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MEASUREMENT OF PERFORMANCE OF SOLAR-HEATED
OFFICE BUILDINGS

Final Report

By
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January 1984

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Center for Energy and Environmental Studies
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**MEASUREMENT OF PERFORMANCE
OF SOLAR-HEATED OFFICE BUILDINGS**

L. N. Norford, A. Rabl and R. H. Socolow

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**Final Report
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ABSTRACT

Prudential Insurance Company is building two new office buildings that are a showcase of innovative energy efficient design and solar energy utilization. In order for this effort to be fully successful, the actual performance of these buildings needs to be monitored. A fairly detailed program of instrumentation and analysis is required because one would like to learn how much energy is saved by each of the novel design features of the buildings and how the energy consumption is affected by operating practice. In June 1982 the Center for Energy and Environmental Studies received a one-year contract to initiate such a program. The contract amount was \$ 260,000, shared equally by the Department of Energy and Prudential Insurance. Out of this amount \$ 60,000 was used for a subcontract to Princeton Energy Group who participated in the analysis of the buildings, and \$ 25,000 was assigned to Flack & Kurtz towards the design of the instrumentation system.

This report summarizes the progress made during the first year. A thorough theoretical analysis has been carried out, using the DOE2.1 computer simulation code (versions a and b). This analysis has been supplemented by shorthand calculations and by special models to provide an independent check of the coding and to evaluate certain features, e.g. the double wall, that cannot be modeled by DOE2.1. A steady state shorthand method has been developed to calculate annual energy use; it is a modification of the ASHRAE bin method and agrees with the computer simulation within about 15% for cooling and 2% for heating. Energy savings due to daylighting have been evaluated using both shorthand methods and the computer code DOE2.1b.

A thorough examination of the operating rules for the energy systems in the building reveals several rules which appear to be holdovers from an earlier era of unconsciousness about energy costs. The rules for mixing outdoor air with recirculated air and for adjusting the temperature of the main supply air are two important examples where significant savings appear attainable without capital cost and without sacrifice in comfort.

The calculations of annual energy use that were performed at the design stage have been reproduced, and changes during later design phases, e.g. the outdoor air flow rate, have been identified. Even without a variety of further energy savings that appear feasible, these buildings promise to be among the most efficient in the current stock of office buildings. The South Building may use as little as 311 MJ/m² (27,400 BTU/ft²) and the North building 400 MJ/m² (35,000 BTU/ft²) per year, if operated as currently intended.

A 100-channel instrumentation and data acquisition system has been designed, and installation should be complete by February 1984. Extensive software has been prepared to confront the model predictions with field data. In spite of the US Department of Energy's inability to continue funding beyond one year, Prudential Insurance has continued its share of the funding for this project. Data collection and analysis, therefore, will continue.

Table of Contents

Abstract

1	Description of Buildings	1
2	Data Acquisition System	5
3	Meteorological Data	7
4	Daylighting	12
5	Thermal Analysis	14
	5.1 Shorthand Methods	14
	5.2 Computer Simulation with DOE 2.1	19
	5.3 Thermal Network Models	21
6	Operating Strategies and the Cost of Comfort	27
7	Summary of Work for this Contract	32
	References	34
	Figures and Tables	37

1. DESCRIPTION OF BUILDINGS

Prudential Insurance Company is building two $12,000 \text{ m}^2$ ($130,000 \text{ ft}^2$) office buildings that are an outstanding example of energy efficient design [Prudential 1981]. Together these two buildings display many of the most innovative ideas on energy conservation and solar energy utilization. The anticipated energy savings are dramatic. While a typical pre-1973 office building would consume on the order of $3,000 \text{ MJ/m}^2\text{-yr}$ ($250,000 \text{ Btu/ft}^2\text{-yr}$) [Johnson and Pierce 1980], and while current guidelines recommend approximately $850 \text{ MJ/m}^2\text{-yr}$ ($75,000 \text{ Btu/ft}^2\text{-yr}$) [ASHRAE 1975; BEPS 1976], the ENERPLEX buildings are expected to stay below $400 \text{ MJ/m}^2\text{-yr}$ ($35,000 \text{ Btu/ft}^2\text{-yr}$) [Nall 1981]. The buildings are part of a prestigious and highly visible office park, the Princeton Forrestal Center, and as an experiment in energy conscious design they have received a great deal of publicity [ENERPLEX; Norford et al. 1982].

As shown in Fig.1.1 the buildings are similar in shape and they face each other across a walkway. The plan view in Fig.1.2 shows that they are aligned along the north-south direction. Each building has a large enclosed atrium with glass facades adjacent to the walkway. In the interior they contain a U-shaped corridor, designed as light slot with large skylights. Windows make up about fifty percent of the outer wall area. The lightslots are conditioned, whereas the temperature of the atria is allowed to float.

The perimeter of the South Building is a single wall with limestone facade. The east and west windows have an upper transom portion with reflective blinds to direct daylight to the ceiling. On the south facade the transom windows have a light shelf to reflect light to the ceiling. The light shelf projects as an overhang over the lower vision windows, thereby

reducing solar gain in summer.

The North Building has a double envelope. The inner shell is a conventional wall with 50% glazing. This inner shell is enclosed by a glass curtain wall, separated by an 0.45 m (18 inch) air space. On the south side this double layer expands to create a large atrium. This atrium is designed to act as solar collector in winter. Warm air drawn from top of the atrium is forced down through a network of concrete underground pipes and then distributed through the double envelope, thus reducing heat losses from the interior. The underground pipes provide some storage for excess heat collected during the day. In summer, cool night air can be circulated through the system and then exhausted to ambient.

All windows that are directly between conditioned space and ambient are double glazed. This includes the skylights. On the other hand the windows that face enclosed spaces are single glazed and so are their outer enclosures (atria and double wall); together they are equivalent to double glazing.

The central theme of the design is control of solar gain and daylighting. Skylights, atria and corridors that are open to the top admit daylight to most of the offices, and create a pleasant open and airy environment. Daylighting is a crucial conservation feature which reduces not only the electricity consumption for lights but also the cooling load. The influx of solar radiation is controlled by shading devices that keep the solar gain to a minimum in summer yet permit passive heating in winter. The actual light levels are controlled by photovoltaic sensors.

The South Building receives its heating and cooling from a groundwater source heat pump. The heat extracted from the groundwater in winter more or

less compensates for the heat put into the groundwater in summer, thus maintaining an approximate annual average heat balance. Both buildings are all-electric.

Since the ground water was not adequate to supply heat pumps for both buildings, the North Building was given electric resistance heating. (The heat demand of the North Building occurs mostly at times of low outdoor temperatures; thus an air-based electric heat pump was not considered economical). Cooling for the North Building comes from 5,000 tons of ice/snow stored in an ice pond [Kirkpatrick et al. 1982], and an air-cooled electric centrifugal chiller system is available as backup.

Each building has a variable air volume (VAV) space conditioning system which circulates cool air to all conditioned spaces. A schematic can be seen in Fig.1.3. Part (a) shows the entire system, part (b) the VAV fan-powered induction boxes. This system derives its name from the fact that it varies the flow rate of supply air to the conditioned spaces while keeping the temperature of the supply air constant (at 12.8 C (55 F) year-round in the ENERPLEX). This choice of supply air temperature has been made to keep the interior offices from overheating. During cold weather the perimeter offices require heating; this is first provided by utilizing the heat from lights, people and equipment, and when that is not sufficient it is supplemented by heating coils located downstream of the fan-powered VAV boxes serving the perimeter offices.

The VAV system operates whenever the building is occupied, and the supply flow rate is at least $9.4 \text{ m}^3/\text{s}$ (20,000 cfm) larger than the return flow. The difference between supply and return flow is made up by fresh outdoor air, and it is extracted from the building through toilet, elevator

and electric closet exhausts, or leaves through doors, cracks and other leaks. This controlled exfiltration insures that the offices are adequately ventilated, with 0.7 air changes/hr. During occupied periods the buildings require cooling when ambient is above 1 C (34 F), and this cooling can be provided by outdoor air when ambient is below 14.4 C (58 F); in this range of ambient temperatures the flow of outdoor air is increased above 9.4 m³/s (20,000 cfm), an operating mode called economizer. For the analysis we have made the usual assumption that infiltration into the building is negligible while the ventilation system is operating. At night the ventilation system is shut down, and infiltration rates in the range of 0.15 to 0.4 air changes/hr can be expected from experience in other office buildings. For the present study we have assumed 0.2 air changes/hr during all unoccupied periods.

The major power consumers are listed in Table 1.1, and Table 1.2 summarizes the assumptions made for our analysis. Fig.1.4 shows the energy consumption versus time of year, calculated by DOE2.1a (note that the program includes a calendar with holidays, and the month-to-month variation of equipment use reflects the actual number of working days). Table 1.3 gives an annual breakdown by end use. The total energy consumption of the South Building is predicted to be 311 MJ/m²-yr (27,400 BTU/ft²-yr). Within the accuracy of the analysis the basic heating and cooling loads of the North Building are the same as for the South Building. The actual energy consumption is, however, higher because the equipment has a much lower COP than the groundwater based heat pump of the South Building. The lighting energy includes the benefits of daylighting, as described in Section 4. The fans require a large share of the total energy; this

suggests that low-energy fan systems and low-energy strategies for using fans may not have received sufficient attention in the decade of technological innovation which these buildings represent.

2. DATA ACQUISITION SYSTEM

Designing a suitable instrumentation and data acquisition system for this application has been a challenge because of severe budget constraints. A careful search was made to identify means of reducing the cost of the system, and each proposed data point was scrutinized to find any that might be eliminated without compromising the quality of the whole effort. The final design for this system evolved after evaluating several possible alternatives and after many discussions between the Center for Energy and Environmental Studies (CEES), Flack & Kurtz (F&K) and Princeton Energy Group (PEG). Location and function of each data point are listed in Table 2.1. There are approximately 50 data channels in each building. This selection of sensors will provide adequate information about equipment performance, energy flows, indoor conditions, and ambient driving forces.

Final drawings and specifications for this system were prepared by F&K, and sent out for bids. Several firms submitted bids for the installation, and ELEMCO was chosen as subcontractor for this task. The contract was signed in April; the amount of the contract was \$ 86,000, or \$ 860 per channel. Prudential Insurance agreed to cover the incremental cost beyond the \$ 50,000 originally budgeted. Prudential also specified TORCON, the ENERPLEX construction contractor, rather than CEES, as manager for the ELEMCO contract. Installation of the system is almost complete.

The heart of the data acquisition system is an IBM PC microcomputer.

The IBM PC at the site will be located in the equipment room of the South Building, and it will sample the data channels of both buildings at intervals programmable by the user. The data will be stored on disk. The data are to be analysed on the IBM PC at CEES and on the IBM 3081 mainframe computer of Princeton University. These computers have been interfaced and transfer of data has been demonstrated. (The IBM PC was chosen for the data acquisition system because several similar units are available at CEES for computation and for word processing. Using the same microcomputer minimizes problems of data transfer.)

In addition to the fixed instrumentation system we have some portable instrumentation: a pyranometer, photometers, temperature sensors, and equipment for infrared thermography and for air infiltration measurements. Some of this instrumentation (temperature sensors, thermography and air infiltration) is available from other projects at CEES.

For daylight measurements in the offices an adequate number of fixed photometers would have been too expensive. Portable photometers offer greater flexibility at lower cost. During the first phase of this project PEG has kindly provided a portable photometer; we are now purchasing our own. A small portable data acquisition system with 9 photometers has been designed by R. Seroussi who is doing his M.S.E. thesis on daylighting. For insolation measurements we have bought an Eppley PSP pyranometer. This permits accurate calibration of the insolation sensors of the fixed instrumentation system, as well as spot checks of the solar radiation on various surfaces inside and outside the buildings.

3. METEOROLOGICAL DATA

The dominant building loads are determined by ambient meteorological conditions. In the absence of actual data at the building site one must base the calculations on data from surrounding weather stations. The quality and availability of the data varies from location to location. Most weather stations keep records of temperature and cloud cover, but measured solar radiation data are rare. For the New Jersey area the only official stations with a systematic long term record spanning several years are New York (Central Park) and Philadelphia (Airport), and even those stations have only measured the hemispherical (i.e. direct plus diffuse) insolation on the horizontal surface. There is one additional station with hemispherical insolation measurements, Rutgers University, but these data are not available on computer tape. Insolation data that have been published for other locations are interpolated using procedures based on cloud cover observations and statistical correlations. Of the stations closest to the ENERPLEX site (Trenton, New Brunswick and Newark), only the Newark data are supplied on a computer tape compatible with the DOE2.1 program. The simulations performed by D. Nall [1981] during the design of the ENERPLEX used data for Allentown, PA.

Most of the solar energy absorbed by the ENERPLEX buildings enters through vertical windows. Until the data acquisition system comes on line we have essentially no insolation data for tilted surfaces and the insolation must be estimated from the horizontal data. The crucial step of this estimation procedure is the separation of direct and diffuse insolation; this has already been done for the TMY weather tapes [NCC 1978], based on an algorithm developed by the Aerospace Corporation

[Aerospace 1978]. For the other data bases we have used the algorithms published in Duffie and Beckman [1980].

We have carefully evaluated the available insolation data. An example of the many comparisons we have carried out is shown in Fig.3.1. Here the average solar radiation [in W/m^2] on a south facing vertical surface for each month is plotted for all the available data bases. The spread is considerable, especially in the winter months when the highest and the lowest values differ by about 40%. The uncertainty would be even greater if different algorithms for the separation of direct and diffuse insolation were considered. The choice of the data base for our analysis involves a certain amount of judgment about the reliability of the data and the importance of using data that are generally accessible. We have decided to use the TMY (typical meteorological year) weather tapes for Newark, NJ [NCC 1978]. The name TMY expresses the fact that these data have been selected in such a way as to represent the long term average weather conditions.

The uncertainty about solar radiation is further compounded by site specific effects that are difficult to evaluate in advance. For example the venetian blinds in the North Building can be adjusted by the occupants, thus affecting both solar loads and daylighting. There is a group of deciduous trees to the west of the buildings, and their shading is difficult to calculate accurately.

For a better understanding of the solar loads it is instructive to present tables with solar radiation on each of the principal building surfaces. Since the ENERPLEX buildings are aligned along the cardinal directions, the relevant orientations are east, west, north and south vertical, in addition to horizontal (for the roof). The average monthly

radiation, in W/m^2 , for each of the cardinal orientations and for each month is shown in Fig. 3.2, with a breakdown into direct radiation, diffuse sky radiation and radiation reflected from the ground (with an assumed reflectivity of 0.2). Such a breakdown gives an indication of the possibilities for controlling solar gains. One would like to minimize solar gains in summer while admitting solar radiation in winter. As far as direct rays are concerned this goal is easy to achieve with passive shading devices on the south side of a building, and to a certain extent it is possible even on the east and west sides. This has been done quite successfully in the ENERPLEX buildings. On the other hand the radiation from sky and ground is diffuse and cannot be controlled by simple directional devices. As Fig.3.2 shows, most of the undesirable solar gains through vertical windows are diffuse. Also, in summer the solar flux on the north facade is quite large, comparable to the diffuse flux on the south facade.

The bulk of the solar load enters through the windows and depends on the transmissivity of the glazings. In some windows the radiation is further reduced by overhangs, shading devices or venetian blinds. The behavior of the shading devices varies with solar incidence angle and with the ratio of direct and diffuse insolation. In the North Building the calculation of the transmittance is complicated by the fact that several different glass types are used in adjacent facets of the double wall: since the inner and outer glazing are not close together, the effective overlap between different glass types varies with angle of incidence. Algorithms have been developed [PEG 1983] for taking all of these effects into account.

In Table 3.1 we present the average solar heat gain for each month and for all the orientations, including the tilted openings of the skylights. Part (a) of the table refers to the South Building, part (b) to the North Building. The first portion of the tables shows the solar heat gain factor; it is defined as the solar heat gain per unit area [in BTU/ft²-day] through a single pane of standard glass [ASHRAE 1981]. The solar heat gain factor is the sum of transmitted radiation (assumed to be entirely absorbed inside building) and an appropriate fraction of the radiation absorbed in the glass (taking into account heat flow from glass to ambient). The heat gain factors in Table 3.1 have been calculated according to the ASHRAE procedure, and they include the variation of transmittance with incidence angle. The portions headed "SOLAR HEAT GAIN" show the actual heat gain for each facade, obtained by multiplying the solar heat gain factor by area and shading coefficient. The shading coefficient [ASHRAE 1981] accounts for the solar and thermal properties of each glass type, and is defined in such a way that the product of shading coefficient and solar heat gain factor is the actual heat gain through the particular glazing. For example, in December the solar heat gain factor for a vertical north window is 121 BTU/ft²-day. The product of glazing area and shading coefficient for the north facade of the South Building is 2,642 ft² without blinds. Including venetian blinds with a shading coefficient of 0.6 the total solar heat gain through this north facade is $0.6 \times 2,642 \text{ ft}^2 \times 121 \text{ BTU/ft}^2\text{-day} = 192 \text{ kBTU/ft}^2\text{-day}$.

The overhang factors listed just below the solar heat gain factors in Table 3.1a give some indication how well the direct solar radiation has been controlled by the overhangs of the South Building. The overhang factor

is defined as a multiplicative factor for the solar heat gain: for example, in December the overhang factor for the south glazing of the light slot is 0.84 (less than unity because some radiation is blocked even in winter) and the corresponding solar heat gain is $0.84 \times 1,794 \text{ ft}^2 \times 693 \text{ kBTU/ft}^2\text{-day} = 1,044 \text{ kBTU/day}$. In June the overhang factor is 0.65, some 23% lower than in December. As can be seen from Fig.3.2, the insolation on the south facade in June is predominantly diffuse; the direct component is only about 24 W/m^2 out of 104 W/m^2 . Hence a 23% reduction is all that can be achieved if one eliminates all the direct radiation on the south facade in June.

A listing such as Table 3.1 can be useful because it gives the designer an overview of the solar loads on the individual surfaces, showing at a glance where the energy balance might be improved by changing the windows or by adding shading devices. For example, the light slots of the South Building have their north glazing tilted at 55 degrees, and in June this face alone contributes 2,126 kBTu/day out of the total solar gain of 9,270 kBTu/day. This is quite a large solar load at a time when it is most harmful. Comparing the solar heat gain factors for vertical and tilted north faces one finds that this term could have been reduced by a ratio of 567/944 if one had installed vertical glazing. In December such a change would have reduced the solar gain of this glazing by a ratio 121/146, with negligible effect on the overall heat balance because then this face contributes only a small portion, 329 kBTu/day, of the total solar gain, 5,599 kBTu/day. Of course, heat balance is not the only design criterion. Not only does the tilted glass have some daylighting benefit, but it enhances the bright open atmosphere of the corridors, an aesthetic

consideration that is difficult to quantify.

In addition to solar radiation one needs temperature data. For a shorthand analysis of building loads it is convenient to use the frequency distribution for each 5 F temperature bin. The number of hours per year for each temperature bin is shown in Table 3.2, based on the TMY weather tapes for Newark. The data are separated according to the three time periods of the occupancy schedule of Table 1.2: weekday, weekend day and night.

4. DAYLIGHTING

A threefold approach has been taken to evaluate the energy savings due to daylighting: computer simulation, shorthand analysis and measurements. The computer simulation of the daylighting for the North Building was performed with the b version of DOE2.1. The result indicates an annual reduction of the lighting load of 27%.

The shorthand analysis is based on daylight factors that have been measured [PEG 1983] in a physical model similar to the offices of ENERPLEX. The daylight factor is the ratio of illumination at a suitably chosen reference point inside a building over the sky illumination incident outside the building, excluding any contribution of direct solar radiation. The daylight factor depends on geometry and materials but not on solar radiation or time of day (because the angular distribution of diffuse sky illumination can be treated as fairly constant, and because the contribution of direct solar radiation is not considered useful). Once the daylight factor is known, one can calculate the daylight at the reference point by multiplication with the instantaneous diffuse sky illumination outside the building. For the perimeter offices of ENERPLEX the daylight

factor has been estimated to be 6% in the front of the office (4.5 ft from window) and 2.5% in the back of the office (12 ft from window). Substantial savings due to daylighting are possible for daylight factors above 2%.

The savings due to daylighting depend on the type and placement of the controls chosen for the light switches. The number and placement of the controls in the ENERPLEX are not yet known because they depend on the interior finishing which will be determined only after the tenant has been selected. (The reflectivity of the interior furnishings also has a direct effect on the light levels). In any case the controls will operate in three discrete steps rather than by continuous dimming.

Hence we have performed the base case calculations with the assumption of three-step control. The results are listed in Table 4.1. (In their daylighting aspects the buildings are sufficiently similar that only one set of numbers is shown for both buildings.) This table gives a breakdown of lighting power and energy by time period and building component. The first column lists the installed power. Columns 2 to 7 separate the energy use by time period, and the last 2 columns show the total. For each time period the first column gives the average power, the second the annual energy consumption. The weekday entries display the effect of daylighting: the average power level of the lights in offices and core is reduced from 132 kW to 96.2 kW, a saving of 27%. In corridors and atrium the daylighting saves approximately 80% of the weekday consumption.

Some preliminary measurements of daylight factors have been obtained in the ENERPLEX North Building, as well as in a scale model of the South Building. Since the interior is not yet finished, these values can only be taken as a very rough guide. To that extent they agree with the daylight

factors assumed in the calculations. These measurements also indicate that the daylight savings in the offices facing the first and second floor of the light slot will be negligible, as has been assumed in the calculations for Table 4.1.

5. THERMAL ANALYSIS

In order to be able to learn the most from the data that will be collected it is necessary to have a thorough understanding of the buildings. The most powerful analysis tool is a detailed computer simulation program. For this we have chosen the program DOE 2.1 (both the a and the b version). We have supplemented the computer simulations with a variety of special models. These analysis tools and the results of the calculations are described in this section.

5.1 Shorthand Methods

A shorthand procedure is a good starting point for the thermal analysis because it provides an intuitive understanding of the energy flows in a building. Also, it is a valuable check on the validity of the coding of the input for the computer simulation program. For example in the limit of constant indoor temperatures the results of a shorthand method, like the ASHRAE TC4.7 procedure [Kusuda and Sud 1982], should agree very closely with DOE 2.1. Wherever practical we have cross checked our results in this manner.

Several shorthand procedures are suitable for the analysis of office buildings, e.g. the balance point technique, the bin method, and the ASHRAE TC 4.7 method. They are all based on ASHRAE heating and cooling load

formulas, and differ only in details. We have used the bin method, but paying more than the usual level of attention to details such as operation and performance of the HVAC equipment. The bin method derives its name from the fact that energy gains and losses due to lighting, people, insolation, conduction, infiltration etc. are calculated separately for each 5 degree F bin of ambient temperature. Multiplying by the number of hours of occurrence and summing over all bins yields the total annual loads. As far as heat gains and thermostat settings are concerned, there are three distinct time periods: occupied weekday (8 am - 6 pm, Mo - Fr), unoccupied weekend day (8 am - 6 pm, Sa and Su) and unoccupied nights (6 pm - 8 am, 7 days/week). We have performed a separate set of calculations for each of these periods. Correlations between insolation and ambient temperature have been incorporated as recommended by the TC 4.7 committee of ASHRAE, by correlating the monthly solar gains of Table 3.1 with ambient temperature. Since fan operation and ventilation rate vary with ambient temperature, we have calculated the electricity consumed and the heat produced by the fans for each temperature bin taking into account the partload performance of the fans.

These calculations have been set up on microcomputer, using VISICALC software. The results for the weekday occupied period have been printed out in Table 5.1 and plotted in Figs. 5.1 and 5.2. Fig.5.1 shows each load component, Fig.5.2 the net load. Smooth curves have been drawn through the points that have been calculated at the midpoint of each bin. The terms for people and for ventilation include only sensible heat below $T_{amb} = 15.6\text{ C}$; above this temperature they include both sensible and latent heat. The near equality of conduction and ventilation in winter is a coincidence in these

particular buildings.

It is instructive to examine the balance points. The balance point for heating, $T_{b,heat}$, is that ambient temperature at which the sum of the heat gains Q_{gain} of the building equals the heat loss $(UA)_{total}(T_{int}-T_{amb})$

$$T_b = T_{int} - Q_{gain}/(UA)_{total} \quad (5.1)$$

Heating is needed only when ambient falls below $T_{b,heat}$. For $T_{int} = 20\text{ C}$ (68 F) the ENERPLEX South Building has $T_{b,heat} = 1\text{ C}$ (34 F) during daytime occupied periods. When ambient rises above the balance point for heating, the excess heat generated in the building can be flushed out by increasing the ventilation rate (and hence the $(UA)_{total}$ to be used in Eq.5.1). This mode of operation is called economiser and can maintain the desired indoor temperature until ambient reaches the balance point for cooling, $T_{b,cool}$. The chillers need to be turned on only when ambient rises above this temperature. $T_{b,cool}$ depends on the maximum flow rate of the supply fans. For the ENERPLEX South Building the maximum flow rate is $56.5\text{ m}^3/\text{s}$ (120,000 cfm); inserting the total gain and $(UA)_{total}$ corresponding to the maximum flow rate into Eq.5.1 one finds that $T_{b,cool} = 20\text{ C}$ (68 F) during occupied periods. This is much higher than the upper temperature limit of the supply air 14.4 C (58 F) that has been set by the design specifications for the economiser. As the building operation is specified now, the economiser will be used only when ambient is below 14.4 C (58 F); above this temperature the intake of outside air is again reduced to the minimum, $9.4\text{ m}^3/\text{s}$ (20,000 cfm) and the chillers are needed to maintain the supply air at 12.8 C (55 F). Thus it seems that the full potential of the economiser cannot be realized as long as the supply air temperature is fixed at 12.8 to 14.4 C (55 to 58 F).

The savings achievable by changing the supply air temperature and the economiser operation will be addressed in Section 6. For the moment let us continue with the buildings as currently designed, for which Fig.5.2 shows the net heating and cooling load as a function of ambient temperature. The role of the balance points is clearly visible: heating is needed below the heating balance point $T_{b,heat} = 1\text{ C (34 F)}$, cooling above the effective cooling balance point (i.e. economiser cutoff) of 14.4 C (58 F) . Between these balance points the effective load is zero. Outside this interval the solid line would have a constant slope if all loads were either constant or proportional to $(T_{int} - T_{amb})$. This is nearly the case for the heating portion were the fans run at constant power and only a slight nonlinearity is introduced by the correlation between solar radiation and ambient temperature. For the cooling portion above $T_{amb} = 14.4\text{ C}$ the line in Fig.5.2 is less straight because fan power and latent gain vary nonlinearly with ambient temperature. To highlight the connection with annual loads, we have included on top of Fig.5.2 the histogram of ambient temperatures.

A numerical listing of the loads for each bin can be found in Table 5.1. The last column shows the net building load (negative for heating, positive for cooling). The corresponding results for the other time periods are given in Table 5.2 (nights) and Table 5.3 (weekend day). The sum of the loads for each temperature bin is shown at the bottom of each table, and the totals from each table are summarized in Table 5.4. The total annual heating load is the sum of the heating loads for the three time periods. For the total annual cooling load we disregard the cooling loads of Tables 5.2 and 5.3 because there is no plan to cool the buildings when they are unoccupied. Note that all these table entries are building loads; to obtain

the energy consumption one must divide these loads by the COP's of the equipment.

As a comparison with the computer simulation in the next section will show, the total loads are predicted quite accurately by the bin method. But the day/night split of the loads cannot be calculated by a steady state method if the thermostat setpoints are different for the different periods. The steady state method allocates all heat gains to the day and therefore assigns an excessive proportion of the heat loss to the night, 104 out of 114 MJ/m². But really some of the heat gains of the day are stored in the thermal mass and released at night, thus shifting part of the heating load from night to day. An examination of the operating hours of the heating plant as modeled by the DOE2.1 simulation shows that actually somewhat more than half of the heating load occurs during occupied periods. Therefore the savings achievable by reducing the night time temperature (discussed in Section 6) are not as large as might be guessed from Table 5.4.

Tables 5.1 to 5.4 show a single set of calculations for the entire year. Since this calculation is based only on temperature and not on time, heating and cooling are assumed to be available all year. This is not quite true for the heating and cooling equipment of the South Building: changing the heat pump between summer and winter operation requires a manual drain down and resetting which is performed only twice a year. Thus no heat will be available after the spring changeover and before the fall changeover. Since the annual calculation assumes that heat can be supplied on such nights, we have carried out a separate bin analysis for each month. The results of this monthly analysis differ from the annual one only for the heat load at night; the difference is about 10%. For buildings like the

North Building where heating and cooling are always available there is no difference between a monthly and an annual bin analysis. The results of both monthly and annual bin analysis are summarized in Table 5.5, which also compares the bin analysis with computer simulations as discussed below.

5.2 Computer Simulation

The most accurate results can be obtained with a computer simulation program. As part of the original design process of the ENERPLEX buildings the energy consumption of the buildings was calculated by D. Nall of Berkeley Solar Group, using the NBSGLD computer code. This is a proprietary program which combines elements of the public domain programs NBSLD and BLAST.

For the present project we have chosen the program DOE2.1. Most of the runs have been done with the 2.1a version of the program. The 2.1b version is identical to 2.1a in the thermal parts, but includes in addition an analysis of daylighting. So far the 2.1b version has not yet been distributed outside the Lawrence Berkeley Laboratory. We have carried out several DOE2.1b runs of the North Building, using the IBM computer at Berkeley.

Some results of the computer calculations for the South Building are listed in Table 5.5, as annual heating and cooling loads per unit floor area. These loads are building loads, not equipment loads. The latter, i.e. the actual energy consumption as reported in Table 1.3, are obtained by dividing the building loads by the COP of the HVAC equipment:

South Building heating COP = 2.18 and cooling COP = 4.26

North Building heating COP = 1.0 and cooling COP = 2.4.

The first line, labeled "NBSGLD", states the results obtained by D. Nall [1981] using the NBSGLD computer program. The second line ("NBSGLD emulator") presents our attempt to reproduce as far as possible the results of Nall, but using DOE2.1a. These numbers turn out to be some 20% higher than Nall's, both for heating and for cooling. It is difficult to clearly identify all the causes of this difference. Some of Nall's assumptions had not been documented, and at this point they can no longer be reconstructed with certainty. Nall used weather tapes for Allentown, PA, while we have used the SOLMET TMY (typical meteorological year) tapes for Newark, NJ, because they appear to be the most reliable. Finally there are differences in the programs themselves.

There are several differences between the original design and the actual construction/controls/operation of the buildings. For example the design intake rate for fresh outside air has been increased from 3.0 to 9.4 m^3/s (6,400 to 20,000 cfm). As a consequence of these changes the heating load has increased by 12% and the cooling load by 14% over the "NBSGLD emulator" entries in Table 5.5.

For comparison Table 5.5 also shows the results of the bin method calculation of Section 5.1; the agreement is about 2% for heating and 15% for cooling, well within the range found in other comparisons between shorthand methods and computer simulations for office buildings [Kusuda 1981]. The bin method cooling load is higher than that predicted by DOE2.1, for two equally important reasons: the bin method takes full credit for all radiant gains, and it neglects thermal mass. DOE2.1 assumes that about 10 to 20% of the radiant heat (solar radiation, as well as radiant portion of heat from people, lights and equipment) that is absorbed by the interior

surfaces of the walls leaves the building by conduction to the exterior. Taking instead full credit for these radiant gains, the bin method overestimates the cooling load and underestimates the heating load. As for day-to-night heat storage in the thermal mass, the bin method overestimates the cooling load because it counts the entire heat gain of the day as cooling load, while DOE2.1 shifts some of this gain to the night when it can be removed naturally by conduction and infiltration. In winter the neglect of thermal mass leads to an overestimate of the heating load because during days with ambient above the heating balance point excess heat gains of the day are discarded while DOE2.1 uses them to offset the heat losses at night. In the heating season these two effects (full credit for radiant gains and neglect of thermal mass) are of opposite sign whereas in the cooling season they are additive. These effects have been investigated with a large number of parametric comparisons between bin method and DOE2.1 by Norford [1984], and the reader is referred to this reference for further details.

5.3 Thermal Network Models

The double wall/atrium/underground storage pipe system of the North Building is an innovative design that cannot be adequately modeled with existing computer simulation programs such as DOE2.1 or BLAST. We have therefore used special thermal network models to analyse this system and to evaluate several possible operating modes. A schematic of the double wall system and its design operating mode is shown in Fig.5.3. A particularly simple alternative to the design operating mode is called the "static case"; it does not turn on the air circulation pumps of the double wall

system at all, thus reducing the double wall system to the equivalent of a double glazed window.

It is instructive to begin this analysis with the simple steady state model in Fig.5.4; it has three nodes: ambient air temperature T_{amb} , the air temperature inside the double wall T_{air} , and the temperature T_{int} inside the building. Consider a volume of warm air flowing from atrium or storage through the double wall, entering at $T_{air,in}$ and leaving at $T_{air,out}$. If the product of mass flow rate and specific heat of the air is mc then the air gives up heat at a rate

$$Q_{air} = mc (T_{air,in} - T_{air,out}).$$

Under these conditions the net heat flow from interior is

$$Q = (T_{int} - T_{amb})/R - Q_{air} R_0/R$$

where $R = R_i + R_o$

is the total resistance from interior to ambient,

with R_i = resistance from interior to air in double wall,

and R_o = resistance from air in double wall to ambient.

The first term is the conductive building loss when there is no air flow from storage (=static case), while the second term represents the heat loss reduction due to warm air from storage. For typical wind speeds the numerical values of the resistances (including the respective areas of wall and glass) are approximately

$$R_i = 9.0 \text{ C/MW}$$

$$R_o = 3.0 \text{ C/MW}$$

and $R = 12.0 \text{ C/MW}.$

Thus the coefficient multiplying Q_{air} is

$$R_o/R = 0.25.$$

This implies that each thermal unit of warm air from the storage pipes (or the atrium) reduces the heat loss of the building by only 0.25 thermal units. In other words, putting heat into the double wall seems an indirect and rather ineffective way of heating when compared to a direct solar heating system which would place the warm air directly into the interior of the building. On the other hand, warm air in the double wall can be useful even when its temperature is much lower than what would be required in a direct heating system.

For a more detailed analysis of the double wall system a network model with 31 nodes has been developed [PEG 1983]. This number of nodes is adequate to describe the thermal behavior of the double wall system while being simple enough to run on a microcomputer. The model accounts for thermal mass, both in the building itself and in the double wall system. This model was developed in several stages. First the heat transfer between the storage pipes and the ground was analysed by itself, using a relatively large number of nodes to characterize a cross section of the pipe wall and the surrounding ground. Then these nodes were replaced by a single node with an equivalent effective heat capacity, as recommended by Vol.2 of the Passive Solar Design Handbook [Balcomb et al. 1982]. The accuracy of this approximation was verified by many numerical evaluations and found to be acceptable (average error in duct air temperature less than 1 F under any reasonable operating conditions).

On the basis of this simplification it was possible to represent the various sections of the underground pipes by only nine nodes, and the remaining 20 nodes could be chosen for points in atrium, double wall, building interior and ambient. The location of these nodes is shown in

Fig.5.5. Most of the nodes are associated with the double wall system, while the rest of the building is modeled rather crudely by only two nodes: number 30 for the perimeter offices and number 19 for interior offices. This is acceptable because the model is to be used only for evaluating the behavior of the double wall system, whereas the rest of the building can be simulated with DOE2.1. This thermal network program is run on microcomputer with hourly weather data. Since it was too slow for a complete annual simulation, weather data for a typical winter week and for a typical summer week were synthesized, and the simulation was carried out for a week at a time.

Four different operating strategies were considered for the winter operation of the double wall system. To describe these strategies let us define four running modes for the pumps:

mode 0: no air circulation;

mode 1: circulation around complete loop at low speed (Fig.5.3a);

mode 2: circulation around complete loop at high speed (Fig.5.3a);

mode 3: collection of heat at low speed (Fig.5.3b).

The complete loop for modes 1 and 2 is as follows (see arrows in Fig.5.5): air is drawn upward in the atrium (from node 27 to node 29), then pumped down through two concrete collection pipes in the atrium (from node 1 to node 5) into the underground storage pipes (nodes 9 to 18), and from there up through the wall cavities (from node 20 to node 22); finally the loop is closed by a duct from the top of the wall cavities to the bottom of the atrium (from node 22 to node 27). For mode 3 the underground pipes are charged with heat: outside air enters the bottom of the atrium (from node 31 to node 27), is collected from the top of the atrium (node 29) and

pumped down to the storage pipes, and is exhausted from the end of the collection ducts (from node 11 to node 31), without ever going through the double wall cavities.

Of the four operating strategies for winter the "static case" is the simplest: the double wall fans do not run at all. The "as designed" strategy uses all four modes according to the control logic described in the Mechanical System Specification dated 5/15/1981. The "max COP" strategy differs from "as designed" in that mode 3 is not used and thus no outside air is introduced into the atrium. This turns out to achieve the highest possible coefficient of performance, defined as net heat savings divided by electric input for the fans. Finally the "max. heat saving" strategy attempts to reduce the heat input for the morning startup of the building by circulating air in the double wall system during much of the night. In terms of the pump modes these operating strategies can be summarized as follows:

"static case" - mode 0 at all times.

"as designed" - normal status = mode 0

call for heat = mode 1 (when $T_{30} < 20$ C (68 F) daytime
or $T_{30} < 14.4$ C (58 F) at night)

switch to high = mode 2 (when mode 1 is on
and T_{22} decreases)

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store heat = mode 3 (when  $T_{29} > T_{11}$  and
                        there is no call for heat).
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"max. COP" - same as "as designed" except store heat = mode 2.

"max. heat saving" - same as "max. COP" except call for heat = mode 1
(when $T_{30} < 20$ C (68 F) day or night).

Note that T_{30} = temperature of perimeter office zone,

T_{11} = air temp. near outlet of underground collection duct,

T_{22} = air temp. at top of double wall,

and T_{29} = air temp. at top of atrium.

The calculations show that there is little difference in overall energy consumption between these strategies. To highlight the differences, the results are plotted in Fig.5.6 as savings relative to the "static case", in terms of kWh/day for an average January day. Heat savings and fan energy for the double wall are shown separately. The static case itself uses 4,400 kWh/day heat and 0 fan energy. (This value of 4,400 kWh/day is somewhat larger than the $(42 \text{ MWh}/31 \text{ days}) \times 2.18 = 3,000 \text{ kWh/day}$ heat load implied by Fig.1.4 for January because both the model and the meteorological data are different; however, the comparison between operating strategies should be valid). The heating load includes the thermal benefits of the heat from the fans. Since the building uses electric resistance heating, a strategy is more economical than the "static case" if the heat saving is greater than the energy input for the double wall fans (for other heating systems one would have to include the COP of the heating system and/or the price of heating fuel in this comparison). Fig.5.6 shows that the "as designed" strategy actually consumes slightly more energy than the "static case". Only "max. COP" presents an improvement over the "static case", with a daily saving of 10 kWh (worth approximately one dollar per day at the going electricity price). The COP of this strategy is 1.4.

The 31 node network has also been run for an average July week to compare the "static case" with the "as designed case". As designed, ambient air is circulated through the double wall system if ambient air is cooler

than the air in the double wall. According to the network model, the "static case" has a cooling load of 2,000 kWh/day (6.9 MBTU/day) in July, while the "as designed" strategy reduces the cooling load by 80 kWh/day. However, the latter also requires 200 kWh/day in fan power; this is clearly more costly in energy than the saved cooling load, at any reasonable COP. Actually one can do better than the static case by opening the vents at the bottom and at the top of the double wall to permit outdoor air to circulate by natural convection and provide some cooling to the venetian blinds that are located in the double wall. Because of the construction of the double wall the magnitude and benefit of this convection current is difficult to estimate. In any case, as a result of the above calculations the specifications for the operation of the double wall have been modified to increase the energy efficiency.

6. OPERATING STRATEGIES AND THE COST OF COMFORT

The energy consumption of a building is not a single fixed number, but it depends on how the building is operated and what conditions are maintained inside. The energy use predicted in this report is very much like the EPA rating for the fuel efficiency of cars, and the customary warning that the actual efficiency depends on driving conditions and may differ substantially from the EPA rating applies in analogous form to our numbers. With novel equipment it is quite likely that the design performance may not be achieved during the first year because the maintenance personnel may take some time to learn how to optimize the operation of the building. For instance, the Norris Cotton Federal Office Building in Manchester, NH, which was especially designed for energy

conservation, required about 50% more energy during the first year than during subsequent years [Hill et al. 1981]. In this section we evaluate the variations in energy use that can be expected under different conditions and we identify changes in operation that may actually reduce the consumption below the design value.

Some of the possible changes involve conditions of comfort; for example the heating load increases with the occupied period thermostat setting. We have calculated the energy consumption and cost for several thermostat settings and outdoor air flow rates. A quantitative evaluation of these effects is needed to determine the economic optimum. This kind of information is of particular interest during an energy crisis when it enables the building owner/operator to make a rational response to rising energy prices. Other possible changes, for example a reduction of the night time thermostat setting, have little or no effect on comfort. As it turns out, in the ENERPLEX buildings much larger savings are achievable by such modifications of the building operation than by simply changing the interior conditions during occupied periods.

Table 6.1 shows the annual energy consumption for heating and cooling as a function of indoor conditions, calculated by DOE2.1a for the South Building. These numbers can be applied to the North Building if they are multiplied by the COP ratio: 2.18/1.0 for heating and 4.26/2.4 for cooling. To place a dollar value on the energy figures in Tables 6.1 and 6.2 one needs to look at the applicable rate schedule of the local utility; this is the LPL schedule of PSE&G [1983]. The calculation of cost is complicated by the demand charge, a monthly charge of approximately \$ 8 per kW of maximum instantaneous demand during each month (actually \$ 8.60 per kW in summer, \$

7.70 per kW in winter). The demand charge is added to the basic energy charge of 6.8 c/kWh (= \$ 68 per MWh). The magnitude of the demand charge depends very much on the load pattern. For the energy bills of the ENERPLEX buildings we have calculated that the effective average cost of energy comes to about 11 c/kWh. The dollar savings corresponding to each estimate in Tables 6.1 and 6.2 may be quite different from what would be calculated at 11 c/kWh because they depend on the timing of the demand reduction, but in any case the value per kWh is never less than the basic energy charge of 6.8 c.

Table 6.1 shows that the annual heating energy of the South Building varies by about ± 25 MWh if the occupied thermostat setpoint for heating is raised (lowered) by 1.5 C. At 11 c/kWh this would be worth \$ 2,750. An equal temperature change for cooling changes the cooling energy consumption by only 6 MWh (although the effective cost per kWh may be significantly higher due to the timing of the cooling demand, by an amount that is difficult to predict). The smallness of the energy values in Table 6.1 is partly due to the high efficiency of the groundwater based heat pump of the South Building. For the North Building with its more conventional equipment the corresponding energy and cost figures are on the order of two times larger. But even that is small compared to what one would find in most other buildings. The reason lies in the fact that the ENERPLEX buildings are relatively well insulated and air tight. The lower the heat loss coefficient of a building, the less the energy balance is affected by comfort conditions.

To see how far the minimum outdoor air flow rate could be reduced let us consider the ASHRAE standard 61-81 for ventilation [ASHRAE 61-81]. It

requires 2.5 l/s (5 cfm) per person without smoking, and 10 l/s (20 cfm) per person if smoking is allowed. Thus the design fresh air rate of 9.4 m³/s (20,000 cfm) is a very safe value that can accomodate up to 1,000 smokers. In Table 6.1 we have somewhat arbitrarily considered the effect of lowering the flow rate to 2.4 m³/s (5,000 cfm), corresponding for example to 1,000 nonsmokers. (Actually, as currently designed, 3.9 m³/s (8,200 cfm) is the lowest possible value for the ENERPLEX because that is the design flow through the exhaust fans of toilets, elevators and electric closets.) The smallness of the resulting savings, 1 MWh for heating and 3 MWh for cooling in the South Building, suggests that it may not be worth trying to establish an operating regime with a reduced minimum outdoor air flow rate.

The savings from reducing the outdoor air flow rate may appear to be surprisingly small. For heating the reason lies in the fact that heating during occupied periods is required only in very cold weather. For the base case, more than 9.4 m³/s (20,000 cfm) of outdoor air is needed to cool the building when ambient is above 1 C (34 F). Only below that temperature can a reduction of outdoor air flow bring any savings, and when one reduces the flow rate one soon reaches the point where the building needs almost no heating during occupied hours. Hence the savings are very small. For cooling the savings are larger, about 3 MWh, because the outdoor air contributes to the cooling load during the entire cooling season; however, it is only a relatively small term compared to the other cooling loads.

Table 6.2 addresses savings that may be achieved with little or no effect on comfort, and (apart from changes of fan control) with zero capital cost. Again the numbers are stated for the South Building; for the

North Building they have to be multiplied by the COP ratios which approximately doubles the entries for heating and cooling. The first item, raising the supply air temperature from 12.8 to 15.6 C (55 to 60 F) and extending the economiser operation up to ambient temperatures of 19.5 C (67 F), is predicted to save about 50 MWh per year. This is much more than can be achieved by any reasonable modification of comfort conditions. Is it realistic to expect this saving without any undesirable side effects? Averaged over the building the higher supply air temperature would certainly provide adequate cooling. Only during certain periods, for example a hot, sunny afternoon, may some part of the building require more cooling than can be provided by the maximum supply air flow rate at 15.6 C. Whether this problem is serious is difficult to predict, because it depends on the zone-to-zone heat transfer which in turn depends on interior partitions which have not yet been chosen. By examining the cooling loads of the individual zones we are led to believe that local overheating should not be a serious problem. The best strategy may be to try a higher temperature and see how well it works in practice. Ideally one would like to vary the supply air temperature in response to cooling load, as has been done in some control systems. Another possible side effect of an increased supply air temperature may be increased stratification of air in the office; this, too, depends on the placement of interior partitions and is difficult to foresee.

Another 11 MWh can be saved by lowering the thermostat setting during unoccupied hours from 14.4 to 12.8 C (58 to 55 F). Combining these two measures, items (1) and (2) in Table 6.2, one finds projected savings of 61 MWh per year obtainable at zero capital cost. For the North Building one

finds, by applying the COP correction to Table 6.2, a corresponding saving of 125 MWh. These savings are 6 and 9%, respectively, of the total energy consumption. For both buildings combined they would be worth about 13,000 \$ per year at 6.8 c/kWh and 20,000 \$ at 11 c/kWh.

In addition to these changes in operating mode we have evaluated one possible equipment modification: a change in fan control from the present variable inlet vane to variable speed drive. The savings, listed as item (3) in Table 6.2, are predicted to be 73 MWh per year for the South Building. Variable speed drives are a new technology, and their cost is coming down as the market is growing. This looks promising as a potential retrofit for the future.

For a more detailed analysis of the ENERPLEX the reader is referred to Norford [1984]. This reference includes an analysis of thermal mass, an examination of the differences between the bin method and DOE2.1, and a thorough evaluation of different operating strategies.

7. SUMMARY OF WORK UNDER THIS CONTRACT

The design of the instrumentation and data acquisition system (task 1 of proposal), the shorthand analysis (task 3) and the analysis with DOE2.1 (task 4) are complete. The installation of the instrumentation and data acquisition system system (task 2) was funded by the Prudential share of the contract. Prudential specified TORCON (the general contractor for the ENERPLEX construction) as manager of the installation subcontract. As of January 1, 1984, the subcontractor has installed the instrumentation hardware, the IBM PC microcomputer and the phone lines, and is completing

the software of the data acquisition system. The software for the analysis of the data at CEES has been written [Ryan 1984]. Data collection and analysis lie immediately ahead.

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Fig.1.1. The ENERPLEX buildings. South Building is on left, North Building on right (photo of scale model).

(a) South Building

(b) North Building

Fig. 1.2. Plan view and cross section of South Building (a) and of North Building (b).

Fig.1.3. a) Schematic of variable air volume (VAV) space conditioning system.

VAV Fan-Powered Induction Box

Diagram of typical VAV box

Fig.1.3 b) VAV fan powered induction box.

Base Case Energy Consumption

Fig.1.4. The energy consumption of the South Building, by component,

versus time of year, calculated with DOE 2.1a.

Radiation Incident on Vertical South Facing Surface - Wisconsin and New Brunswick Data Bases

Fig.3.1. Average

solar radiation [in W/m^2] on south facing

vertical surface for all the available data bases. (Based on

separation of direct and diffuse radiation according to

algorithms in Duffie and Beckman [1980]). From PEG [1983].

MONTHLY SOLAR RADIATION BASED ON NEWARK WEATHER DATA

Fig 3.2. Average solar radiation on the principal surface orientations

[24 hr average, in W/m^2 ; to convert to J/m^2 per day multiply

by $24 \times 3,600$ sec; for English units note that

$1 MJ/m^2 = 88.055 BTU/ft^2$].

Fig.5.1. Energy terms for South Building during weekday occupied period, plotted versus ambient temperature.

Fig.5.2. Net heating/cooling load for South Building during weekday occupied period, plotted versus ambient temperature. The corresponding temperature histogram is shown at top.

a) Winter - call for heat

b) Winter - no call for heat

c) Summer - call for cooling

d) Summer - no call for cooling

Fig.5.3. Design operating modes of the double wall system.

Fig.5.4. Very simple steady state model of double wall.

Fig.5.5. The 31 nodes of the detailed thermal network for the atrium/double wall/storage pipe system (schematic, not drawn to scale). From PEG [1983].

Fig.5.6. Energy use in January with different operating strategies for double wall system, relative to static case. From PEG [1983].

Table 1.1. The major power consumers of the South Building.

<u>component</u>	<u>rated power [kW]</u>
<u>heating/cooling equipment</u>	
2 heat pumps	162.5 ^a
2 chilled water pumps	11.2
2 condenser water pumps	11.2
3 well water pumps	14.9
12 electric resistance heaters	69.0
total	268.8
<u>fans</u>	
2 central supply fans	75.0
2 central return fans	30.0
VAV induction box fans	42.0
total	147.0
<u>lights</u>	
office and core	132.0
corridors	20.0
atrium	22.0
parking lot and other outdoor	27.0
total	201.0
<u>office equipment</u>	
estimated average 5.4 W/m ² (0.5 W/ft ²)	53.0
<u>hot water</u>	
backup elec. resistance heater for solar	10.0
<u>elevators</u>	22.4
GRAND TOTAL	702.2

^aIn winter one heat pump operates, rated at 162.5 kW.
In summer two heat pumps operate, rated at 81 kW each.

Table 1.2. The basic input assumptions for the analysis of ENERPLEX.

a) construction and equipment

floor area	12,000 m ² (130,000 ft ²), divided into 5 conditioned zones (north, south, east, west, corridor) 602 m ² (6,500 ft ²) atrium, unconditioned																												
volume	46,000 m ³ (1.6 x 10 ⁶ ft ³) conditioned space, 7,300 m ³ (2.5 x 10 ⁵ ft ³) atrium																												
exterior facade	<table> <tr> <th></th><th colspan="2">conductance (UA)</th><th colspan="2">fraction of total</th></tr> <tr> <th></th><th>[kW/C]</th><th>[kBTU/hr F ft²]</th><th>area</th><th>conductance</th></tr> <tr> <td>opaque</td><td>3.3</td><td>6.2</td><td>0.63</td><td>0.27</td></tr> <tr> <td>glass</td><td>8.9</td><td>16.9</td><td>0.37</td><td>0.73</td></tr> <tr> <td>total</td><td>12.2</td><td>23.1</td><td></td><td></td></tr> </table>					conductance (UA)		fraction of total			[kW/C]	[kBTU/hr F ft ²]	area	conductance	opaque	3.3	6.2	0.63	0.27	glass	8.9	16.9	0.37	0.73	total	12.2	23.1		
	conductance (UA)		fraction of total																										
	[kW/C]	[kBTU/hr F ft ²]	area	conductance																									
opaque	3.3	6.2	0.63	0.27																									
glass	8.9	16.9	0.37	0.73																									
total	12.2	23.1																											
floor	carpet and pad on 0.1 m (4 inch) concrete slab																												
glazing	double glazing, different glass types in different portions. Venetian blinds with shading coefficient 0.6																												
lights	12.6 W/m ² (1.17 W/ft ²) in offices 13.9 W/m ² (1.29 W/ft ²) in corridors 36.9 W/m ² (3.43 W/ft ²) in atrium utilization reduced by daylighting and by schedule (see Table 4.1)																												
office equipment	5.4 W/m ² (0.5 W/ft ²) average																												
heating/cooling equipment	South Building: 2 ground water based heat pump/chillers, seasonal average COP (including auxiliary pumps) winter 2.18, summer 4.26. North Building: electric resistance heat, ice pond (5,000 tons ice net), electric compression chiller, COP 2.4.																												

b) Operation

occupancy	800 people, 8 am - 6 pm Mo - Fr, 252 workdays/yr		
		<u>occupied</u>	<u>unoccupied</u>
thermostat setting	winter	20 C (68 F)	14.4 C (58 F)
	summer	25.6 C (78 F)	floating
infiltration	offices	0	0.2
[air changes/hr]	atrium & corridors	1 (door openings)	0.2
outdoor air intake	minimum	9.4 m ³ /s (20,000 cfm) {= 0.7 air change/hr which corresponds to (UA)-value of 11.4 kW/C (21.6 kBTU/hr F)}	0
	maximum	56.5 m ³ /s (120,000 cfm)	0
supply air flow	minimum	23.9 m ³ /s (51,000 cfm)	0
	maximum	56.5 m ³ /s (120,000 cfm)	0
supply air temperature	12.8 - 14.4 C (55 - 58 F)		

Table 1.3. Annual energy consumption of ENERPLEX (base case, and including COP of equipment).

a) South Building

component	annual energy consumption			
	total building	per floor area		fraction of total
	[MWh]	[MJ/m ²]	[BTU/ft ²]	[%]
heating	156	46.5	4,090	15
cooling	139	41.4	3,650	13
fans	263	78.4	6,900	25
lights	352	104.9	9,240	34
office equipment	134	39.9	3,520	13
<hr/>				
total	1,044	311.	27,400	100

b) North Building

component	annual energy consumption			
	total building	per floor area		fraction of total
	[MWh]	[MJ/m ²]	[BTU/ft ²]	[%]
heating	340	101.3	8,930	25
cooling	247	73.6	6,480	19
fans	263	78.4	6,900	20
lights	352	104.9	9,240	26
office equipment	134	39.9	3,520	10
<hr/>				
total	1,336	398.	35,070	100

Table 2.1. The fixed instrumentation system. The electric meters record both kW and kWh; their number will depend on the number of tenants.

type	North Building	South Building
ambient	1 dry bulb temperature 1 wet bulb temperature 5 pyranometers (insolation on horizontal, E, W, N and S facades) 1 wind speed	
indoor	5 temperatures (zones: E, W, N, S, interior) 1 humidity	5 temperatures (zones: E, W, N, S, interior) 1 humidity
HVAC equipment	2 chillers: kW, chilled water T_{out} 2 chilled water pumps: run time HX: flow rate, T_{in} and T_{out} (all on building side), T_{in} and T_{out} (ice pond side) 2 supply fans: kW and flow 2 return fans: kW and flow 2 return air to mixing plenum: flow 1 supply air temperature 1 return air temperature	2 chiller/heat pumps: kW 3 ground water pumps: run time 8 temperatures (for each heat pump: T_{supply} and T_{return} , both cold and hot) HX: well water flow and 4 temperatures 2 supply fans: kW and flow 2 return fans: kW and flow 2 return air to mixing plenum: flow 1 supply air temperature 1 return air temperature
Electricity	lights: kW equipment: kW electric heat: kW 1 total building electricity: kW	lights: kW equipment: kW 1 total building electricity: kW
atrium	2 temperatures (top and bottom)	2 temperatures (top and bottom)
double wall/underground pipes	8 temperatures (pipes: in and out; E, W, and N walls: top and bottom) 1 double wall fan: kW 1 bypass damper: on/off	

Table 3.1. Monthly average solar heat gain through principal facades. From

PEG [1983].

(a) South Building.

SOLAR HEAT GAIN FACTORS*													(Btu/af-day)
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
HORIZ. (Newark THY)	348	792	1142	1462	1797	1827	1766	1561	1602	952	579	480	
North Vertical	137	200	287	386	521	567	536	422	326	231	148	121	
East Vertical	287	418	546	692	848	842	821	720	647	491	293	261	
South Vertical	717	775	771	670	627	592	593	637	753	843	684	693	
West Vertical	287	418	546	692	848	842	821	720	647	491	293	261	
South Sloping	802	935	1059	1078	1129	1077	1071	1073	1102	1056	782	759	
North Sloping	166	242	348	502	814	944	868	601	394	276	180	146	
Overhang Factors: (for S. skylights)	.82	.74	.64	.55	.59	.65	.63	.54	.59	.71	.8	.84	
SOLAR HEAT GAIN													(kBtu/day)
PERIMETER:	SCxA ⁺	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
w/ blinds @ .6													
North	2642	217	317	455	612	826	899	850	669	517	366	235	192
East	1158	199	291	379	481	589	585	571	500	450	341	204	181
F1 1 So. Int	1167	502	543	540	469	439	415	415	446	527	590	479	485
F 2&3 So. Int	802	386	450	509	518	543	518	515	516	530	508	376	365
So. Clr	1541	608	640	626	548	616	647	624	536	601	693	578	589
West	1158	199	290	379	481	589	585	570	500	450	341	204	181
Total		2112	2530	2890	3109	3602	3649	3545	3167	3074	2840	2075	1994
LIGHT SLOT:													
North	2252	374	545	784	1131	1833	2126	1955	1353	887	622	405	329
South	1794	1055	1029	885	661	664	690	670	617	797	1074	982	1044
TOT NON-ATR:		3540	4104	4559	4901	6099	6465	6170	5138	4759	4535	3462	3367
ATRIUM:													
North	2731	374	546	784	1054	1423	1548	1464	1152	890	631	404	330
S. Sky	3266	1920	1873	1612	1204	1208	1257	1220	1123	1451	1955	1787	1901
Total		2294	2419	2395	2258	2631	2805	2684	2276	2341	2586	2191	2232
TOTAL BLDG:		5835	6523	6954	7159	8730	9270	8854	7414	7100	7121	5654	5599

+ Note: SCxA values do not include blinds,
which are accounted for separately.
A in ft².

Conversion factors:

$$1 \text{ BTU/ft}^2 = 0.315 \text{ W/m}^2$$

$$1 \text{ kBtu/day} = 29.3 \text{ W}$$

where a day is considered to be 10 hours

* A solar heat gain factor is the solar gain (via transmission and absorption) through a single pane of reference glass.

(b) North Building.

Monthly Solar Gain Breakdown — ENERPLEX NORTH BUILDING

S O L A R H E A T G A I N F A C T O R S (Btu/sf-day)												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
HORIZ.(Newark TMY)	548	792	1142	1462	1797	1827	1766	1561	1602	952	579	480
North Vertical	137	200	287	386	521	567	536	422	326	231	148	121
East Vertical	287	418	546	692	848	842	821	720	647	491	293	261
South Vertical	717	775	771	670	627	592	593	637	753	843	684	693
West Vertical	287	418	546	692	848	842	821	720	647	491	293	261
South Sloping	671	860	1100	1270	1460	1444	1412	1314	1203	1004	677	615
North Sloping	183	303	563	916	1275	1362	1291	1037	707	381	202	160
OVERHANG and EFFECTIVE SHADING COEFFICIENTS												
Atrium top gl	.58	.67	.56	.35	.54	.61	.44	.48	.50	.47	.72	.76
mid gl	.66	.69	.68	.45	.61	.60	.49	.66	.68	.66	.69	.69
bot gl	.95	.94	.93	.92	.94	.94	.94	.95	.95	.95	.95	.95
Double Wall E & W	.38	.40	.37	.38	.37	.37	.38	.38	.37	.37	.38	.38
with blinds North	.50	.50	.50	.50	.49	.49	.49	.50	.50	.50	.50	.50
Light Slot, South	.49	.42	.34	.27	.23	.22	.25	.33	.42	.50	.52	.53
& Atrium North	.41	.39	.29	.22	.19	.21	.25	.24	.26	.31	.51	.56
T R A N S M I T T E D R A D I A T I O N (KBtu/day)												
PERIMETER: AREA*	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
(DoubleWall)												
East 6000	654	1003	1212	1578	1883	1869	1872	1642	1436	1090	668	595
West 6000	654	1003	1212	1578	1883	1869	1872	1642	1436	1090	668	595
North 11250	771	1125	1614	2171	2872	3126	2955	2374	1834	1299	833	681
Total	2079	3131	4039	5327	6637	6864	6698	5657	4706	3479	2169	1871
LIGHT SLOT:												
South 2461	809	889	920	844	826	782	869	1067	1243	1235	866	802
North 2461	183	290	397	503	598	693	788	623	458	293	256	219
TOT NON-ATR:	3071	4310	5356	6674	8062	8339	8355	7347	6408	5008	3291	2892
ATRIUM:												
South 5247	1725	1895	1962	1799	1762	1667	1852	2275	2651	2634	1847	1710
North 5247	389	616	844	1071	1273	1475	1677	1326	974	623	545	467
South,top 3375	1404	1752	1457	791	1143	1219	881	1032	1271	1337	1662	1778
South,mid 3375	1597	1805	1769	1018	1291	1199	981	1419	1728	1878	1593	1614
South,bot 3375	2299	2459	2420	2080	1989	1878	1881	2042	2414	2703	2193	2222
TOTAL ATR.	7414	8527	8453	6760	7458	7438	7272	8094	9038	9175	7840	7791
TOTAL BLDG:	10485	12837	13809	13434	15519	15777	15627	15442	15446	14183	11131	10683

* area in ft²

Table 3.2. Frequency distribution of temperature data for Newark
(from TMY weather tapes).

TEMPERATURE midpoint [C]	BINS range [F]	WEEKDAYS (daytime) [hrs/yr]	WEEKEND (daytime) [hrs/yr]	NIGHT [hrs/yr]	TOTAL [hrs/yr]
36.1	95-99	3	1	0	4
33.3	90-94	16	7	0	23
30.6	85-89	141	63	12	216
27.8	80-84	219	98	87	404
25.0	75-79	228	102	233	563
22.2	70-74	228	103	527	858
19.4	65-69	230	104	562	896
16.7	60-64	200	90	523	813
13.9	55-59	125	56	440	621
11.1	50-54	184	82	352	618
8.3	45-49	207	93	396	696
5.6	40-44	201	90	482	773
2.8	35-39	212	95	524	831
0.	30-34	194	87	436	717
-2.8	25-29	79	35	278	392
-5.6	20-24	39	17	144	200
-8.3	15-19	14	6	98	118
-11.1	10-14	1	0	12	13
-13.8	5-9			4	4
-16.7	0-4				0

Table L.1. Annual electricity use for lighting.

Space	Installed power kW	Weekday consumption		Weekend day		Night ¹		Total	
		kW	kWh	kW	kWh	kW	kWh	kW ²	kWh
Office & core	132	96.2 ³	242500	2.0	2300	2.0	10300	29.1	255100
Corridor	20 ⁴	4.1	10300	1.2	1400	6.4	32500	5.0	44200
Atrium	22 ⁴	4.4	11100	1.6	1800	8.1	41200	6.2	54100
Building total	174	104.7	263900	4.9	5500	16.4	84000	40.3	353400
Parking lot & other outdoor lights	27 ⁴	0	0	0	0	13.5 ⁵	69000	7.9	69000
Grand total	201	104.7	263900	4.9	5500	29.9	153000	48.2	422400

¹ Night is defined as the 14-hour period from 1800 to 0800; this is the complement of the 10-hour occupied period.

² The average power in kW is obtained by dividing the total kWh by 8760 hours/year.

³ The weekday power level is based on a 29 percent reduction in office lights due to daylighting.

⁴ The power level may be reduced in practice by use of a dimming system.

⁵ These outdoor lights are assumed to operate an equivalent of 7 full-strength hours per night.

Table 5.1. Results of bin method analysis for South Building during weekday occupied period.

59

Ambient Temperature			Conduction and Infiltration	Ventilation Sensible Gain	Ventilation Latent Gain	People Gain	Lights	Office Equipment	Sol-Air Gain	Solar Gain	Fan KW	Econoo. Heat Reject.	BIN TOTAL Day	NET BIN TOTAL WITH ECONO.	Temp Dist.	NET ENERGY LOAD
C	F	Tout-Tin	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW	BW	hrs/yr	kWH/yr
34	97	19	129	120	82	104	102	53	6	226	105	0	930	930	3	2789
33	92	14	95	89	110	103	102	53	5	205	105	0	867	867	16	13871
31	87	9	61	57	82	102	102	53	5	206	101	0	770	770	101	168596
28	82	4	27	25	68	101	102	53	5	203	98	0	682	682	219	149375
25	77	-1	-7	-6	61	99	102	53	5	198	94	0	590	590	220	136466
22	72	-6	-48	-38	53	98	102	53	4	190	91	0	513	513	228	116880
19	67	-11	-79	-70	0	97	102	53	4	185	87	0	385	385	230	88657
17	62	-16	-109	-101	0	96	102	53	4	176	87	0	308	308	200	61662
14	57	-16	-109	-101	0	60	102	53	3	172	87	161	260	107	175	13383
11	52	-16	-109	-101	0	60	102	53	3	160	87	256	256	0	184	0
8	47	-21	-142	-133	0	60	102	53	2	151	87	181	181	0	207	0
6	42	-26	-176	-165	0	60	102	53	2	147	87	110	110	0	201	0
3	37	-31	-210	-196	0	60	102	53	2	143	87	41	41	0	212	0
0	32	-36	-244	-228	0	60	102	53	1	139	87	0	-29	-29	194	-5611
-3	27	-41	-277	-259	0	60	102	53	1	138	87	0	-96	-96	79	-7553
-6	22	-46	-311	-291	0	60	102	53	1	137	87	0	-167	-162	39	-6321
-8	17	-51	-345	-323	0	60	102	53	1	137	87	0	-227	-227	14	-3181
-11	12	-56	-379	-354	0	60	102	53	1	151	87	0	-278	-278	1	-278

total net heating load -23 MWh/yr
total net cooling load 691 MWh/yr

Table 5.2. Results of bin method analysis for South Building during night.

Ambient Temperature		Conduction and Infiltration E2 Tin, cool Tin, heat	Sol-Air Gain	Ambient Lights	Fan KW Winter Heating	NET B19 TOTAL Night Setback	Temp Dist.	NET ENERGY LOAD
		58				58 F		58 F
C	F	kW	kW	kW	kW	kW	hrs/yr	kWh/yr
36	97	283	0	12	0	295	0	0
33	92	247	0	12	0	259	0	0
31	87	211	0	12	0	222	12	2668
28	82	174	0	12	0	186	87	16185
25	77	0	0	12	0	12	233	2713
22	72	0	0	12	0	12	527	6135
19	67	0	0	12	0	12	562	6543
17	62	0	0	12	0	12	523	6089
14	57	-7	0	12	0	4	440	1925
11	52	-44	0	12	2	-30	352	-10694
8	47	-80	0	12	3	-65	396	-25708
6	42	-116	0	12	5	-99	482	-47940
3	37	-153	0	12	7	-134	524	-70216
0	32	-189	0	12	9	-169	636	-73483
-3	27	-225	0	12	11	-203	278	-56456
-6	22	-262	0	12	12	-238	144	-34217
-8	17	-298	0	12	14	-272	98	-26672
-11	12	-334	0	12	16	-307	12	-3680
-14	7	-371	0	12	18	-341	4	-1365
-17	2	-407	0	12	19	-376	0	0

total net heating load -351 MWh/yr

total net cooling load 42 MWh/yr

Table 5.3. Results of bin method analysis for South Building during weekend day.

Ambient Temperature		Conduction and Infiltration 82 °F in, cool T in, heat	Sol-Air Gain	Ambient Lights	Fan KW Winter Heating	Solar Gain, Includes	NET BIN TOTAL Night Setback	Temp Dist.	NET ENERGY LOAD
		58 F					58 F		58 F
C	F	Btu	Btu	Btu	Btu	Btu	Btu	hrs/yr	kWh/yr
36	97	283	6	4	0	222	516	1	516
33	92	247	5	4	0	202	458	7	3206
31	87	211	5	4	0	203	424	63	26681
29	82	174	5	4	0	200	384	90	37596
25	77	0	5	4	0	195	204	102	20801
22	72	0	5	4	0	187	196	103	20170
19	67	0	5	4	0	182	191	104	19839
17	62	0	4	4	0	173	180	90	16229
14	57	-7	3	4	0	169	169	56	9470
11	52	-44	3	4	0	157	120	82	9864
8	47	-80	2	4	0	148	75	93	6934
6	42	-116	2	4	0	144	33	90	2996
3	37	-153	2	4	0	140	-7	95	-646
0	32	-189	1	4	2	136	-45	87	-3954
-3	27	-225	1	4	4	135	-81	35	-2836
-6	22	-262	1	4	6	134	-116	17	-1978
-8	17	-298	1	4	7	134	-151	6	-903
-11	12	-334	2	4	9	149	-171	0	0

total net heating load -10 MWh/yr

total net cooling load 174 MWh/yr

Table 5.4. Summary of annual heating and cooling loads from annual bin method, base case (excluding COP). Note that bin method does not predict correct day/night split of loads.

	HEATING		COOLING	
	[MWh/yr]	[MJ/m ² -yr]	[MWh/yr]	[MJ/m ² -yr]
weekday	23	7	691	206
weekend day	10	3	0	0
night	351	104	0	0
total	474	114	691	206

Table 5.5. Comparison of different predictions for heating and cooling loads of South Building (building loads, excluding COP).

<u>method</u>	<u>heating</u>		<u>cooling</u>	
	[MJ/m ² -yr]	difference ^e	[MJ/m ² -yr]	difference ^e
NBSGLD ^a	78	-23%	122	-31%
NBSGLD emulator ^b	95	-6%	145	-18%
DOE2.1a ^c	101		177	
bin method monthly ^d	103	+2%	204	+15%
bin method annual ^d	114	+13%	206	+16%

notes:

^a calculation by D. Nall during design of ENERPLEX (Aug.1981), using NBSGLD computer program.

^b an attempt to follow, as much as possible, the same assumptions as used by D. Nall, but with DOE2.1a.

^c system as built, modeled with DOE2.1a.

^d steady state bin method described in Section 5.1.

^e difference relative to system as built, modeled with DOE 2.1a.

Table 6.1. Variation of annual energy consumption with comfort conditions as predicted by DOE2.1a for South Building (for North Building multiply by COP ratio: 2.18/1.0 for heating, 4.26/2.4 for cooling). ** designates base case, change designates change relative to base case.

(a) heating season - thermostat setpoint

	heating energy		change
T [C] ([F])	[MWh]	[MWh]	
18.3 65	131	-25	
** 20.0 68	156		
21.1 70	176	+20	

(b) heating season - minimum outdoor air flow rate

	heating energy		change
flow [m ³ /s] [cfm]	[MWh]	[MWh]	
** 9.4 20,000	156		
2.0 5,000	155	-1	

(c) cooling season - thermostat set point

	cooling energy		change
T [C] ([F])	[MWh]	[MWh]	
27.2 81	133	-6	
** 25.6 78	139		
23.9 75	145	+6	
22.2 72	151	+12	

(d) cooling season - minimum outdoor air flow rate

	cooling energy		change
flow [m ³ /s] [cfm]	[MWh]	[MWh]	
** 9.4 20,000	139		
2.0 5,000	136	-3	

Table 6.2. Energy savings predicted by DOE2.1a for the South Building, for changes that do not affect comfort conditions. (For North Building multiply by COP ratio: 2.18/1.0 for heating, 4.26/2.4 for cooling).

	heating [MWh]	cooling [MWh]	fans [MWh]	total [MWh]
base case	156	139	263	567
<u>savings relative to base case</u>				
(1) supply air temperature raised from 12.8 to 15.6 C (55 to 60 F)	-21	-34	+5	-50
(2) winter night temperature lowered from 14.4 to 12.8 C (58 to 55 F)	-11	0	0	-11
(3) fan control changed from variable inlet vane to variable speed drive	+2	-9	-66	-73
(1) and (2) above	-32	-34	+5	-61
(1) and (3) above	-16	-40	-53	-109
(1), (2) and (3) above	-27	-40	-53	-120