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COMMERCIAL BUILDING UNITARY HEAT PUMP SYSTEM WITH SOLAR HEATING

Final Report, May 1, 1976—October 31, 1977

By
E. E. Drucker
M. Ucar
J. E. LaGraff

May 1978

MASTER

Work Performed Under Contract No. EY-76-S-02-2979

Syracuse University
Syracuse, New York

U.S. Department of Energy

Solar Energy

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SYRACUSE, NEW YORK 13210

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Prepared for

THE U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. E(11-1)-2979

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SYRACUSE UNIVERSITY - PROGRESS REPORT

May 1, 1976 - May 1, 1977.

Commercial Building Unitary Heat Pump System
with Solar Heating
EY-76-S-02-2979

MAJOR CONCLUSIONS OF THE STUDY

- 1) For commercial buildings in the 100,000 ft² area class, collector areas equal to 5 to 15% of the building area only are feasible.

In the case of very large hot water demand, larger collectors may be justified.
- 2) Very large water storage volumes are cost effective. Ratios as high as 40 lb. of water per square foot of collector are economic in moderate climates and 60 in areas with colder climate.
- 3) Since collector cost increases almost linearly with size, but the rate of increase of useful energy collected decreases sharply with size, the cost/benefit ratio increases with collector size. There is no optimum collector size from an economic point of view, except perhaps for trivially small collectors.
- 4) The attractiveness of solar assisted heat pump systems for heating is greatest in the colder climates, where despite lower collector efficiencies, the total amount of solar energy actually used is maximized.
- 5) The solar assisted heat pump system virtually removes the necessity for auxiliary heat at very low collector area to floor area ratios.
- 6) The system, with large storage volume, is capable of maintaining space conditions over periods of several cloudy days. The yearly performance of the system does not change appreciably when random cloud cover sequences are substituted for a uniform cloud cover equal to the average of the random sequences.
- 7) The system performance is not highly dependent upon collector orientation or angle of inclination.

- 8) For a system with collectors sized for commercially available heat pumps, an improvement in the COP of the heat pumps does not reduce significantly the total electrical energy consumption. To achieve an overall reduction, the collector area must increase.
- 9) For the purpose of generating domestic hot water, a water-to-water heat pump with storage water as the source, is highly cost effective relative to electric resistance heating.
- 10) It is essential to do multi-zone analysis of a larger building since there may be appreciable amounts of heating and cooling done simultaneously, even though the net thermal load on the building may be small or zero.
- 11) Dry bulb and dew point temperature data for any particular city may be accurately represented by sinusoidal temperature functions (with harmonics). These functions predict average monthly temperatures with an average error of less than 0.5F.
- 12) Using empirical single glazed collector efficiency data, simulation runs for a whole system produce seasonal efficiencies for heat collection of the order of 60%. That this could be achieved in a Northern climate illustrates the effectiveness of the low temperature water loop system.
- 13) Ventilation heat recovery systems can save a considerable amount of energy only if proper control logic is used.
- 14) Desiccant dehumidification systems, with solar heat regeneration, reduce the required electrical energy for heat pump cooling. Secondly, dehumidification permits a higher interior dry bulb temperature for a given comfort level. However, more work needs to be done in this area.
- 15) High intensity uniform lighting is very wasteful. Natural sunlight and

task lighting should be used as much as possible to cut down energy consumption for lighting and cooling.

- 16) The stratification effects in the main storage tank are negligibly small. Therefore, it is concluded that the main storage tank can be assumed to be perfectly mixed.
- 17) High ventilation rates are very detrimental to energy conservation.

TABLE OF CONTENTS

	<u>Page</u>
I. ABSTRACT	1
II. INTRODUCTION	2
III. TECHNICAL TASKS	4
A. Generalized Temperature Functions	4
B. Domestic Hot Water Production	9
C. Stratified Storage Tank	13
D. New Heat Pump Heating Model	14
E. Experimental Improvements on a Heat Pump	17
F. Full Year Simulation	20
G. Solar-Regenerated Desiccant Dehumidification	24
H. Effect of Sunny and Cloudy Day Sequences	25
I. Effect of Random Temperature Fluctuations	31
J. Effect of High Lighting Levels	36
K. Effects of Solar Collector Orientation and Inclination	38
L. Comparison of Three Collectors	42
M. Effect of Ventilation Heat Recovery	45
N. Effect of Internal Load Variations	47
O. Residential High Rise Building Model	52
IV. REFERENCES	60
V. APPENDIX	61

I. ABSTRACT

A generalized dynamic computer program (SYRSOL) has been developed for the mathematical simulation of the thermal behavior of multi-zone solar heated buildings. The system modeled employs a series of water-to-air heat pumps connected in a closed loop, flat-plate liquid cooled solar collector, a water storage tank, and a cooling tower. Weather data are represented by sinusoids, which provide a convenient and economical alternative to weather tapes. Results indicate that the use of sinusoidal functions for temperature and monthly average values for cloud cover is quite realistic and accurate. Temperature functions for thirteen cities are presented. A preliminary analysis has been done of the feasibility of using solar-energized desiccant dehumidification systems to reduce summer cooling loads. Service hot water production using a water-to-water heat pump from the storage tank is shown to be highly effective and idle solar collectors can be used directly to make service hot water in the summer. A new mathematical heat pump heating model, in which the COP increases linearly with the source water temperature, has been developed and incorporated into SYRSOL. The computer simulation capability has been extended from a heating season to an entire year. The results of some experiments, that have improved the COP of a heat pump, are also reported.

II. INTRODUCTION

Several years ago, technological developments in small heat pumps and solar energy collectors reached a level of potential feasibility for HVAC systems built up of these components. The rapidly rising costs of energy made these systems economically attractive for certain classes of buildings.

A research team composed of Syracuse University, and architect/engineer firm and a heat pump manufacturer conducted a study of a closed loop, decentralized water-to-air heat pump system augmented by solar collectors for space and water heating. The system soon became recognized by ERDA as one of the more promising ones for the early utilization of solar energy in commercial, institutional and multi-family residential structures. An outcome of the study was a versatile computer program, SYRSOL, for predicting the performance of these systems which have become known as solar assisted heat pump systems. Several types of buildings have been analyzed in ten different climates using the computer program. A schematic drawing of the basic solar assisted heat pump loop appears in Figure 1. The results of the various analyses made have been presented in a series of reports and papers (References 1-7). The most recent results and plans for the remaining portion of the contract period are described in the body of this report.

FIGURE 1 : SCHEMATIC OF TYPICAL SOLAR ASSISTED CLOSED LOOP UNITARY HEAT PUMP SYSTEM

III. TECHNICAL TASKS

A. Generalized Temperature Functions

In the modeling and optimization of solar buildings it is necessary to employ representations of the weather conditions. When the purpose of the analysis is to predict the energy consumption of a building in a previous year, then one could use the measured weather data for that year. However, when the purpose is to predict the future energy consumption of a building, then one is faced with the problem of determining a "typical or expected weather year". Such an "expected weather year" can be presented in the form of expected hourly values of weather parameters (dry-bulb temperature, wet-bulb temperature, relative humidity, wind speed, insolation, etc.) for the 8760 hours of a year, stored on a magnetic computer tape.

Generalized weather functions have been developed consisting of sinusoids derived from long-term records of weather data. These generalized weather functions are used in the Solar Building Energy Analysis Program (SYRSOL) in place of magnetic tapes of a single year's weather or tapes of an "expected weather year".

Wind speed has been treated as a constant because of its erratic or random nature. The cloud cover data is represented in terms of a "cloud cover modifier" defined as the ratio of measured insolation to clear-sky insolation. The resulting cloud cover modifiers consist of 12 constants, one for each month of the year (Table II).

The generalized weather functions provide an alternative to the weather tapes. These functions have the following significant advantages over the tapes:

- 1) They represent the average of many years of weather data.

- 2) They can be derived once and for all.
- 3) They make programming easier and cheaper.
- 4) They eliminate the need for computer tape drives, thus enabling the user to run his/her program on very small computer installations (such as mini-computers) in the absence of a powerful computer system.
- 5) They reduce the residence time of the program in the computer core, thus providing much shorter turn-around times.
- 6) They generally reduce the cost of computing.
- 7) Weather functions, once derived, cost little to use.

These functions are very concise and easily communicated equivalents of costly magnetic tapes. Weather tapes would have cost over \$1,000 for the thirteen cities for which we present these functions.

- 8) Lastly, weather functions are simply more convenient to use.

The detailed derivation of these functions has already been presented in an ASME paper.² The present report provides the most up-to-date version of the temperature functions with the necessary coefficients listed in Table I.

The following equations predict the dew point temperature, daily temperature swing, and dry bulb temperature and are readily applicable in the FORTRAN IV language:

DPT = DEW POINT TEMPERATURE (C)

$$DPT = T_0 + T_1 \cos(OY) + T_2 \sin(OY) + T_3 \cos(2 \cdot OY) + T_4 \sin(2 \cdot OY)$$

TAS = DAILY TEMPERATURE SWING (C)

$$TAS = T_5 + T_6 \cos(OY) + T_7 \sin(OY) + T_8 \cos(2 \cdot OY) + T_9 \sin(2 \cdot OY)$$

TABLE I: COEFFICIENTS FOR WEATHER FUNCTIONS

NAME OF THE CITY : WASHINGTON, DC	LATITUDE=38.85				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	7.5250	-10.8600	-4.3860	0.0052	0.5418
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	9.8070	-3.7410	0.2470	-0.7620	-0.4970
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	13.9600	-11.3500	-3.8490	-0.1860	0.1580
NAME OF THE CITY : BOSTON, MA	LATITUDE=42.22				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	4.8950	-10.5100	-4.7800	0.0016	0.8623
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	9.5850	-1.2350	0.1950	-0.1420	-0.3140
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	9.3330	-11.4700	-4.9810	-0.2600	-0.1480
NAME OF THE CITY : MINNEAPOLIS, MN	LATITUDE=45.00				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	2.2430	-12.5200	-5.1200	-0.0994	0.6504
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	12.0100	-1.3080	-0.0910	-0.3450	0.0910
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	6.6770	-14.1500	-5.1510	-0.9750	-0.4120
NAME OF THE CITY : FRESNO, CA	LATITUDE=36.77				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	5.8730	-3.7970	-1.7310	-0.6032	0.3451
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	16.1300	-3.9620	-1.9330	-1.0740	0.0800
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	16.9200	-4.9440	-3.0840	-0.5700	1.1470
NAME OF THE CITY : INDIANAPOLIS, IN	LATITUDE=39.73				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	6.7250	-11.0900	-3.5900	-0.0246	0.4330
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	11.0400	-1.4420	-0.7340	-0.8450	-0.1490
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	11.2200	-12.5900	-4.3470	-0.4590	0.2990
NAME OF THE CITY : KANSAS CITY, MO	LATITUDE=39.01				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	6.9990	-11.4600	-3.9610	-0.0503	0.8504
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	10.8300	-0.4090	-0.3180	-1.0210	-0.0740
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	13.4900	-13.1900	-4.5270	-0.5880	0.4650
NAME OF THE CITY : BINGHAMTON, NY	LATITUDE=42.10				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	4.7500	-10.5700	-3.8000	0.2827	0.5013
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	10.8200	-2.2480	-0.3830	-0.4980	-0.0910
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	5.4100	-12.1900	-4.6800	-0.1070	-0.3170
NAME OF THE CITY : BUFFALO, NY	LATITUDE=42.93				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	4.4410	-10.2300	-4.6420	0.4224	0.5872
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	9.5500	-2.5080	-0.5830	-0.4420	-0.0670
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	8.0000	-12.2500	-5.4520	-0.0680	-0.1990
NAME OF THE CITY : NEW YORK CITY, NY	LATITUDE=40.78				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	6.8470	-9.6740	-4.8690	-0.2280	0.9863
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	9.5950	-1.4220	0.0110	-0.3640	-0.1780
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	12.5700	-11.5100	-4.8990	-0.1380	-0.0290
NAME OF THE CITY : CLEVELAND, OH	LATITUDE=41.40				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	4.8410	-10.6250	-3.9810	0.1154	0.6026
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	10.7800	-2.1900	-0.4820	-0.8610	-0.4970
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	9.4220	-11.8900	-4.3980	-0.6970	0.0830
NAME OF THE CITY : CHARLESTON, SC	LATITUDE=32.90				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	13.5700	-8.2730	-3.1420	-0.2986	0.8453
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	11.8600	1.0220	0.6000	-0.3390	-0.8500
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	13.3900	-8.6280	-2.5990	-0.3560	0.4860
NAME OF THE CITY : DALLAS, TX	LATITUDE=32.85				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	11.2600	-9.6100	-2.4450	-0.1695	0.2160
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	11.3500	0.3370	-0.1480	-0.6640	-0.1060
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	18.8000	-10.6000	-3.3630	-0.5750	0.7530
NAME OF THE CITY : SEATTLE, WA	LATITUDE=47.60				
DEW POINT CONSTANTS (T0,T1,T2,T3,T4)=	5.6180	-4.3190	-2.5570	-0.4263	-0.1107
DAILY SWING CCNSTS (T5,T6,T7,T8,T9)=	7.5770	-2.7590	-0.0310	-0.2320	0.3390
DRY-BULB CCNST (T10,T11,T12,T13,T14)=	11.8100	-6.2370	-2.3630	-0.1400	0.5300

TABLE II: CLOUD COVER MODIFIERS

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
* * * * * WASHINGTON , DC * * * * *											
0.694	0.674	0.692	0.714	0.729	0.780	0.760	0.737	0.764	0.750	0.699	0.686
* * * * * BOSTON , MA * * * * *											
0.735	0.689	0.689	0.687	0.722	0.752	0.733	0.733	0.736	0.730	0.635	0.705
* * * * * MINNEAPOLIS , MN * * * * *											
0.899	0.893	0.831	0.709	0.700	0.726	0.729	0.784	0.732	0.713	0.653	0.720
* * * * * FRESNO , CA * * * * *											
0.642	0.744	0.839	0.896	0.936	0.980	0.980	0.974	0.953	0.908	0.795	0.617
* * * * * INDIANAPOLIS , IN * * * * *											
0.616	0.619	0.641	0.674	0.799	0.774	0.777	0.780	0.802	0.774	0.640	0.635
* * * * * KANSAS CITY , MO * * * * *											
0.565	0.533	0.620	0.643	0.752	0.780	0.780	0.770	0.740	0.702	0.517	0.564
* * * * * BINGHAMTON , NY * * * * *											
0.575	0.629	0.619	0.625	0.705	0.746	0.755	0.729	0.721	0.662	0.471	0.507
* * * * * BUFFALO , NY * * * * *											
0.565	0.533	0.620	0.643	0.752	0.780	0.780	0.770	0.740	0.702	0.517	0.564
* * * * * NEW YORK CITY , NY * * * * *											
0.560	0.584	0.614	0.624	0.635	0.661	0.662	0.624	0.661	0.648	0.556	0.558
* * * * * CLEVELAND , OH * * * * *											
0.565	0.533	0.620	0.643	0.752	0.780	0.780	0.770	0.740	0.702	0.517	0.564
* * * * * CHARLESTON , SC * * * * *											
0.765	0.735	0.724	0.709	0.795	0.777	0.752	0.768	0.736	0.784	0.804	0.762
* * * * * DALLAS , TX * * * * *											
0.773	0.761	0.794	0.773	0.818	0.893	0.881	0.913	0.884	0.892	0.828	0.797
* * * * * SEATTLE , WA * * * * *											
0.456	0.483	0.605	0.651	0.668	0.680	0.746	0.752	0.711	0.573	0.502	0.463

DBD = DAILY AVERAGE DRY BULB TEMPERATURE (C)

$$DBD = T_{10} + T_{11} \cdot \cos(OY) + T_{12} \cdot \sin(OY) + T_{13} \cdot \cos(2 \cdot OY) + T_{14} \cdot \sin(2 \cdot OY)$$

AMP = AMPLITUDE OF DAILY SWING (C)

$$AMP = TAS / (2 \cdot 1.115)$$

DBH = HOURLY DRY BULB TEMPERATURE (C)

$$DBH = AMP \cdot [\sin(OZ) + 0.2706 \cdot \sin(2 \cdot OZ)]$$

DBT = INSTANTANEOUS DRY BULB TEMPERATURE (C)

$$DBT = DBD + DBH$$

WHERE $T_1, \dots, T_{14}$ = CONSTANT COEFFICIENTS GIVEN IN TABLE II:

$$OY = OM1 \cdot (DY - 0.5)$$

$$OM1 = \text{ANGULAR FREQUENCY} = 2 \cdot \pi / 365.$$

$$DY = \text{DAY OF THE YEAR} = 1.0, 2.0, \dots, 365.0$$

$$OZ = (OM2 \cdot I) - FZ$$

$$OM2 = \text{ANGULAR FREQUENCY} = 2 \cdot \pi / 24.$$

$$I = \text{HOUR OF THE DAY } 1, 2, 3, \dots, 24$$

$$FZ = \text{PHASE ANGLE} = 10.5 \cdot 2 \cdot \pi / 24.$$

* = MULTIPLICATION

/ = DIVISION

B. Domestic Hot Water

The existence of a large water storage tank in the water-source-heat-pump system described in this research made the possibility of its use as a source of energy for domestic hot water (DHW) of interest. Heating water from this source, which draws upon both solar inputs and heat rejected from some or all of the building zones, has obvious energy conserving advantages.

Two approaches to the production of DHW were evaluated in the simulation and compared to the energy requirements of the direct resistance heating mode common in buildings with this HVAC system. The first scheme involved the use of a water-to-water heat pump operating between the storage tank source and a smaller DHW tank. The performance of this heat pump was based on actual COP data for a commercial five-ton water chiller given as a function of evaporator entering water temperature (EWT) from the storage tank. The maximum COP value reached 3.87 for EWT above 60°F (15.6C). This value was limited because the temperature of DHW circulating through the condenser was held to 120°F (48.9C) for the heat pump chosen, due to compressor back pressure limits. Temperature topping to 140°F (60C) was accomplished by resistance heating. A characteristic water schedule was assumed for each building (1600 gallons/day for the school; 735 gallons/day for the office building). More descriptive details of this system can be found in Ref. 5.

The second approach to DHW heating involved direct solar heating of the water through a heat exchanger in the smaller tank during that portion of the year when solar collection capacity exceeded the auxiliary energy needs of the building. The example used for a representative comparison was for the Kay Office Building in New York City using

8000 ft² (743 m²) of collector area (6 months of excess collection capacity). Table III summarizes the electrical energy needs of each system. The resistance heating energy use and the combined heat pump/resistance energy are essentially independent of the geographical location and solar system size. This is due to the nearly constant COP of the heat pump in the temperature range of the tank. The system using some direct solar heating, however, does depend on the location and the collector size in that this determines the portion of the year when excess collection capacity exists. The collector size would normally be set by building heating economics independent of hot water economics.

The energy reduction of each system is significant. The rate of return on a capital investment in a water-to-water heat pump added onto an existing closed-loop-water-source system would be very attractive compared to resistance heating (2-3 year pay back, see Ref. 5). The savings by direct solar heating during the summer months would also certainly improve the cost effectiveness of the solar installation by utilizing excess collection capacity during one half of the year.

TABLE III

ELECTRICITY USE OF THE DOMESTIC HOT WATER SYSTEM (KILOWATT HOURS/YEAR, MINNEAPOLIS, MINN.)			
	RESISTANCE ONLY	HEAT PUMP + RESISTANCE (% REDUCTION)	HEAT PUMP + RESISTANCE + SOLAR DIRECT (% REDUCTION)
OFFICE	65,000	23,000 (65%)	12,000 (82%)
SCHOOL	133,000	56,000 (58%)	29,000 (78%)
RESIDENTIAL			
HIGH-RISE	1,229,000	535,000 (56%)	363,000 (70%)

Table IV and Fig. 2 indicate the amount of energy saved with a water-to-water heat pump for heating the domestic hot water.

SUBJECT: EFFECT OF USING A WATER-TO-WATER HEAT PUMP FOR HEATING THE DOMESTIC HOT WATER

REMARK: 4-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD COP.

LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (1 FULL YEAR)

OPERATIONAL MODE OF THE WATER-TO-WATER HEAT PUMP	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON
SOLAR COLLECTOR AREA (AP, ft ²)	0	0	10,000	10,000	30,000	30,000	50,000	50,000	50,000	70,000
THERMAL STORAGE WATER (WM, lb)	300,000	300,000	600,000	600,000	1,800,000	1,800,000	3,000,000	3,000,000	4,200,000	4,200,000
(1b OF WATER)/(ft ² COLLECTOR AREA)	0	0	60	60	60	60	60	60	60	60
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	50	50	50	50	50
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+0°	LAT+0°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	0	0	0	0	0
OUTPUT NUMBER	52 526	52 576	52 526	52 526	53 637	53 637	53 637	53 637	54 151	54 151
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	0	0	582,000	630,000	1,423,000	1,631,000	1,945,000	2,311,000	2,355,000	2,635,000
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0	0	0.363	0.392	0.295	0.339	0.242	0.288	0.210	0.234
AUXILIARY HEAT USED (TOX, kWh)	2,147,000	2,541,000	1,590,000	1,950,000	754,000	972,000	157,000	422,000	13,800	70,600
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	847,000	8,470,000	867,000	852,000	950,000	908,000	1,055,000	989,000	1,136,000	1,094,000
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	281,000	270,000	293,000	284,000	297,000	294,000	297,000	297,000	297,000	297,000
NET HEATING LOAD (QNHT, kWh)	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000
NET COOLING LOAD (QNCT, kWh)	526,000	526,000	526,000	526,000	526,000	526,000	526,000	526,000	526,000	526,000
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	0	629,000	0	653,000	0	677,000	0	694,000	0	708,000
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	1,230,000	601,000	1,230,000	577,000	1,230,000	552,000	1,230,000	535,000	1,230,000	521,000
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	17.75	17.10	16.45	15.62	14.57	13.28	13.33	12.08	13.18	11.43

TABLE IV

FIGURE 2: EFFECT OF USING A WATER-TO-WATER HEAT PUMP TO HEAT THE DOMESTIC HOT WATER

C. Stratified Storage Tank

Manufacturers of water source heat pumps generally recommend a flow rate of about 4.5 gpm (gallons per minute) for a two-ton-heating capacity unit. The school building modeled in this study has the equivalent of about 100 such units installed in parallel. The total water flow rate through all heat pumps is about 450 gpm, or 225,000 lb/hour. Typical heat pump installations have less than 225,000 lb of water storage. Even with storage capacity of 1,000,000 lb., which would require a cylindrical tank 36m long by about 2m in radius, the entire mass of storage water would be circulated through the heat pumps about once every four hours.

Therefore, it can be concluded that for storage tank volumes of the order of magnitude that we have been dealing with, temperature stratification in the tank will not be a significant effect. Should substantially larger volumes of water become attractive in the future for some other reason, and the tanks vertically oriented, then stratification should be reconsidered. Stratification experiments have been performed by the National Bureau of Standards, and it was indicated by Dr. James Hill that the results are consistent with our analysis. It should be noted that before this obvious but elusive characteristic of the storage system was noticed, considerable time was spent in studying the relevant literature, and developing several strategies to model the stratification phenomenon in tanks.

D. A New Heat Pump Heating Model

Theoretically, the coefficient of performance (COP) of a heat pump in the space heating mode should increase with source loop temperature. However, most commercially available heat pumps behave differently. Their COP increases up to a certain loop temperature (in our model about 21C or 70F), and then starts dropping. It is of considerable interest to know the consequences of this unexpected behavior (Figure 3).

A theoretical model has been developed for the space heating mode of water-to-air unitary reversible heat pumps. In this new model the COP is equal to the COP of the actual heat pump up to its maximum point. But when the actual COP starts dropping, the COP of the theoretical model keeps increasing linearly. Although heat pumps with this characteristic are not currently available, it is anticipated that market demand will provide the necessary incentive for manufacturers to develop them. There is no inherent reason for which these desirable heat pumps can not be built. They simply have not been built because conventional closed loop water temperatures do not rise above 80 to 90F in the heating season.

This new model has been added to the computer program SYRSOL. Henceforth both heat pump heating subroutines will be retained in SYRSOL. The user can choose one by specifying an index, MODHPH.

Some computer runs have been made for a comparison of this theoretical model with the model that describes an actual heat pump closely. The comparison is, of course, in terms of the total energy use of the building.

The results indicate that for a heat pump equipped building without solar collectors, the two heat pump models give virtually identical energy

use. This is not surprising because without solar heat loop temperatures rarely exceed 80°F, and stay mostly around 70°F in the heating season. At these temperatures the two models give identical COP's. With solar collectors, the effectiveness of the improved heat pump increases with collector area. Thus, with the better heat pumps, more collector area can be economically justified (Table V).

For an office building with 9294m² of floor area and about 1800m² of solar collector area the heat pumps with the ever-increasing COP reduce the building energy use by about 4%. This is a reduction of about 110,000 kWh/year which, at 0.04\$/kWh, represents savings of about 4400\$/year.

FIGURE 3: COMPARISON OF THE TWO HEAT PUMP HEATING MODES

SUBJECT: COMPARISON OF THE TWO HEAT PUMP HEATING MODELS								
REMARK: 1 = MANUFACTURER'S DATA; 2 = LINEARLY INCREASING COP DATA								
LOCATION: KAY OFFICE BUILDING IN MINNEAPOLIS, MINNESOTA								
PERIOD SIMULATED: JANUARY-DECEMBER (1 FULL YEAR)								
HEAT PUMP HEATING MODEL	1	2	1	2	1	2	1	2
SOLAR COLLECTOR AREA (AP, ft ²)	0	0	3,500	3,500	10,000	10,000	20,000	20,000
THERMAL STORAGE WATER (WM, lb)	200,000	200,000	210,000	210,000	600,000	600,000	1,200,000	1,200,000
(lb OF WATER)/(ft ² COLLECTOR AREA)	0	0	60	60	60	60	60	60
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	50	50	50
ANGLE OF INCLINATION OF COLLECTORS (S, °)	0	0	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	0	0	0
OUTPUT NUMBER	32267/1	32267/2	32267/3	32267/4	32267/5	32267/6	32267/7	32267/8
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	0	0	232,045	236,422	587,070	607,627	884,464	965,654
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0	0	0.413	0.421	0.366	0.378	0.275	0.301
AUXILIARY HEAT USED (TOX, kWh)	994,006	922,361	781,952	714,842	387,951	346,060	48,316	39,696
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	428,790	492,437	437,142	489,934	475,298	483,766	566,895	465,188
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	457,585	458,005	466,532	465,314	489,723	489,240	498,699	498,303
NET HEATING LOAD (QNHT, kWh)	1,483,208	1,483,208	1,483,208	1,483,208	1,483,208	1,483,208	1,483,208	1,483,208
NET COOLING LOAD (QNCT, kWh)	572,721	572,721	572,721	572,721	572,721	572,721	572,721	572,721
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	35,464	35,461	35,260	35,282	35,136	35,179	35,061	
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	23,363	23,364	23,194	23,198	22,847	22,854	22,592	
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	33.468	33.407	31.519	31.364	28.204	27.850	25.811	24.689

TABLE V

E. Experimental Heat Pump Improvement

Early in the program, we acquired an American Standard CHP-2.5V water-to-air heat pump and set it up in the laboratory. After calibration of air and water flow measuring equipment, a series of tests were made to check the performance of the heat pump against the manufacturer's ratings. We found that the equipment did in fact meet the manufacturer's specifications.

We then modified the heat pump by placing a small water cooled condenser in the refrigerant circuit between the compressor and the regular refrigerant-air heat exchanger which serves as the condenser when the heat pump is in the heating mode. The circuit diagram is shown in Fig. 4. The purpose of the modification was to reduce the load on the compressor under conditions of high source water temperature. The heating capacity of the air coil is reduced by this device, but it is precisely when the source water temperature is high that full heating capacity is not needed. Therefore, the use of the water coil to precool the hot gas from the compressor will save electrical energy without compromising the ability of the heat pump to meet the building or room load.

Tests made on the heat pump with the added water coil showed a substantial increase in the coefficient of performance, typically from about 2.75 to 3.25.

The heating capacity with the water coil decreased compared to operation without it. Also, the increase in heating capacity which normally occurs as the source water temperature increases, was limited with the water coil addition. Furthermore, the vapor superheat increased substantially with source water temperature, since the capillary expansion

FIGURE 4 : SCHEMATIC OF MODIFIED HEAT PUMP

tube was not capable of preventing the evaporator pressure from falling to a low level.

The conclusion is that the water coil addition can significantly improve the performance of the heat pump if the capillary tube is replaced by a thermostatic expansion valve. In that way, the pressure difference across the compressor can be reduced, while the capacity for heating increases. This will cause a reduction in electrical input to the compressor, and a large increase in the COP.

F. Full Year Simulation

During the past nine months of the contract, SYRSOL has been extended to simulate the summer months as well as the heating season. Now, 12 months of a year can be simulated. For program versatility, the feature to simulate only a portion of one year has been retained. The computer program was set up in such a way that, only several days out of a month can be simulated, and the results extrapolated to a full month.

To check on the magnitude of error introduced by extrapolating monthly energy use on the basis of only a few day simulation, computations were made for several extrapolation schemes. Figure 5 summarizes the results. It is obvious that extrapolation on the basis of four or more days per month is adequate. Tables VI and VII are the more detailed results of the computer runs.

FIGURE 5

EFFECT OF THE EXTRAPOLATION OF SIMULATION RESULTS ON THE
PREDICTION ACCURACY

LOCATION: KAY OFFICE BUILDING IN MINNEAPOLIS, MN

LENGTH OF SIMULATION = 12 MONTHS (JANUARY-DECEMBER)

SOLAR COLLECTOR AREA = 10,000 ft²

MASS OF THERMAL STORAGE WATER = 600,000 lb

STORAGE WATER TO COLLECTOR AREA RATIO = 60 lb/ft²

ANGLE OF INCLINATION OF SOLAR COLLECTORS = LATITUDE + 15°

ORIENTATION OF SOLAR COLLECTORS = SOUTH

NUMBER OF DAYS SIMULATED	OVERALL ENERGY USE	
	kWh/ft ²	DISCREPANCY
a) 1 DAY A MONTH (NO WEEKEND)	27.85	15%
b) 2 DAYS A MONTH (NO WEEKEND)	28.82	19%
c) 3 DAYS A MONTH (NO WEEKEND)	29.30	21%
d) 4 DAYS A MONTH (NO WEEKEND)	29.19	20%
e) 5 DAYS A MONTH (NO WEEKEND)	29.65	22%
f) 365 DAYS (NO WEEKENDS)	29.82	23%
g) 365 DAYS (1-DAY WEEKENDS)	27.07	11%
h) 365 DAYS (2-DAY WEEKENDS)	24.31	REFERENCE

SUBJECT: EFFECT OF THE NUMBER OF DAYS SIMULATED PER MONTH ON THE SIMULATION ACCURACY

REMARK:

LOCATION: KAY OFFICE BUILDING IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (1 FULL YEAR)

NUMBER OF DAYS SIMULATED EACH MONTH	1 DAY	2 DAYS	3 DAYS	4 DAYS	5 DAYS	
SOLAR COLLECTOR AREA (AP, ft ²)	10,000	10,000	10,000	10,000	10,000	
THERMAL STORAGE WATER (WM, lb)	600,000	600,000	600,000	600,000	600,000	
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60	60	
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	
OUTPUT NUMBER	10,190	10,190	10,190	10,190	10,190	
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	467,957	443,380	437,981	442,364	443,255	
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.292	0.276	0.273	0.275	0.276	
AUXILIARY HEAT USED (TOX, kWh)	374,937	473,728	511,411	506,931	561,837	
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	499,268	467,788	462,428	457,340	448,972	
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	452,672	479,301	488,792	487,295	488,677	
NET HEATING LOAD (QNHT, kWh)	1,483,754	1,483,514	1,483,282	1,483,208	1,483,256	
NET COOLING LOAD (QNCT, kWh)	571,762	572,088	572,418	572,721	573,074	
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	35,074	34,897	34,915	34,927	34,949	
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	22,833	22,856	22,857	22,858	22,958	
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	27.8532	28.8222	29.3007	29.1900	29.6550	

TABLE VI

SUBJECT: EFFECT OF THE WEEKEND BUILDING USE SCHEDULE OF SIMULATION ACCURACY						
REMARK: CONTINUOUS 365-DAYS-YEAR RUNS						
LOCATION: KAY OFFICE BUILDING IN MINNEAPOLIS, MINNESOTA			PERIOD SIMULATED: JANUARY-DECEMBER (1 FULL YEAR)			
NUMBER OF WEEKEND DAYS (WHEN BUILDING IS NOT USED)	0 DAYS	1 DAY	2 DAYS			
SOLAR COLLECTOR AREA (AP, ft ²)	10,000	10,000	10,000			
THERMAL STORAGE WATER (WM, lb)	600,000	600,000	600,000			
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60			
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50			
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°			
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0			
OUTPUT NUMBER	06059	08962	08028			
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	424,840	439,480	438,171			
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.265	0.268	0.273			
AUXILIARY HEAT USED (TOX, kWh)	575,925	557,997	540,025			
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	451,737	445,749	439,628			
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	488,929	430,094	371,107			
NET HEATING LOAD (QNHT, kWh)	1,488,388	1,464,802	1,441,192			
NET COOLING LOAD (QNCT, kWh)	572,593	503,519	434,471			
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	35,060	30,441	25,835			
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	22,992	19,964	16,942			
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	29.8299	27.0716	24.3146			

TABLE VII

G. Solar-Regenerated Desiccant Dehumidification

The feasibility of a solar space heating system improves substantially if the solar collectors can be used 12 months of the year rather than only several months of the heating season. One way of accomplishing this in a solar-assisted heat pump system is to use the solar heat collected during the cooling season to regenerate a desiccant dehumidification system which would remove moisture from the ventilation air. Naturally, drier air would give better heat pump cooling performance, thus reducing energy consumption of the building.

A series of computer runs were made to get an approximate idea about the feasibility of solar-regenerated desiccant dehumidification in the cooling season. This preliminary study was based on an office building in Charleston, S. C. with 9294m^2 ($100,000\text{ft}^2$) of floor area and 929m^2 ($10,000\text{ft}^2$) of collector area, and 272,000 kg (600,000 lb) of water storage. The results indicate that savings of 3 to 8% of the total annual energy use can reasonably be expected, the exact value being dependent on the efficiency of the desiccant system. This translates into 80,000 KWH/year to 220,000 KWH/year. Assuming an electricity cost of \$0.04/KWH, this represents savings between \$3,200/year and \$8,800/year. It is noted that these figures are preliminary. More work needs to be done before conclusions and recommendations can be made with confidence. It is also noted that localities that have hot and humid summers require only small amounts of auxiliary heat with a heat pump system in the winter. Hence, small collector areas are needed for space heating, which means small collector areas are available for regenerating the desiccant system. However, it is conceivable that some of the heat rejected by the cooling tower could also be used for regeneration.

H. Effect of Sunny and Cloudy Day Sequences

The computer program SYRSOL treats insolation intensities during any month as a constant fraction of the instantaneous clear sky (or maximum available) insolation. This fraction is different for different months. Therefore, the cloud cover modifier consists of a set of twelve constants, one for each month of the year. It is important to know how much error this method introduces into the simulation results in comparison to actual insolation patterns which are more nearly random combinations of clear and cloudy days.

A series of computer runs were made for the office building in the Boston area with various combinations of daily cloud cover modifiers, representing combinations of sunny and cloudy days, for a five-day period in January. The results are summarized in Tables VIII through XI. It can be seen that the total energy used varies by less than 2% in most cases regardless of the sequence of sunny and cloudy days, as long as the average cloud cover for the five-day period is the same. The results do vary somewhat with collector area and storage volume. Some other runs in the same tables were made to examine the effect of different average cloud covers. Figures 6 and 7 show the effect of various cloud covers on the total energy use for a five-day period, as a function of collector area. For clear or almost clear skies, the energy consumption actually increases for large collector areas due to the fact that loop temperatures remain high and the COP of the heat pump decreases when the loop temperature exceeds the normal operating range.

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 50,000 ft²

WATER IN THERMAL STORAGE TANK = 2,000,000 lb

STORAGE WATER TO COLLECTOR AREA = 40 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
1	0.7	0.7	0.7	0.7	0.7	0.7	32,768	0.328	3.53	0.0 REFERENCE
2	1.0	1.0	0.9	0.3	0.3	0.7	33,701	0.337	3.63	2.8
3	0.3	0.3	0.9	1.0	1.0	0.7	34,432	0.344	3.70	4.8
4	1.0	0.6	0.3	0.6	1.0	0.7	32,830	0.328	3.53	0.0
5	1.0	1.0	0.3	0.3	0.9	0.7	33,271	0.333	3.58	1.4
6	1.0	1.0	1.0	1.0	1.0	1.0	33,400	0.334	3.59	1.7
7	0.4	0.4	0.4	0.4	0.4	0.4	31,887	0.319	3.43	-2.8
8	0.2	0.2	0.2	0.2	0.2	0.2	43,671	0.437	4.70	33.1
9	0.0	0.0	0.0	0.0	0.0	0.0	58,059	0.581	6.25	77.0

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 50,000 ft²

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 8 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
10	0.7	0.7	0.7	0.7	0.7	0.7	34,630	0.346	3.72	0.0 REFERENCE
11	1.0	1.0	0.9	0.3	0.3	0.7	34,664	0.347	3.73	0.2
12	0.3	0.3	0.9	1.0	1.0	0.7	36,637	0.366	3.94	5.9
13	1.0	0.6	0.3	0.6	1.0	0.7	34,467	0.345	3.71	-0.2
14	1.0	1.0	0.3	0.3	0.9	0.7	34,824	0.348	3.75	0.8
15	1.0	1.0	1.0	1.0	1.0	1.0	35,012	0.350	3.77	1.3
16	0.4	0.4	0.4	0.4	0.4	0.4	33,451	0.335	3.60	-3.2
17	0.2	0.2	0.2	0.2	0.2	0.2	44,310	0.443	4.77	28.2
18	0.0	0.0	0.0	0.0	0.0	0.0	58,059	0.581	6.25	68.0

TABLE VIII

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 10,000 ft²

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 40 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
19	0.7	0.7	0.7	0.7	0.7	0.7	41,667	0.417	4.48	0.0 REFERENCE
20	1.0	1.0	0.9	0.3	0.3	0.7	41,762	0.418	4.49	0.2
21	0.3	0.3	0.9	1.0	1.0	0.7	42,338	0.423	4.56	1.8
22	1.0	0.6	0.3	0.6	1.0	0.7	42,376	0.424	4.56	1.8
23	1.0	1.0	0.3	0.3	0.9	0.7	41,942	0.419	4.51	0.7
24	1.0	1.0	1.0	1.0	1.0	1.0	35,098	0.351	3.78	-15.6
25	0.4	0.4	0.4	0.4	0.4	0.4	49,052	0.491	5.28	17.9
26	0.2	0.2	0.2	0.2	0.2	0.2	53,809	0.538	5.79	29.2
27	0.0	0.0	0.0	0.0	0.0	0.0	58,059	0.581	6.25	39.5

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 0 (Without Solar Collectors)

WATER IN THERMAL STORAGE TANK = 250,000 lb

STORAGE WATER TO COLLECTOR AREA = 0 lb/ft²

COMMENTS:

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
28	0.7	0.7	0.7	0.7	0.7	0.7	52,165	0.522	5.61	0.0 REFERENCE

TABLE IX

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 30,000 ft²

WATER IN THERMAL STORAGE TANK = 1,200,000 lb

STORAGE WATER TO COLLECTOR AREA = 40 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
30	0.7	0.7	0.7	0.7	0.7	0.7	32,148	0.321	3.46	0.0 REFERENCE
31	1.0	1.0	0.9	0.3	0.3	0.7	33,089	0.331	3.56	2.9
32	0.3	0.3	0.9	1.0	1.0	0.7	37,329	0.373	4.02	16.2
33	1.0	0.6	0.3	0.6	1.0	0.7	32,171	0.322	3.46	0.0
34	1.0	1.0	0.3	0.3	0.9	0.7	32,600	0.326	3.51	1.4
35	1.0	1.0	1.0	1.0	1.0	1.0	32,930	0.329	3.54	2.3
36	0.4	0.4	0.4	0.4	0.4	0.4	38,362	0.384	4.13	19.4
37	0.2	0.2	0.2	0.2	0.2	0.2	48,699	0.487	5.24	51.4
38	0.0	0.0	0.0	0.0	0.0	0.0	58,059	0.481	6.25	80.6

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 30,000 ft²

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 13.3 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
39	0.7	0.7	0.7	0.7	0.7	0.7	33,209	0.332	3.57	0.0 REFERENCE
40	1.0	1.0	0.9	0.3	0.3	0.7	34,130	0.341	3.67	2.8
41	0.3	0.3	0.9	1.0	1.0	0.7	38,449	0.385	4.14	16.0
42	1.0	0.6	0.3	0.6	1.0	0.7	33,776	0.338	3.63	1.7
43	1.0	1.0	0.3	0.3	0.9	0.7	35,190	0.352	3.79	6.2
44	1.0	1.0	1.0	1.0	1.0	1.0	34,272	0.343	3.69	3.4
45	0.4	0.4	0.4	0.4	0.4	0.4	39,252	0.392	4.22	18.2
46	0.2	0.2	0.2	0.2	0.2	0.2	48,722	0.487	5.24	46.8
47	0.0	0.0	0.0	0.0	0.0	0.0	58,059	0.581	6.25	75.1

TABLE X

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 0. ft² (Without Solar Collectors)

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 0 lb/ft²

COMMENTS:

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
48	0.7	0.7	0.7	0.7	0.7	0.7	52,516	0.525	5.65	0.0 REFERENCE
49	1.0	1.0	0.9	0.3	0.3	0.7	52,528	0.525	5.65	0.0
50	0.3	0.3	0.9	1.0	1.0	0.7	52,499	0.525	5.65	0.0
51	1.0	0.6	0.3	0.6	1.0	0.7	52,514	0.525	5.65	0.0
52	1.0	1.0	0.3	0.3	0.9	0.7	52,520	0.525	5.65	0.0
53	1.0	1.0	1.0	1.0	1.0	1.0	50,014	0.500	5.38	-4.8
54	0.4	0.4	0.4	0.4	0.4	0.4	55,013	0.550	5.92	4.8
55	0.2	0.2	0.2	0.2	0.2	0.2	56,677	0.567	6.10	8.0
56	0.0	0.0	0.0	0.0	0.0	0.0	58,341	0.583	6.28	11.2

EFFECT OF THE SUCCESSION OF SUNNY AND CLOUDY DAYS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 0 (Without Solar Collectors)

WATER IN THERMAL STORAGE TANK = 1000 lb

STORAGE WATER TO COLLECTOR AREA = 0

COMMENTS:

RUN	DAILY CLOUD COVER MODIFIER, FOR JANUARY					AVERAGE CLOUD COVER MODIFIER FOR JANUARY 15.-19.	TOTAL ENERGY USE FOR JANUARY 15.-19.			
	15.	16.	17.	18.	19.		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
57	0.7	0.7	0.7	0.7	0.7	0.7	52,516	0.525	5.65	0.0 REFERENCE
58	1.0	1.0	0.9	0.3	0.3	0.7	52,521	0.525	5.65	0.0
59	0.3	0.3	0.9	1.0	1.0	0.7	52,491	0.525	5.65	0.0
60	1.0	0.6	0.3	0.6	1.0	0.7	52,507	0.525	5.65	0.0
61	1.0	1.0	0.3	0.3	0.9	0.7	52,512	0.525	5.65	0.0
62	1.0	1.0	1.0	1.0	1.0	1.0	49,995	0.500	5.38	-4.8
63	0.4	0.4	0.4	0.4	0.4	0.4	55,013	0.550	5.92	4.8
64	0.2	0.2	0.2	0.2	0.2	0.2	56,677	0.567	6.10	8.0
65	0.0	0.0	0.0	0.0	0.0	0.0	58,341	0.583	6.28	11.2

TABLE XI

DEPENDENCE OF HEATING SEASON ENERGY
CONSUMPTION ON CLOUD COVER

FIGURE 6

DEPENDENCE OF HEATING SEASON ENERGY
CONSUMPTION ON CLOUD COVER

FIGURE 7

I. Effect of Random Temperature Fluctuations.

Actual weather has a random variation above and below the expected seasonal temperature. It is of importance to determine the relative contribution of this random variation to the energy consumption of a building. To estimate the magnitude of the error introduced by the use of the smoothed temperature functions, computer runs were made for several ambient temperature random fluctuation schemes. A four-day period in January was selected, and sinusoidal variations of 2.8C (5F) and 5.6C (10F) amplitudes were superimposed on the basic dry bulb temperature function, such that the average temperature of the four-day period remained unchanged. The results of these runs, Tables XII-XV show that these perturbations do not affect the building energy use significantly.

Some computer runs were also made for the same four-day period with a constant and fixed reduction superimposed on the basic dry bulb temperature function. The last two runs in Tables XII-XV illustrate the effect of decreasing the average temperature by 3.3C (6F) and 5.6C (10F), respectively. It is apparent that the average temperature levels affect the energy use substantially.

It is concluded from this analysis that random variations in temperature can be disregarded without introducing a significant error into the results as long as the average temperature levels correspond to the weather of the locality being simulated. It is also concluded that the use of temperature functions for building energy consumptions is reasonable and dependable.

EFFECT OF TEMPERATURE FLUCTUATIONS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 50,000 ft²

WATER IN THERMAL STORAGE TANK = 2,000,000 lb

STORAGE WATER TO COLLECTOR AREA = 40 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN NO.	BASIC TEMPERATURE FUNCTION (TB) + PERTURBATION (PER)	TOTAL ENERGY USE FOR JANUARY 15.-18.			
		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
1	TB + 0 (F)	26,358	0.264	2.84	0.0 REFERENCE
2	TB + 5 sin (0.5π(TY-2))* (F)	26,454	0.265	2.85	0.4
3	TB - 5 sin (0.5π(TY-2)) (F)	26,284	0.263	2.83	-0.4
4	TB + 10 sin (0.5π(TY-2)) (F)	26,632	0.266	2.87	1.1
5	TB - 10 sin (0.5π(TY-2)) (F)	26,314	0.263	2.83	-0.4
6	TB - 6 (F)	28,613	0.286	3.08	8.5
7	TB - 10 (F)	30,092	0.301	3.24	14.1

*TY is the day of the year (i.e., total number of days from January 1st).

EFFECT OF TEMPERATURE FLUCTUATIONS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 50,000 ft²

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 8 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN NO.	BASIC TEMPERATURE FUNCTION (TB) + PERTURBATION (PER)	TOTAL ENERGY USE FOR JANUARY 15.-18.			
		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
8	TB + 0 (F)	27,958	0.280	3.01	0.0 REFERENCE
9	TB + 5 sin (0.5π(TY-2))* (F)	27,907	0.279	3.00	-0.4
10	TB - 5 sin (0.5π(TY-2)) (F)	27,907	0.279	3.00	-0.4
11	TB + 10 sin (0.5π(TY-2)) (F)	27,952	0.280	3.01	0.0
12	TB - 10 sin (0.5π(TY-2)) (F)	27,941	0.280	3.01	0.0
13	TB - 6 (F)	30,472	0.305	3.28	9.0
14	TB - 10 (F)	31,915	0.319	3.43	14.0

*TY is the day of the year (i.e., total number of days from January 1st).

TABLE XII

EFFECT OF TEMPERATURE FLUCTUATIONS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 30,000 ft²

WATER IN THERMAL STORAGE TANK = 1,200,000 lb

STORAGE WATER TO COLLECTOR AREA = 40 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN NO.	BASIC TEMPERATURE FUNCTION (TB) + PERTURBATION (PER)	TOTAL ENERGY USE FOR JANUARY 15.-18.			
		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
15	TB + 0 (F)	25,978	0.260	2.80	0.0 REFERENCE
16	TB + 5 sin (0.5π(TY-2))* (F)	26,044	0.260	2.80	0.0
17	TB - 5 sin (0.5π(TY-2)) (F)	25,911	0.259	2.79	-0.4
18	TB + 10 sin (0.5π(TY-2)) (F)	26,206	0.262	2.82	0.7
19	TB - 10 sin (0.5π(TY-2)) (F)	25,963	0.260	2.80	0.0
20	TB - 6 (F)	27,930	0.279	3.00	7.2
21	TB - 10 (F)	30,758	0.308	3.31	18.2

*TY is the day of the year (i.e., total number of days from January 1st).

EFFECT OF TEMPERATURE FLUCTUATIONS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 30,000 ft²

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 13.3 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN NO.	BASIC TEMPERATURE FUNCTION (TB) + PERTURBATION (PER)	TOTAL ENERGY USE FOR JANUARY 15.-18.			
		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
22	TB + 0 (F)	26,919	0.269	2.90	0.0 REFERENCE
23	TB + 5 sin (0.5π(TY-2))* (F)	27,071	0.271	3.91	34.8
24	TB - 5 sin (0.5π(TY-2)) (F)	26,759	0.268	2.88	-0.7
25	TB + 10 sin (0.5π(TY-2)) (F)	27,298	0.273	2.94	1.4
26	TB - 10 sin (0.5π(TY-2)) (F)	27,229	0.272	2.93	1.0
27	TB - 6 (F)	28,564	0.286	3.07	5.9
28	TB - 10 (F)	32,664	0.327	3.52	21.4

*TY is the day of the year (i.e., total number of days from January 1st).

TABLE XIII

EFFECT OF TEMPERATURE FLUCTUATIONS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 0. ft²

WATER IN THERMAL STORAGE TANK = 250,000 lb

STORAGE WATER TO COLLECTOR AREA = 0. lb/ft²

COMMENTS:

RUN NO.	BASIC TEMPERATURE FUNCTION (TB) + PERTURBATION (PER)	TOTAL ENERGY USE FOR JANUARY 15.-18.			
		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
29	TB + 0 (F)	41,483	0.415	4.46	0.0 REFERENCE
30	TB + 5 sin (0.5π(TY-2))* (F)	41,483	0.415	4.46	0.0
31	TB - 5 sin (0.5π(TY-2)) (F)	41,483	0.415	4.46	0.0
32	TB + 10 sin (0.5π(TY-2)) (F)	41,480	0.415	4.46	0.0
33	TB - 10 sin (0.5π(TY-2)) (F)	41,480	0.415	4.46	0.0
34	TB - 6 (F)	48,058	0.481	5.17	15.9
35	TB - 10 (F)	52,441	0.524	5.64	26.5

*TY is the day of the year (i.e., total number of days from January 1st).

EFFECT OF TEMPERATURE FLUCTUATIONS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 0 ft²

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 0. lb/ft²

COMMENTS:

RUN NO.	BASIC TEMPERATURE FUNCTION (TB) + PERTURBATION (PER)	TOTAL ENERGY USE FOR JANUARY 15.-18.			
		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
36	TB + 0 (F)	41,483	0.415	4.46	0.0 REFERENCE
37	TB + 5 sin (0.5π(TY-2))* (F)	41,483	0.415	4.46	0.0
38	TB - 5 sin (0.5π(TY-2)) (F)	41,483	0.415	4.46	0.0
39	TB + 10 sin (0.5π(TY-2)) (F)	41,480	0.415	4.46	0.0
40	TB - 10 sin (0.5π(TY-2)) (F)	41,480	0.415	4.46	0.0
41	TB - 6 (F)	48,059	0.481	5.17	15.9
42	TB - 10 (F)	52,441	0.524	5.64	26.5

*TY is the day of the year (i.e., total number of days from January 1st).

TABLE XIV

EFFECT OF TEMPERATURE FLUCTUATIONS ON SYSTEM PERFORMANCE

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

SOLAR COLLECTOR AREA = 10,000 ft²

WATER IN THERMAL STORAGE TANK = 400,000 lb

STORAGE WATER TO COLLECTOR AREA = 40 lb/ft²

COMMENTS: Collector inclination angle = Latitude + 15°; Orientation = South.

RUN NO.	BASIC TEMPERATURE FUNCTION (TB) + PERTURBATION (PER)	TOTAL ENERGY USE FOR JANUARY 15.-18.			
		kWh	kWh/ft ²	kWh/m ²	% DISCREPANCY
43	TB + 0 (F)	32,621	0.326	3.51	0.0 REFERENCE
44	TB + 5 sin (0.5π(TY-2))* (F)	32,640	0.326	3.51	0.0
45	TB - 5 sin (0.5π(TY-2)) (F)	32,638	0.326	3.51	0.0
46	TB + 10 sin (0.5π(TY-2)) (F)	32,643	0.326	3.51	0.0
47	TB - 10 sin (0.5π(TY-2)) (F)	32,950	0.329	3.54	0.9
48	TB - 6 (F)	39,631	0.396	4.26	21.4
49	TB - 10 (F)	44,308	0.443	4.77	35.9

*TY is the day of the year (i.e., total number of days from January 1st).

TABLE XV

J. Effect of High Lighting Levels

It is intuitively obvious that high levels of uniform lighting are wasteful in two respects: it takes more electricity to obtain high levels of lighting, and also more electricity to remove the extra heat added to the room. This intuition was verified by a set of simulation runs made with the computer program SYRSOL. In Figure 8 the lighting level is the parameter that varies between 5.38 W/m^2 (0.5 W/ft^2) and 32.28 W/m^2 (3.0 W/ft^2). The ordinate gives the total annual energy consumption of the building; that is, electricity used for heat pump cooling, and electricity used for lighting. The abscissa represents the fraction of lighting energy that becomes a heat gain for the room.

Figure 8 illustrates the energy waste involved in high lighting levels. Yet many newly constructed commercial buildings use as much as 60 W/m^2 (6 W/ft^2) of lighting throughout the building. The amount of potential conservation of electricity in these buildings is indeed staggering.

FIGURE 8 : EFFECTS OF LIGHTING LEVELS

K. Effect of Solar Collector Orientation and Inclination

Typical of the results obtained from investigations of the effects of collector inclination and orientation are those for the office building in Boston, Mass. These are shown in Tables XVI and XVII and Figures 9 and 10. It is obvious that the overall performance of the solar assisted system is not very sensitive to these variables. This is indeed fortunate, and important to the architect, engineer and builder. Small deviations of these variables from their optimum values may be made to accommodate building features without appreciable penalty in energy consumption.

It is important to add that the results shown here are valid for only the Kay Office Building with a prescribed occupancy and use schedule and in the Boston area. Although similar to these, the variation of the energy consumption with collector inclination and tilt will be different for different buildings, different occupancy and use schedules and different cities.

SUBJECT: EFFECT OF SOLAR COLLECTOR INCLINATION ON ENERGY CONSUMPTION							
REMARK: 5-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD C.O.P.; LATITUDE ANGLE (LAT) = 42.4°.							
LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS. PERIOD SIMULATED: JANUARY-DECEMBER (FULL YEAR)							
SOLAR COLLECTOR ORIENTATION	SOUTH	SOUTH	SOUTH	SOUTH	SOUTH	SOUTH	SOUTH
SOLAR COLLECTOR AREA (AP, ft ²)	10,000	10,000	10,000	10,000	10,000	10,000	10,000
THERMAL STORAGE WATER (WM, lb)	400,000	400,000	400,000	400,000	400,000	400,000	400,000
(lb OF WATER)/(ft ² COLLECTOR AREA)	40	40	40	40	40	40	40
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	50	50
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT-42.4	LAT-15	LAT	LAT+15	LAT+23.5	LAT+30	LAT+47.6
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	0	0
OUTPUT NUMBER	64133/1	64133/2	64133/3	64133/4	64133/5	64133.6	64133/7
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	212,711	318,938	349,749	355,508	352,608	343,531	300,000
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.162	0.300	0.317	0.344	0.247	0.257	0.297
AUXILIARY HEAT USED (TOX, kWh)	317,799	222,685	196,200	183,612	186,601	194,723	235,910
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	258,051	267,787	270,866	270,778	270,427	269,554	263,246
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	479,926	481,554	481,691	480,571	479,367	482,306	476,972
NET HEATING LOAD (QNHT, kWh)	-836,333	-836,333	-836,333	-836,333	-836,333	-836,333	-836,333
NET COOLING LOAD (QNCT, kWh)	589,433	589,433	589,433	589,433	589,433	589,433	589,433
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	34,885	35,182	35,427	35,084	35,065	35,032	35,349
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	22,850	22,857	22,895	22,747	22,743	22,740	22,931
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	25.31	24.50	24.27	24.11	24.11	24.20	24.51

TABLE XVI

SUBJECT: EFFECT OF SOLAR COLLECTOR ORIENTATION ON ENERGY CONSUMPTION

REMARK: 5-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD C.O.P.; LATITUDE ANGLE (LAT) = 42.4°.

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

PERIOD SIMULATED: JANUARY-DECEMBER (FULL YEAR)

SOLAR COLLECTOR ORIENTATION	EAST	SOUTHEAST	SOUTHEAST	SOUTH	SOUTHWEST	SOUTHWEST	WEST	EAST	EAST
SOLAR COLLECTOR AREA (AP, ft ²)	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
THERMAL STORAGE WATER (WM, lb)	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000	400,000
(lb OF WATER)/(ft ² COLLECTOR AREA)	40	40	40	40	40	40	40	40	40
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	50	50	50	50
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15	LAT+15	LAT+15	LAT+15	LAT+15	LAT+15	LAT+15	LAT+15	LAT+15
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	-90	-30	-15	0	15	30	90	-90	-90
OUTPUT NUMBER	64133/8	64133/9	64133/9	64133/11	64133/12	64133/13	64133/14	64133/15	64133/16
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	172,166	324,155	348,705	355,508	351,050	332,365	183,050	120,056	145,617
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.183	0.232	0.238	0.233	0.239	0.238	0.195	0.191	0.175
AUXILIARY HEAT USED (TOX, kWh)	356,316	213,076	191,086	183,612	188,302	206,536	345,905	396,189	377,885
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	253,148	268,597	269,933	270,778	270,866	269,167	257,416	251,017	252,066
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	479,509	481,619	483,534	480,571	481,285	479,418	479,303	473,794	475,143
NET HEATING LOAD (QNHT, kWh)	-836,333	-836,333	-836,333	-836,333	-836,333	-836,333	-836,333	-836,333	-836,333
NET COOLING LOAD (QNCT, kWh)	589,433	589,333	589,333	589,333	589,333	589,333	589,433	589,433	589,433
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	35,234	35,354	35,268	35,084	35,231	35,301	34,818	35,480	35,333
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	23,054	22,885	22,824	22,747	22,817	22,876	22,841	23,182	23,117
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	25.64	24.40	24.22	24.11	24.17	24.32	25.56	25.96	25.79

TABLE XVII

FIGURE 9: EFFECT OF SOLAR COLLECTOR INCLINATION ANGLE ON ENERGY CONSUMPTION

FIGURE 10: EFFECT OF WALL AZIMUTH ANGLE OF SOLAR COLLECTORS ON ENERGY CONSUMPTION

L. Solar Collector Comparisons

The system energy performance of the two building models was evaluated in two northern cities with three types of solar collectors. The collectors modeled represented a range of state-of-the-art commercially available units: A) a single glazed, moderate performance, non-selective flat plate; B) a single glazed, high performance, selective surface flat plate; and C) a moderately concentrating (10X) tracking collector. Collector efficiency was expressed as a function of temperature difference between the incoming fluid and the ambient and on the insolation (total for the flat plates, direct only for the concentrator). The collector performance curves are shown in Figure 11. Analytical expressions were fitted to each. It is obvious that with the different slopes of the curves that seasonal system performance could not be adequately evaluated until a complete yearly simulation had been conducted. One collector may have a low efficiency at high ΔT 's but a high efficiency at low ΔT 's. The average collector fluid inlet temperature of course, depends on the collector area and storage tank volume in addition to building heat load and use.

The results of the system evaluation is shown in Table XVIII. The two building types were evaluated in Boston and Minneapolis with a fixed collector area, storage volume, etc. It is seen that in all cases the high performance flat plate collector resulted in the least yearly building electrical energy use. This strongly illustrates the advantage of low collection temperature.

The performance advantage was due primarily to the average storage tank temperature (and therefore collection temperature) being in the range of 50 - 70° during the bulk of the heating season. Comparing

FIGURE 11: EFFICIENCY CURVES FOR THE THREE COLLECTOR MODELS USED IN SYRSOL*

- *A IS BASED ON A SINGLE GLAZED NON-SELECTIVE FLAT PLATE COLLECTOR
 B IS BASED ON A SINGLE GLAZED-SELECTIVE SURFACE FLAT PLATE COLLECTOR
 C IS BASED ON A MODERATELY CONCENTRATING (10X) TRACKING COLLECTOR

TABLE XVIII

<u>COLLECTOR SYSTEM COMPARISONS</u>			
Total Energy Use (KWH/M ² Year)			
AP = 5000 ft ² ; WAR = 60 lb/ft ² ; S = AL + 15°			
	Flat Plate Non-Selective	Flat Plate High Performance	10X Concentrator
<u>Boston</u>			
Office	273.0	269.1	278.6
School	251.3	245.8	246.1
<u>Minneapolis</u>			
Office	334.4	327.6	333.0
School	307.4	298.3	298.9

these two, the choice would probably be one of least installed cost (flat plate system). The more moderate performance (and priced) flat plate collector did not perform as well as the other two but could conceivably be the installation of choice for this heat pump system if detailed economic analysis was performed.

In summary, it is shown that the differences in performance between the simplest and the more advanced solar thermal collector cannot be justified for a water-source heat pump system in a commercial building if the improvement comes at too great of an incremental cost addition. This is a direct result of the low average loop temperature of the system during the heating system.

Table XVIII summarizes the total energy use of the buildings with different collector systems and Fig. 11 shows the efficiencies of the different collectors.

M. Effect of Ventilation Heat Recovery

Commercial buildings have very high rates of ventilation. Therefore ventilation heat recovery can save substantial amounts of energy if applied properly. The key words here are "if applied properly". One may actually waste energy, or save less than the maximum possible, by improper control logic. Table XIX indicates clearly that one does not realize maximum savings by simply turning the recovery system on every time the outside air temperature drops below the inside temperature. Under some conditions, cool outside air can be used to remove excess heat from the building. Therefore Control Logic I in the table produces higher savings.

Some definitions and assumption used for the simulations in Table need to be indicated here. The effectiveness of the heat recovery units i.e., the fraction of the sensible energy in the exhaust air that is transferred to the fresh make-up air, was taken to be 65%. 0% heat recovery means that none of the exhaust air goes through a heat recovery unit, and 100% heat recovery means that all of the exhaust air goes through the heat recovery unit. It is important to observe that energy savings in Table XIX are measured in terms of a percentage reduction in the total annual power bill of the building as this is the most significant energy use datum. The savings would be 52% for Logic I and 78% for Logic II if the comparison were to be made in terms of the auxiliary heat used.

TABLE XIX: EFFECT OF HEAT RECOVERY FROM EXHAUST
AIR ON ENERGY CONSUMPTION

LOCATION: KAY OFFICE BUILDING IN BOSTON, MASS.

LENGTH OF SIMULATION = 12 MONTHS (JANUARY-DECEMBER)

NUMBER OF DAYS OF EACH MONTH SIMULATED = 6

SOLAR COLLECTOR AREA = 930 m² (10,000 ft²)

MASS OF THERMAL STORAGE WATER = 182,000 kg (400,000 lb)

STORAGE WATER TO COLLECTOR AREA RATIO = 196 kg/m² (40 lb/ft²)

ANGLE OF INCLINATION OF SOLAR COLLECTORS = LATITUDE + 15°,
DUE SOUTH

CONTROL LOGIC I: TURN ON HEAT RECOVERY WHEN OUTSIDE TEMPERA-
TURE FALLS BELOW INSIDE TEMPERATURE, AND THE HEAT PUMPS
ARE IN THE HEATING MODE

CONTROL LOGIC II: TURN ON HEAT RECOVERY WHEN OUTSIDE TEMPERA-
TURE FALLS BELOW INSIDE TEMPERATURE

	HEAT RECOVERY		
	0%	100% LOGIC I	100% LOGIC II
HEAT COLLECTED BY COLLECTORS (kWh)	362,000	325,814	265,510
COLLECTOR UTILIZATION EFFICIENCY	0.238	0.214	0.174
AUXILIARY HEAT USED (kWh) .	183,596	87,340	40,786
H.P. HEATING ELECTRICITY (kWh)	271,339	222,082	234,933
H.P. COOLING ELECTRICITY (kWh)	476,925	484,094	568,012
NET HEATING LOAD (kWh) . .	-836,559	-640,436	-640,436
NET COOLING LOAD (kWh) . .	589,499	589,499	684,703
MAKE-UP AIR HEATING LOAD (kWh)	-291,328	-95,204	0
MAKE-UP AIR COOLING LOAD (kWh)	24,063	24,063	24,063
OVERALL ENERGY USE (kWh/m ² -year)	259	244	250
ENERGY SAVINGS FROM HEAT RECOVERY	REFERENCE	5.8%	3.4%

N. Effect of Internal Load Variations

The following four tables describe in detail the effect of internal load variations on the annual total energy consumption of the buildings. High ventilation rates can be the most detrimental to building energy efficiency. Occupancy is not expected to influence energy consumption nearly as much, since occupancy density in residences in this country is quite low. The effect of sources of heat gain in the building, whether it is lights or miscellaneous equipment, is substantial.

SUBJECT: EFFECT OF LIGHTING LEVELS ON ENERGY CONSUMPTION

REMARK: 4-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD COP.

LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (FULL YEAR)

LIGHTING LEVEL (WATTS/FT ² OF FLOOR)	0.0	0.5	1.0	2.0	4.0	
SOLAR COLLECTOR AREA (AP, ft ²)	50,000	50,000	50,000	50,000	50,000	
THERMAL STORAGE WATER (WM, lb)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60	60	
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	
OUTPUT NUMBER	56 188	56 188	56 188	56 188	56 188	
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	2,498,000	2,416,000	2,311,000	2,007,000	1,764,000	
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.311	0.301	0.288	0.250	0.220	
AUXILIARY HEAT USED (TOX, kWh)	682,000	594,000	422,000	150,000	27,000	
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	1,176,000	1,080,000	989,000	855,000	614,000	
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	195,000	245,000	297,000	398,000	607,000	
NET HEATING LOAD (QNHT, kWh)	3,627,000	3,308,000	3,010,000	2,487,000	1,682,000	
NET COOLING LOAD (QNCT, kWh)	350,000	436,000	526,000	705,000	1,064,000	
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	693,000	694,000	694,000	705,000	709,000	
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	537,000	536,000	535,000	525,000	521,000	
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	10.11	11.20	12.08	14.18	19.42	

TABLE XX

SUBJECT: EFFECT OF MISCELLANEOUS EQUIPMENT HEAT GENERATION ON ENERGY CONSUMPTION

REMARK: 4-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD COP

LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (FULL YEAR)

MISC. EQUIPMENT CAPACITY (WATTS/FT ² OF FLOOR)	0.00	0.25	0.50	1.00	2.00	
SOLAR COLLECTOR AREA (AP, ft ²)	50,000	50,000	50,000	50,000	50,000	
THERMAL STORAGE WATER (WM, lb)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60	60	
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	
OUTPUT NUMBER	56 327	56 327	56 327	56 327	56 327	
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	2,501,000	2,418,000	2,311,000	2,008,000	1,726,000	
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.311	0.301	0.288	0.250	0.215	
AUXILIARY HEAT USED (TOX, kWh)	679,000	592,000	422,000	152,000	34,000	
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	1,175,000	1,081,000	989,000	847,000	571,000	
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	194,000	245,000	297,000	397,000	602,000	
NET HEATING LOAD (QNHT, kWh)	3,626,000	3,310,000	5,010,000	2,472,000	1,575,000	
NET COOLING LOAD (QNCT, kWh)	350,000	437,000	826,000	703,000	1,058,000	
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	693,000	694,000	694,000	705,000	709,000	
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	537,000	536,000	535,000	525,000	521,000	
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	10.06	11.16	12.08	14.22	19.48	

TABLE XXI

SUBJECT: EFFECT OF OCCUPANCY LEVELS ON ENERGY CONSUMPTION						
REMARK: 4-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD COP.						
LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS, MINNESOTA			PERIOD SIMULATED: JANUARY-DECEMBER (FULL YEAR)			
OCCUPANCY LEVEL (PERSONS/1000 FT ² OF FLOOR)	NO. OCCUPANTS	1.25	2.50	5.00	10.00	
SOLAR COLLECTOR AREA (AP, ft ²)	50,000	50,000	50,000	50,000	50,000	
THERMAL STORAGE WATER (WM, lb)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60	60	
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	
OUTPUT NUMBER	56.334	56.334	56.334	56.334	56.334	
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	2,418,000	2,381,000	2,311,000	2,092,000	1,923,000	
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.301	0.297	0.288	0.261	0.239	
AUXILIARY HEAT USED (TOX, kWh)	590,000	547,000	422,000	185,000	123,000	
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	1,085,000	1,035,000	989,000	906,000	765,000	
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	281,000	288,000	297,000	308,000	336,000	
NET HEATING LOAD (QNHT, kWh)	3,317,000	3,161,000	3,010,000	2,722,000	2,206,000	
NET COOLING LOAD (QNCT, kWh)	496,000	511,000	526,000	556,000	616,000	
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	694,000	694,000	694,000	697,000	706,000	
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	536,000	535,000	535,000	533,000	523,000	
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	12.70	12.48	12.08	11.37	10.92	

TABLE XXII

SUBJECT: EFFECT OF VENTILATION RATES ON ENERGY CONSUMPTION

REMARK: 4-DAYS-MONTH RUNS; MONTHLY CLOUD COVER; STANDARDS CLOUD COVER

LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (FULL YEAR)

VENTILATION RATE (CFM/PERSON)	0	10	20	40	80	
SOLAR COLLECTOR AREA (AP, ft ²)	50,000	50,000	50,000	50,000	50,000	
THERMAL STORAGE WATER (WM, lb)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60	60	
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	
OUTPUT NUMBER	56 707	56 707	56 707	56 707	56 707	
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	1,855,000	2,014,000	2,311,000	2,555,000	3,042,000	
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.231	0.251	0.288	0.318	0.379	
AUXILIARY HEAT USED (TOX, kWh)	53,000	132,000	422,000	951,000	2,140,000	
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	707,000	858,000	989,000	1,306,000	1,999,000	
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	353,000	325,000	297,000	246,000	186,000	
NET HEATING LOAD (QNHT, kWh)	1,964,000	3,478,000	3,010,000	4,129,000	6,549,000	
NET COOLING LOAD (QNCT, kWh)	593,000	559,000	526,000	460,000	354,000	
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	708,000	706,000	694,000	689,000	676,000	
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	521,000	524,000	535,000	540,000	554,000	
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	9.87	10.76	12.08	14.83	20.94	

TABLE XXIII

O. Residential High Rise Building Model

A simulation model has been developed for a residential high rise building. The basis of this model is an actual building designed and built by our subcontractor on this research program, VVKR Partnership in Alexandria, Virginia. The model has 400,000 ft² of total floor area, and 568 tons of heat pumps. The model has two identical zones, one being rotated 180° with respect to the other. This section summarizes the various parametric studies that we have conducted with this model.

Fig. 12 represents the basic performance of the heat pump system in the residential high rise building for different values of water storage. It is noted that increasing the water storage to collector area ratio from 30 LB/FT² to 90 LB/FT² improves the performance significantly. Fig. 13 shows the reduction in the yearly total energy use with improved COP. Fig. 14 shows the dramatic increase of the yearly enregy use with increasing window area of the building.

Table XXV is an analysis of the effect of the building orientation on energy consumption.

SUBJECT: SYSTEM PERFORMANCE								
REMARK: 4-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD COP.								
LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS, MINNESOTA								
PERIOD SIMULATED: JANUARY-DECEMBER(1 FULL YEAR)								
SOLAR COLLECTOR AREA (AP, ft ²)	10,000	30,000	50,000	70,000	10,000	30,000	50,000	70,000
THERMAL STORAGE WATER (WM, lb)	300,000	900,000	1,500,000	2,100,000	900,000	2,700,000	4,500,000	6,300,000
(lb OF WATER)/(ft ² COLLECTOR AREA)	30	30	30	30	90	90	90	90
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	50	50	50
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	0	0	0
OUTPUT NUMBER	55 274	55 274	55 274	55 274	55 417	55 417	55 417	55 417
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	613,000	1,452,000	2,027,000	2,297,000	637,000	1,667,000	2,452,000	3,033,000
COLLECTOR UTILIZATION EFFICIENCY (ET _{YA})	0.382	0.301	0.252	0.204	0.397	0.346	0.305	0.270
AUXILIARY HEAT USED (TOX, kWh)	1,959,000	1,140,000	528,000	83,000	1,932,000	945,000	236,000	67,000
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	855,000	924,000	1,016,000	1,103,000	851,000	915,000	1,005,000	1,078,000
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	269,000	291,000	294,000	295,000	289,000	294,000	296,000	297,000
NET HEATING LOAD (QNHT, kWh)	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000
NET COOLING LOAD (QNCT, kWh)	526,000	526,000	526,000	526,000	526,000	526,000	526,000	526,000
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	658,000	684,000	699,000	706,000	650,000	681,000	700,000	706,000
ELECTRICITY USED BY D.H.W. SYSTEM (DOWTE, kWh)	572,000	546,000	530,000	523,000	580,000	548,000	529,000	523,000
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	15.60	13.71	12.38	11.47	15.59	13.22	11.63	11.38

TABLE XXIV

FIGURE 12: SYSTEM PERFORMANCE OF THE HIGHRISE RESIDENTIAL BUILDING

SUBJECT: EFFECT OF BUILDING ORIENTATION ON ENERGY CONSUMPTION

REMARK: 4-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER: STANDARD COP

LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (1 FULL YEAR)

BUILDING ORIENTATION (IN DEGREE MEASURED CLOCKWISE FROM DUE SOUTH) (ROT)	45°	90°	135°	180°	225°	270°	315°	0°
SOLAR COLLECTOR AREA (AP, ft ²)	50,000	50,000	50,000	50,000	50,000	50,000	50,000	50,000
THERMAL STORAGE WATER (WM, lb)	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000	3,000,000
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60	60	60	50	60
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	50	50	50
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	0	0	0
OUTPUT NUMBER	55647	55647	55647	55647	55647	55647	55647	55647
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	2,173,000	2,154,000	2,293,000	2,316,000	2,169,000	2,156,000	2,292,000	2,311,000
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.271	0.268	0.286	0.288	0.270	0.268	0.285	0.288
AUXILIARY HEAT USED (TOX, kWh)	573,000	577,000	547,000	434,000	574,000	577,000	544,000	422,000
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	1,025,000	1,017,000	1,002,000	989,000	1,027,000	1,016,000	1,002,000	989,000
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	387,000	391,000	316,000	293,000	385,000	389,000	316,000	297,000
NET HEATING LOAD (QNHT, kWh)	3,156,000	3,127,000	3,070,000	3,013,000	3,158,000	3,127,000	3,067,000	3,010,000
NET COOLING LOAD (QNCT, kWh)	686,000	692,000	562,000	522,000	682,000	690,000	562,000	526,000
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	693,000	693,000	694,000	694,000	693,000	693,000	694,000	694,000
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	536,000	537,000	536,000	535,000	536,000	537,000	536,000	535,000
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	12.86	12.87	12.47	12.09	12.86	12.86	12.46	12.08

TABLE XXV

SUBJECT: EFFECT OF IMPROVED HEAT PUMP COP

REMARK:

LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (1 FULL YEAR)

COP OF THE WATER-TO-AIR HEAT PUMPS	STANDARD COP	STANDARD COP	STANDARD COP	STANDARD COP	IMPROVED BY 1	IMPROVED BY 1	IMPROVED BY 1	IMPROVED BY 1
SOLAR COLLECTOR AREA (AP, ft ²)	0	30,000	50,000	70,000	0	30,000	50,000	70,000
THERMAL STORAGE WATER (WM, lb)	300,000	1,800,000	3,000,000	4,200,000	300,000	1,800,000	3,000,000	4,200,000
(1b OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60	60	60	60	60
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50	50	50	50	50
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°	LAT+15°
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0	0	0	0	0
OUTPUT NUMBER	70785/1	70785/2	70785/3	70785/4	73975/1	73975/2	73975/3	73975/4
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	0.0	1,631,000	2,311,000	2,635,000	0	1,651,000	2,410,000	2,778,000
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.0	0.339	0.288	0.234	0	0.343	0.300	0.247
AUXILIARY HEAT USED (TOX, kWh)	2,541,000	972,000	422,000	71,000	2,726,000	1,279,000	633,000	122,000
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	847,000	908,000	989,000	1,094,000	661,000	691,000	734,000	783,000
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	269,000	294,000	297,000	297,000	179,000	189,000	189,000	190,000
NET HEATING LOAD (QNHT, kWh)	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000	3,010,000
NET COOLING LOAD (QNCT, kWh)	526,000	526,000	526,000	526,000	526,000	526,000	526,000	526,000
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	629,000	677,000	694,000	708,000	633,000	676,000	693,000	707,000
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	601,000	552,000	535,000	521,000	596,000	554,000	536,000	522,000
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	17.10	13.28	12.06	11.43	16.86	13.25	11.70	10.51

TABLE XXVI

FIGURE 13: EFFECT OF CHANGING COP TO COP+1

SUBJECT: EFFECT OF WINDOW AREA ON ENERGY CONSUMPTION

REMARK: 4-DAYS-A-MONTH RUNS; MONTHLY CLOUD COVER; STANDARD COP

LOCATION: RESIDENTIAL HIGHRISE IN MINNEAPOLIS,
MINNESOTA

PERIOD SIMULATED: JANUARY-DECEMBER (1FULL YEAR)

WINDOW AREA AS A PERCENTAGE OF OVERALL WALL AREA	100%	75%	50%	5%		
SOLAR COLLECTOR AREA (AP, ft ²)	30,000	30,000	30,000	30,000		
THERMAL STORAGE WATER (WM, lb)	1,800,000	1,800,000	1,800,000	1,800,000		
(lb OF WATER)/(ft ² COLLECTOR AREA)	60	60	60	60		
LOWER LIMIT OF TANK TEMPERATURE (TLL, F)	50	50	50	50		
ANGLE OF INCLINATION OF COLLECTORS (S, °)	LAT+15°	LAT+15°	LAT+15°	LAT+15°		
WALL AZIMUTH ANGLE OF COLLECTORS (REV, °)	0	0	0	0		
OUTPUT NUMBER	76755/1	76755/2	76755/3	76755/4		
HEAT COLLECTED BY COLLECTORS (TCOL, kWh)	1,481,000	1,470,000	1,460,000	1,638,000		
COLLECTOR UTILIZATION EFFICIENCY (ETYA)	0.307	0.305	0.303	0.340		
AUXILIARY HEAT USED (TOX, kWh)	1,455,000	1,220,000	943,000	840,000		
ELECTRICITY USED FOR H.P. HEATING (HPHTE, kWh)	1,056,338	971,000	896,000	833,000		
ELECTRICITY USED FOR H.P. COOLING (HPCTE, kWh)	490,000	418,000	346,000	217,000		
NET HEATING LOAD (QNHT, kWh)	3,533,000	3,236,000	2,960,000	2,779,000		
NET COOLING LOAD (QNCT, kWh)	868,000	743,000	618,000	393,000		
HEAT REMOVED BY D.H.W. FROM STORAGE (HRST, kWh)	676,000	677,000	679,000	677,000		
ELECTRICITY USED BY D.H.W. SYSTEM (DOTE, kWh)	553,000	552,000	551,000	553,000		
OVERALL ENERGY USE (ENDO, kWh/ft ² -YEAR)	15.41	14.43	13.34	12.55		

TABLE XXVII

FIGURE 14: EFFECT OF INCREASING THE WINDOW AREA

V. REFERENCES

1. Ucar, M., et al, "Thermal Simulation of a Building With Solar Assisted Closed Liquid Loop Unitary Heat Pumps", ASME Publication 76-WA/Sol-23, 1976.
2. Card, W. H., et al, "Generalized Weather Functions for Computer Analysis of Solar Assisted HVAC Systems", ASME Publication 76-WA/Sol-20, 1976.
3. Ucar, M., et al, "Compter Model for a Solar Assisted Closed Liquid Loop Heat Pump System", ASHRAE Transactions, Volume 82, Part I, 1976.
4. Drucker, E. E., "Commercial Building Solar Heat Pump Systems", ERDA Workshop on "Solar Energy Heat Pump Systems for the Heating and Cooling of Buildings", The Pennsylvania State University, University Park, Pa., 12-14, June 1975.
5. Ucar, M., "Solar Building Energy Use Analysis", Dissertation, Syracuse University, Syracuse, New York, 1976.
6. Drucker, E. E., et al, "Commercial Building Unitary Heat Pump System with Solar Heating", Final Report to ERDA, Syracuse University, Syracuse, New York, 31 October 1975.
7. Drucker, E. E., et al, "Commercial Building Unitary Heat Pump System with Solar Heating", Semi-annual Report to NSF, Syracuse University, Syracuse, New York, 31 December 1974.

VI. APPENDIX
PUBLIC DISSEMINATION OF SYRSOL

Written documentation of the research described in this report has been widely disseminated through presentation at technical society meetings. These include meetings of ASME, ASHRAE, ISES and other jointly sponsored specialist's meetings. In addition, the following two groups have requested and received actual copies of the computer card deck for their own use:

1. The Singer Company
Climate Control Division
Auburn, New York
2. Inatome and Associates
Consulting Engineers
10140 West Nine Mile Road
Oak Park, Michigan 48237
3. Brookhaven National Laboratory
Department of Applied Science
Upton, New York 11973
4. Newcomb & Boyd
1700 Commerce Drive, Northwest
Atlanta, Georgia 30318
5. Various other organizations.