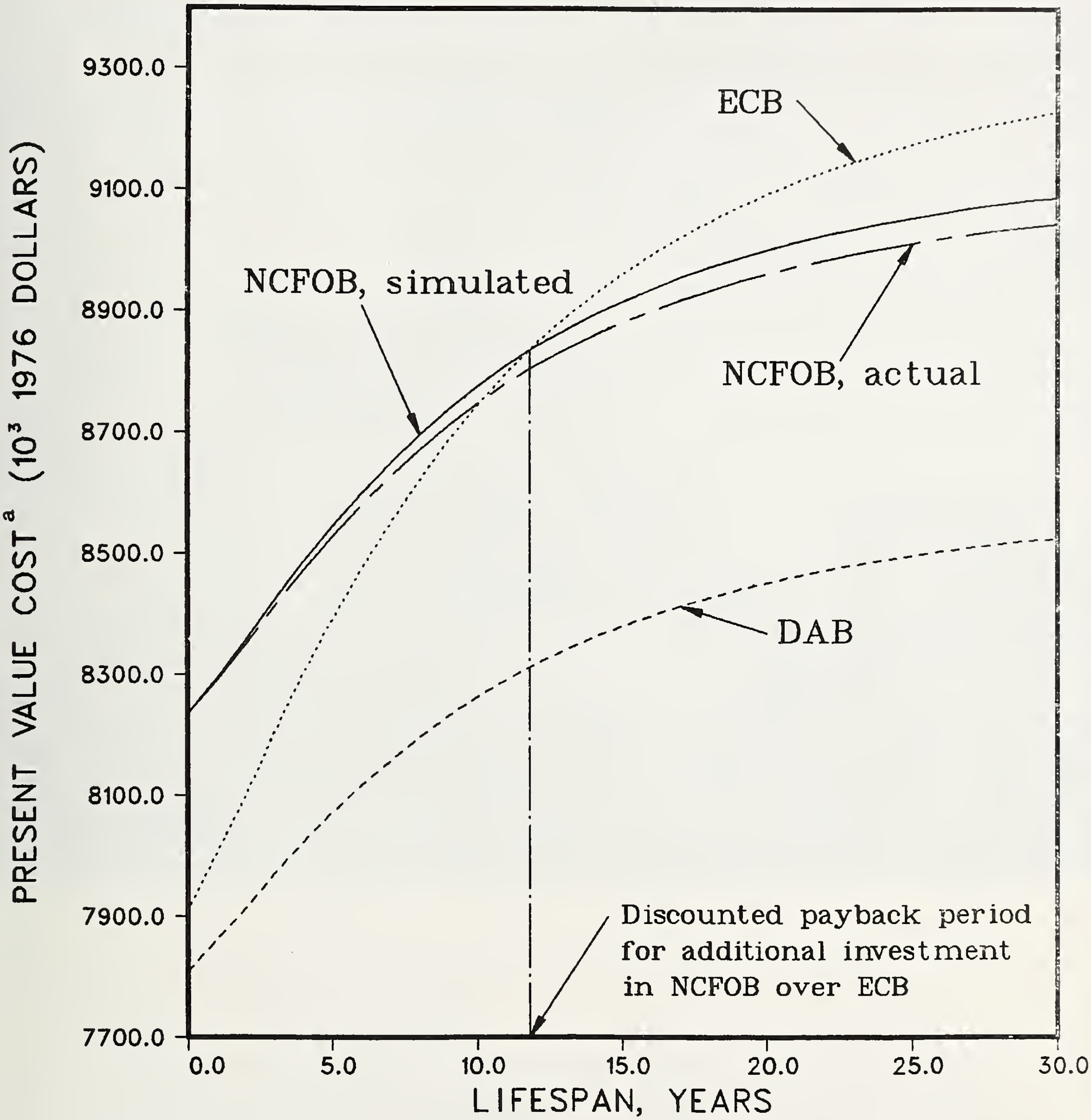
BUILDING	LIFESPAN					
	0 Years		15 Years		30 Years	
	Cost	Saving	Cost	Saving	Cost	Saving
NCFOB	8235		8,916		9,088	
ECB	7908	(327)	8,962	46	9,229	141
DAB	7808	(427)	8,381	(535)	8,526	(562)

a/ Present value savings of the NCFOB over the ECB and DAB. Savings in parenthesis indicate negative savings, or more costly expenditures.

As mentioned, the NCFOB and DAB are designed to different criteria and a comparison is difficult because the benefits from the two buildings are different. The DAB type is intended to have a low first cost. The present value cost of the DAB from table 27 is $427,000, at the end of 0 years (or completion of construction), which is less than the equivalent present value cost of the NCFOB. The DAB would probably be used for rental and sold after a short time period to maximize tax benefits. On the other hand, the NCFOB type is designed to provide a location to house government agencies for the life of the building and mechanical systems are designed to meet criteria for reliability and maintenance. Figure 62 shows that for all lifetimes of the NCFOB up to 30 years, the present value cost is lower for the DAB. The major factors not taken into account in the cost analysis are as follows:

a) Sixty-three percent of the air-conditioning requirement in the DAB is furnished by through-the-wall units. According to the ASHRAE Journal [27], the median service life of through-the-wall units is 10 years and the median service life of central units such as those used in the NCFOB and the ECB is 20 years. The replacement costs due to aging equipment have not been included in the calculations.

b) Operation and maintenance costs (including manpower requirements) are not included in the calculations and the DAB is apparently not designed to GSA's standards for operation and maintenance.



[a] Present value cost is assumed to include Building Construction Cost, Energy Cost as computed for 1962 consumption and DoE estimates for annual energy price increases.

Figure 62. Present value cost[a] vs lifespan for NCFOB, ECB & DAB

c) The NCFOB was built as an experimental building and contains redundancies in equipment which would not be found in a non-experimental building.

This example shows the danger involved in comparing buildings built to different criteria.

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A computerized monitoring and supervisory control system is based in an operations room at the Norris Cotton Building.

7. CONCLUSIONS AND RECOMMENDATIONS

Over the 3 years that the Norris Cotton Federal Office Building has been in operation, several experiments have been performed which have resulted in some valuable conclusions. In addition, three years of experience in operating the building have been accumulated and lessons have been learned when problems with the building have been corrected or circumvented by the building operator. A number of conclusions concerning design and operation of an energy-conserving building have resulted from the study of the building.

After 3 years of operation, the building, although operated differently than originally intended, now performs reasonably well and proves that:

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)).

The performance of the building and the benefits from the study of the building would have been improved if certain lessons had been learned before the conception of the project:

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 building for low energy use. In this building, a number of different energy conserving subsystems 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.

The addition of a solar system to the building allowed a number of lessons to be learned with regard to design and operation of a solar system on a commercial building:

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. Thermal storage capacity in solar systems should be carefully sized relative to load and solar collector capacity. The storage tanks in this building are far oversized and under-insulated and prevent temperatures in the tanks from reaching design levels.

6. The design strategy for solar energy use in this building was to increase the amount of energy in storage up to a usable temperature level before transferring any collected energy to the building heating and cooling systems. Excess storage capacity and storage standby losses have prevented effective use of the collected energy. A strategy to use the collected energy directly to meet a load and store it only if collected energy exceeds the load should be a much more effective strategy.

7. Four different flat-plate collector types are used on this building. They range from a double-glazed collector with a selective-surface on the absorber to a single-glazed collector with a flat-black surface. The use of such a range of collectors in one array both degrades the performance of the more efficient collectors and creates difficulties in flow balancing. Each type of collector has a different design flow rate.

8. The original solar system control scheme was found to be ineffective, because it relied on solar irradiance levels to actuate collectors without regard to ambient temperature or load.

9. Unless a solar system control scheme has been used previously in a similar application, an innovative mechanical system including solar should always include a control system whose logic can be altered by system operators. In this building, an inflexible control scheme produced undesirable sequences of equipment operation; as a result automatic control had to be abandoned and manual control used.

10. When variable speed pumps are employed in a solar installation, the speed of the pumps should not be a simple function of collector inlet and outlet temperatures. Under certain conditions, such control can result in collector stagnation and boiling of the heat transfer fluid under high irradiation conditions.

11. Changing the tilt angle of the large collector array on this building twice a year was found to be ineffective when the cost of the tilting mechanism and difficulty of tilting the arrays was taken into account. Changing the tilt of stationary south-facing collectors provides little advantage for space heating and domestic hot water heating applications.

12. Solar collector arrays designed for cooling in conjunction with absorption chillers should be able to supply heated fluid at the absorption unit rated input temperature during substantial portions of the cooling season, not just under peak conditions.

In addition to findings from the operation of a solar system, the application of energy-conservation and heat recovery concepts in this building has resulted in valuable experience which can be summarized in the following findings:

13. The use of chilled water storage to reduce peak cooling loads in this building has been found ineffective due to chiller safety interlocks cycling the chiller off before design storage temperatures are reached, heat gain through tanks and long piping runs, insufficient storage capacity to meet building peak loads, and inability to automatically remove the chilled water tank from the chilled water loop when it is no longer useful.

14. When a heat recovery chiller (energy recovery from the condenser) is designed into a mechanical system, there must be a heating load which can be met while the chiller is required to operate and the load must be satisfied by the fluid temperature level and flow rate from the chiller condenser. In this building, heating and cooling loads are simultaneous only for brief periods in the spring or fall. However, during those periods, the small heating loads can be met by the solar system.

15. The use of a natural gas engine-generator to drive an electric chiller and use of the engine waste heat to drive an absorption chiller is a possible method to extract more energy from natural gas than by conventional means. However, such a system must be very carefully designed and critical factors such as the maximum temperature level deliverable to the absorption chiller at maximum engine operating temperatures after heat exchanger losses have been considered, and the relative rates of engine heat recovery and absorption machine input energy under all conditions of loading must be considered.

16. The engine-generator, electric chiller, and absorption chiller set has been found to not function well as a secondary chilled water source when used in an intermittent fashion.

17. The temperature set point of the hot water heating system should have been automatically adjustable as a function of load (or outside air temperature) to allow solar heated water to be used most effectively.

18. Special care must be taken when using water-to-air-coil systems with water temperatures below 41°C (105°F). Unless air registers are properly designed with diffusers to limit air velocity in the space, space occupants will feel discomfort from the relatively cool air blowing into the room.

19. Even operating the ventilation system in this building in a complete recirculation mode (no outside air), CO_2 levels were found to be less than the levels implied by the ventilation rates recommended for office space in ASHRAE Standard 62-73 (0.0118-0.0071 m^3/sec•person or 15-25 cfm/person).

20. Flushing the building with outside air and cooling the building spaces below thermostat settings in the summer prior to switching the building into the occupied mode has been found to be effective in reducing start-up cooling load and lengthening the time before mechanical cooling is required. This strategy was not in the original design.

The study of the Norris Cotton Building involved performing simulations with a building simulation computer program. The following conclusions were drawn from the analysis of the simulation results:

21. Actual total energy consumption per year measured at the building for the calendar year 1979 was within 14 percent of the predicted value using the Ross Meriwether Energy System Analysis computer program for 1962 weather.

22. The simulation of the building in the "as-designed with solar" case with the computer program resulted in a prediction of total energy consumption per year which was within 2 percent of the original design goal of 625 MJ/m^2•year (55 kBtu/(ft^2•year)).

23. Actual energy consumption for lights and non-HVAC purposes at the building for the third year of operation was within 8 percent of the predicted value from the "as-operated" simulation case.

24. Actual energy consumption for fuel and fan energy at the building for the third year of operation was within 12 percent of the predicted value for the "as-operated" simulation case using 1962 weather data.

25. Actual energy consumption for operating energy at the building for the third year of operation was within 9 percent of the predicted value from the "as-operated" simulation case using 1962 weather data.

26. As a result of modeling the mechanical systems in the building, a maximum efficiency of approximately 64 percent was predicted for meeting the heating loads in the building when heating requirements approached 470 GJ/month (500 x 10^6 Btu/month). For cooling, an overall coefficient of performance for the building was predicted to approach 0.75 as cooling requirements approached 285 GJ/month (300 x 10^6 Btu/month) for the "as-operated" case. These values include the operating energy for the mechanical system as well as fuel consumption.

27. Based on a comparison of the performance predicted by the simulation of the two major mechanical systems, the heat pump system on floors 1-3 and the central system on floors 4-7, they were found to use approximately the same amount of energy to meet a given load for the range of heating and cooling loads occurring in the building. However, the heat pump system used more costly electric energy.

28. A "design alternative" was simulated which had approximately twice the lighting per unit area, five times more window area, one-third the insulation value in the roof and walls, and a much simpler mechanical system than the present building. The yearly heating energy requirement or heating load was predicted to be similar to that of the present building. The additional transmission losses in the "design alternative" were offset by increased solar gains and higher internal loads.

29. When the simulation results for the "design alternative" to the building were compared to the results for the other simulation cases, the predicted operating energy for the "design alternative" with its less complex and less efficient mechanical systems was approximately two percent of the total energy consumption of the building. This is in comparison to the 16-21 percent for the "actual design" case.

30. Selected modifications to the building as currently operated were predicted by simulation to reduce total energy consumption by six percent if implemented.

A comparative study of lighting in the building led to the conclusion that:

31. Based on physical measurements to determine lighting system efficacy, the fluorescent system on the first floor and the high pressure sodium system on floor 4 were found to be the most effective. The differences between the other systems were not significant. However, the task lighting system on floor 5 was found to be the least effective.

Surveys of the attitudes and feelings of the occupants of the building resulted in important conclusions about the response of the occupants to energy-conserving features of the building:

32. The most positive design feature of the building as determined by surveying the occupants with two detailed questionnaires was the lighting. However, the reaction to the high pressure sodium system on floor 4 was strongly negative. Illumination level alone was found not to be a good predictor of occupant response. There was some indication that color rendition, glare, and amount of daylight affect satisfaction.

33. Reaction to the thermal environment was extremely negative throughout the building. Ventilation levels in the building were considerably in excess of ASHRAE recommendations and may have exaggerated the effects of low temperatures during the winter months. Lower ventilation levels on the upper four floors were associated with more complaints of stuffiness, particularly during the summer.

34. Opinion on noise levels and disturbances was slightly more positive than negative overall, but about evenly divided in the open-plan offices. Response was very negative on the sixth floor possibly due to the use of white noise generators. Voices were the most disturbing source of noise.

35. Most occupants were dissatisfied with the small windows in the building. The windows were also perceived to be too narrow to provide a sufficient view. The increased window area on the second floor did not substantially improve opinion.

Finally, examples of life cycle cost analysis for this energy-conserving building design were performed. Based on the results:

36. The construction of a building such as the Norris Cotton Federal Office Building was determined to be feasible when such a building is constructed as an alternative to a Federal office building not incorporating energy conserving design features. With the assumptions made in this report, the discounted payback period was determined to be approximately 12 years for a thirty year building lifetime.

37. It is important to consider parameters other than annual energy cost and construction cost when comparing buildings built to different criteria. Maintenance costs, equipment replacement costs and benefits from differences in building quality should also be considered.

8. REFERENCES

1. Hill, J. E. and Kusuda T., "Manchester's New Federal Building: An Energy Conservation Project," ASHRAE Journal, August 1975.

2. Kusuda, T., Hill, J. E., Liu, S. T., Barnett, J. P., and Bean, J. W., "Pre-Design Analysis of Energy Conservation Options for a Multi-Story Demonstration Office Building," NBS Building Science Series 78, November 1975.

3. Kusuda, T., "Energy Instrumentation and Supervisory Control System in the GSA/Manchester Federal Office Building," Letter Report to GSA, April 1975.

4. ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating, and Air Conditioning Engineers, 345 East 47th Street, New York, NY 10017, 1977.

5. May, Jr., W. B., "Analysis of Data from the Energy Monitoring and Control System at the Norris Cotton Federal Office Building," NBSIR in preparation, June 1981.

6. Hill, J. E. and Richtmyer, T. E., "Thermography Measurements in the Norris Cotton Federal Office Building in Manchester, New Hampshire," Letter Report to DoE, August 1977.

7. Hunt, C. M., "Air Exchange and Ventilation System Measurements in the Norris Cotton Federal Office Building in Manchester, New Hampshire, Letter Report to DoE, May 1977.

8. Hunt, C. M., "Ventilation Measurements in the Norris Cotton Federal Office Building in Manchester, NH," ASHRAE Transaction, Vol. 85, Part I, 1979.

9. Hunt, C. M. and Richtmyer, T. E., "Remeasurement of Air Exchange Rates in the Norris Cotton Federal Office Building After Retrofitting to Reduce Leakage," Letter Report to DoE, April 1979.

10. Harrje, D. T., et al., "Automated Instrumentation for Air Infiltration Measurements in Buildings," Center for Environmental Studies, Princeton, New Jersey, Report No. 13, April 1975.

11. Hunt, C. M. and Treado, S. J., "A Prototype Semi-Automatic System for Measuring Air Infiltration in Buildings Using Sulfur Hexafluoride as a Tracer," NBS Technical Note 898, March 1976.

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

13. "Shelter Design and Analysis - Environmental Engineering for Shelters," TR 20, Vol. 3, Office of Civil Defense, May 1969.

14. ASHRAE Standard 93-77, "Methods of Testing to Determine the Thermal Performance of Solar Collectors," American Society for Heating, Refrigerating, and Air Conditioning Engineers, 345 East 47th Street, New York, NY 10017, 1978.

15. "Solar Collector Performance Tests," Desert Sunshine Exposure Tests, Inc. Report No. 78SA0524, August 1978.

16. "Solar Collector Test Report," Desert Sunshine Exposure Tests, Inc. Report No. 79S0130-31, February 1979.

17. May, W. B., "Options for Solar System Improvement at the Norris Cotton Federal Office Building in Manchester, New Hampshire, Letter Report to GSA, January 3, 1980.

18. Klein, S. A., "Calculation of Flat-Plate Collector Utilizability," Solar Energy, Vol. 21, pp. 393-402, 1978.

19. "DOE-2 Reference Manual," Los Alamos Scientific Laboratory, document No. LA-7689-M or Lawrence Berkeley Laboratory document No. LBL-8706, April 1979.

20. Hittle, D. C., "The Building Loads Analysis System Thermodynamics (BLAST) Program, Version 2.0: Users Manual, Volume I," U.S. Army Construction Engineering Research Laboratory, Champagne, IL, NTIS Report CERL-TR-E-153, June 1979.

21. May, W. B. and Spielvogel, L. G., "Analysis of Computer-Simulated Thermal Performance of the Norris Cotton Federal Office Building," NBSIR-80-2093, March 1980.

22. "Energy Conservation Design Guidelines for New Office Buildings," General Services Administration/Public Buildings Service, 2nd Edition, 324 pages, 1977.

23. Elder, J. and Tibbott, R. L., "User Acceptance of an Energy Efficient Office Building - A Study of the Norris Cotton Federal Office Building," NBS Building Science Series 130, January 1981.

24. Gagge, A. P. and Nevins, R. G., "Effect of Energy Conservation Guidelines on Comfort, Acceptability, and Health," Final Report, Contract No. CO-04-51891-00, Federal Energy Administration, March 1976.

25. Chen, P. T., "Economic Analysis of the Norris Cotton Federal Office Building," NBS Report NBSIR 78-1568, November 1978.

26. The National Archives of the United States, "Methodology and Procedures for Life Cycle Cost Analysis," Federal Register, Vol. 45, No. 16, January 23, 1980.

27. Akalin, M. T., "Equipment Life and Maintenance Cost Survey," ASHRAE Journal, October 1978.

9. BIBLIOGRAPHY

1. Issak, N. and Isaak, A., "Designing an Energy Efficient Building," published by the General Services Administration/Public Buildings Service, September 1975.

2. Kusuda, T., Liu, S. T., Bean, J. W., and Barnett, J. P., "Analysis of the Solar Energy System for the GSA Demonstration Office Building in Manchester, New Hampshire," NBS Report NBSIR 76-1056, March 1976.

3. Murdoch, J. P., "A Simplified Procedure for Calculating the Direct Components of Contract Rendition Factor and Equivalent Illumination," NBS Report NBSIR 77-1303, November 1977.

4. Chen, P. T., "Economic Analysis of the Norris Cotton Federal Office Building," Letter Report to DoE, February 1978.

5. Elder, J., "Norris Cotton Federal Building -- User Acceptance," Letter Report to DoE, February 1978.

6. Elder, J., "Norris Cotton Federal Building User Acceptance -- Results of the Second Questionnaire," Letter Report to DoE, March 1978.

7. Rensberger, R. A., "The Norris Cotton Building - A Living Laboratory in Energy Conservation," brochure, March 1978.

8. Yonemura, G. T., Hattenburg, A. T., and Tibbott, R. L., "Luminous Efficacy of Lighting Systems Installed in the Norris Cotton Federal Office Building, Manchester, New Hampshire, Letter Report to DoE, April 1978.

9. Richtmyer, T. E., "The Use of Computer-Controlled Data Acquisition Systems in Determining Solar Heating and Cooling System Performance," <u>Proceedings of the Conference on Performance Monitoring Techniques</u> for <u>Evaluation of Solar Heating and Cooling Systems</u>, held in Washington, D.C., April 1978.

10. Richtmyer, T. E., May, W. B., Hunt, C. M., and Hill, J. E., "Thermal Performance of the Norris Cotton Federal Office Building in Manchester, New Hampshire," <u>Proceedings of the DoE/ASHRAE Conference on Thermal Performance of Exterior Envelopes of Buildings</u>, Orlando, Florida, December 3-5, 1979.

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBS BSS 133	2. Performing Organ. Report No.	3. Publication Date August 1981

4. TITLE AND SUBTITLE

Performance of the Norris Cotton Federal Office Building for the First 3 Years of Operation

5. AUTHOR(S) James E. Hill, William B. May, Jr., Thomas E. Richtmyer, Jacqueline Elder, Robert L. Tibbott, Gary T. Yonemura, Charles M. Hunt, and Phillip T. Chen

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Architecture and Engineering Systems Branch Buildings Division
Office of Buildings and Community Systems
Department of Energy
Washington, DC 20545

10. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 81-600082

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The Norris Cotton Federal Office Building is a medium-size seven-story Government office building of approximately 11,000 m^2 (117,000 ft^2) total floor area. It is located in Manchester, New Hampshire, and was 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.

A team from the Center for Building Technology, National Bureau of Standards (NBS), has been monitoring the performance of the building since it was occupied in September 1976. The project has involved not only an analysis of building energy consumption, but also a study of the effectiveness of the various lighting systems, a determination of the response of the occupants to the building, and a cost analysis of the construction and operation of an energy conserving building. This report will describe the building's performance for the first 3 years of operation.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Building models, computer; energy conservation, user acceptance; energy conservation in commercial buildings; lighting measurements; performance data for commercial office buildings in New England; solar energy in commercial buildings.

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☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

140

15. Price

$5.50

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