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SIMULATION STUDY OF SEVERAL SOLAR HEATING SYSTEMS
WITH OFFPEAK AUXILIARY

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ABSTRACT

In essentially all climates, solar heating systems for buildings must incorporate back-up conventional (auxiliary) heating equipment sized to meet the maximum load of the building. In areas with high densities of solar heated buildings using auxiliary energy supplied by utilities, unacceptable peaks in auxiliary energy demand (during cloudy weather) can be prevented via limited on-site storage of the utility supplied energy. In this paper several "offpeak auxiliary" solar air heating systems are compared using simulation methods.

Two basic types of offpeak systems have been studied; Systems I and II, which separate the storage of auxiliary and solar energy, and Systems III and IV, which store all energy in the same pebble bed. Simulation methods are used to determine the effect of system configuration, collector loss coefficient, controls, storage size and collector flow rate on system performance.

INTRODUCTION

In essentially all climates, solar heating systems for buildings must incorporate back-up conventional heating equipment sized to meet the maximum load of the building. Auxiliary energy can be stored on-site, (oil, LP gas), or supplied by a utility (electricity, natural gas). In areas with high densities of solar heated buildings using auxiliary energy primarily supplied by utilities, unacceptable peaks in demand will occur during periods of cloudy weather. Limited on-site storage of the utility supplied energy can be used to minimize these demand peaks by controlling the times at which consumption of utility supplied energy occurs.

In this paper, several offpeak auxiliary solar air heating systems are compared, using simulation methods, to determine the best ways of incorporating on-site thermal storage of energy supplied by a utility. These systems would allow owners of solar heated buildings to minimize their peak-period use of auxiliary energy, and thus help utilities match demand to generating capacity.

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DESCRIPTION OF SYSTEMS

Two basic types of offpeak electric auxiliary solar air heating systems have been studied. The first systems have the storage of auxiliary energy isolated from the storage of solar energy. The second type uses a single storage unit for both solar and auxiliary energy. All of the systems are designed so that sufficient energy is available, either from stored solar or auxiliary energy, to carry the entire space heating load during peak demand periods without resorting to direct use of utility supplied energy.

From a thermal standpoint, the best offpeak auxiliary design is one which allows the solar heating system to perform as well as if auxiliary energy were added in the conventional manner. Such a system can either have two pebble bed storage units, one for solar and one for auxiliary, or one central store for solar energy with commercially available offpeak electric "heat banks" in each room to act as auxiliary. In either case the stored auxiliary energy does not affect the temperature at which the solar portion of the system will operate.

System I in Figure 1, and System II in Figure 2, are two variations of the dual pebble bed concept. Systems I and II are thermally identical except that in System II, when the building requires heat from the auxiliary storage unit, air is moved through both the solar and auxiliary stores. These systems are also thermally identical to non-offpeak solar space and domestic water heating systems with the same system parameters, ignoring heat losses from the auxiliary storage unit; as far as the solar portion of the system is concerned, the offpeak furnace and auxiliary store (together) function like a conventional furnace. System I requires relatively complicated control functions to operate the fans and dampers. System II, suggested by Austin Whillier to perform similarly to I, is arranged so that the fans and dampers can easily be controlled with independently operating on-off controllers.

From the mechanical viewpoint, the simplest offpeak heating system would be identical to the conventional solar air heating system except that the pebble bed store is charged by auxiliary during offpeak hours as needed. System III in Figure 3 and System IV in Figure 4 are two variations of this concept. Since the pebble bed store must always be hot enough to meet the space heating load during peak demand periods, the solar collectors in III and IV will operate at higher temperatures than in I and II. Consequently, I and II will have thermal performance advantages over III and IV.

System III requires relatively complicated control functions to operate the fans and dampers, while System IV is arranged so that fans and dampers can easily be controlled with independently operating on-off controllers. Thermally, III and IV are identical so that simulations of III apply also to IV.

Although the hardware required to control the four systems varies, the control variables in each case are the same. A differential controller

Figure 1 SYSTEM I

System I is a dual storage offpeak auxiliary system requiring relatively complicated controls. The damper positions for the modes of operation are as follows:

Collector to solar storage	A1, B1, CO, DO
Collector to house	A1, BO, - , DO
Solar storage to house	AO, B1, CO, DO
Aux. storage to house	AO, B1, CO, D1
Furnace to house	AO, B1, C1, -
Furnace to aux. storage	A1, B1, C1, D1

Figure 3 System III

System III is a combined storage offpeak auxiliary system requiring relatively complicated controls. The damper positions for the modes of operation are as follows:

Collector to storage	A1, B1, CO
Collector to house	A1, BO, -
Storage to house	AO, B1, CO
Furnace to house	AO, B1, C1
Furnace to storage	A1, BO, C1

Figure 2 SYSTEM II

System II is a dual storage offpeak auxiliary system controlled with independently operating on-off controllers. The damper positions for the modes of operation are as follows:

Collector to solar storage	A1, B1, - , DO
Collector to house	A1, B1, C1, D1
Solar storage to house	AO, B1, C1, D1
Aux. storage to house	AO, B1, CO, D1
Furnace to house	AO, B1, CO, D1
Furnace to aux. storage	AO, B1, - , DO

Figure 4 System IV

System IV is a combined storage offpeak auxiliary system controlled with independently operating on-off controllers. The damper positions for the modes of operation are as follows:

Collector to storage	A1, B1, CO
Collector to house	A1, B1, CO
Storage to house	AO, B1, CO
Furnace to house	AO, B1, C1
Furnace to storage	AO, B1, C1

between the collector outlet and cold end of the pebble bed determines when there is energy to collect. In Systems I and II, a two-stage thermostat in the conditioned space controls room temperature. The first stage calls for heat from the collector or solar storage unit, and the second stage calls for heat from the auxiliary storage unit. In Systems III and IV, which have no separate auxiliary pebble beds, the solar storage unit is never fully depleted because each day during off-peak hours the auxiliary furnace is used to charge the store to the minimum required level. In these systems, the first stage calls for heat to the building either from the collector or storage unit, and the second stage calls for heat from the storage unit.

In each system, the time of offpeak charging of the pebble bed store is assumed to be controlled by a time clock, "ripple" control or other equivalent means. A differential controller compares the average pebble bed temperature to a set minimum average bed temperature (T_{min}) which can change each month, to assure that enough energy is stored to meet the next days' requirements. For service hot water, a differential controller between the preheat tank and air upstream from the heat exchanger controls the operation of the pump which circulates water through the cross-flow heat exchanger. In the summer, the load thermostat is disconnected and the manual damper is moved to allow energy for domestic hot water to be collected without heating the storage unit.

Knowing the size of the thermal storage, the number of offpeak hours in a day, and the lowest daily temperature in the month (T_{LD}) and the lowest hourly temperature on the coldest day of the month (T_{LH}) from weather bureau monthly summaries, the amount of energy which must be in the storage unit at the end of an offpeak period is,

$$Q_{min} = UA(T_{ROOM} - T_{LD})(24 - \text{number of offpeak hours}) \quad (1)$$

The minimum average temperature (T_{min}), which the storage unit must have at the end of an offpeak period to ensure that the space heating load can always be met from storage until the beginning of the next offpeak period, is calculated as follows,

$$Q_{min} = \rho_b V(1 - \epsilon)C_b(T_{min} - T_{MU}) \quad (2)$$

where T_{MU} is the minimum useful temperature. This minimum useful temperature is related to the maximum rate at which energy must be supplied to the load. That is,

$$mC_f(T_{MU} - T_{ROOM}) = UA(T_{ROOM} - T_{LH}) \quad (3)$$

The minimum temperature, T_{min} , is then

$$T_{min} = (1 + C_1 + C_2)T_{ROOM} - (C_1)T_{LH} - (C_2)T_{LD} \quad (4)$$

where,

$$C_1 = \frac{UA}{\dot{m}C_f}$$

$$C_2 = \frac{UA(24. - \text{number of offpeak hours})}{\rho_b V(1-\epsilon)C_b}$$

This method of estimating $T_{\min}$ is conservative for a number of reasons. The above calculation assumes that the coldest hour of the coldest day of each month occurs immediately before the start of an offpeak period, when storage is depleted the most. Also, it is assumed that the thermal store is of uniform temperature during the coldest hour, thus ignoring stratification in the pebble bed. And it is assumed that the coldest day of each month occurs after a string of sunless days. These considerations should offset the possibility that a future year may be colder than the weather records used to estimate T_{LD} and T_{LH} .

SIMULATION MODELS

All simulations were performed using hour-by-hour meteorological data for a design year heating season (October through April) in Madison, chosen in the manner described by Klein, et al. [1]. The total solar radiation incident on the tilted surface is estimated from data available for solar radiation incident on a horizontal surface. Beam and diffuse components are estimated from the total radiation on a horizontal surface using the empirical relationship of Liu and Jordan [2] on an hour-by-hour basis. The beam component is converted to the beam radiation falling on a tilted surface using standard trigonometric relationships. The tilt correction for the diffuse component is estimated by assuming that diffuse radiation is uniformly distributed over the sky and the ground is a diffuse reflector of solar radiation with a reflectance of 0.2.

Systems I, II and III were all modeled with two collectors: a flat plate collector, and an evacuated cylindrical glass tube collector with a very low loss coefficient. Flat plate air heating collectors were modeled using the methods of Hottel, Whillier and Bliss [3]. The low loss coefficient collectors were assumed to be those made by Owens-Illinois. Beekley and Mather [4] have analyzed this collector using water as the transfer fluid; with air, the analysis is identical, except radiative heat transfer between the absorber and delivery tubes must be considered. Eberlein [5] presents a detailed description of the model used.

A model of the pebble bed thermal store can be obtained by solving the partial differential equations of the Schumann model as described by Jakob [6]. However, when these equations are solved as part of a long-term simulation, the computing costs become unacceptably high.

A simpler model, used here, has been derived by Hughes, et al. [7] by noting that for systems of practical design, long-term solar air heating system performance is insensitive to the number of transfer units (NTU) of the pebble bed. This simple model is valid if NTU_c , the corrected value of NTU, which accounts for the effects of axial dispersion and finite conductivity of the rock, is greater than 10.

The domestic hot water load is modeled as a constant 20 kg/hr mass flow rate of water required at 60°C for 13 hours of the day. The supply main or well water temperature is assumed to be 11°C throughout the year. A more detailed hot water load distribution throughout the day has little effect on system performance.

The space heating load is modeled using the UA-degree hour concept. Capacitive effects in actual buildings delay and "smooth out" instantaneous heat requirements, but Klein [8] has shown that the effect of the time distribution of the load on long-term solar heating system performance is small.

For a more detailed description of the simulation models, see Hughes [9]. System parameter values for all of the simulations are tabulated in Appendix A.

SIMULATION RESULTS

Comparative Performance of Four Systems

The performance of Systems I, II and III has been simulated, using the Madison design year weather data (October through April) and design parameters for a proposed experimental house at Arlington, Wisconsin.[†] Both evacuated tubular (ET) and standard two-cover nonselective flat plate (FP) collectors were used. Table 1 contains the results; runs are coded with the system Roman numeral followed by the collector abbreviation.

The Arlington House roof has room for 50.6 m² of FP collectors in 0.92 by 1.98 m modules (Solaron Corporation air heater dimensions) or 194 ET collector tube pairs covering 44 m² (using Owens-Illinois dimensions) when spaced one tube diameter apart. The ET collector flow rate was chosen to be 8.18 kg/hr of air per tube pair (4 SCFM/tube pair), a reasonable compromise between pressure drop and thermal performance. The same total air flow rate was used through the FP collector bank (3.14 kg/hr-m² or 1.5 SCFM/ft²).

Aside from the collectors, all other system parameters were kept the same in all of the simulations where possible. The volume of the

[†]An experimental solar home being constructed by the University of Wisconsin Solar Energy Laboratory.

solar pebble bed store in System I was 22 m^3 , as was the volume of the store in System III. The combined volume of the split pebble bed of System II, including a plenum space of 0.21 m between the sections, was also 22 m^3 resulting in a pebble volume in the combined beds of 20.5 m^3 . All of the flow rates in all of the systems were identical. The space and domestic water loads and control temperatures were also the same.

From Table 1, System I performed the best, followed by II and III. System II is thermally identical to I, except that room air passes through the solar pebble bed on its way to the auxiliary store during second stage heating. This suggests that System II should be superior to I, since the solar pebble bed is always driven to the lowest possible temperature; however, the larger volume of the solar pebble bed in System I more than offsets this effect. System III was not expected to perform as well as the others because of the consistently higher temperature at which the pebble bed store, and thus the collectors, must operate.

The evacuated tubular collector performed better than the two-cover nonselective flat plate collector in all of the systems. The ET collector has a low loss coefficient and is thus relatively insensitive to inlet temperature. It is interesting to note that with the ET collector, System III performs nearly as well as I and II. This fact led us to study the effects of various system design parameters on the performance of System III with ET collectors.

Effects of Tube Spacing and Flow Rate on System III Performance

The effects of tube spacing and flow rate can be seen in Table 2. Tube spacings of 1.5 diameters, 1.0 diameters and 0.5 diameter result in 156, 194, and 260 tube pairs on the 44 m^2 backing area. Flow rates of 6.135 kg/hr (3 SCFM), 8.18 kg/hr (4 SCFM) and 10.225 kg/hr (5 SCFM) of air per tube pair were used.

There is an apparent anomaly in Table 2; the run with $m = 1984$ kg/hr shows a decrease in performance as compared to identical simulations with lower flow rates. However, this is due to the fact that in all three simulations, the collector was controlled with a differential controller using the same temperature deadband. At low radiation levels the collectors with lower flow rates will operate more often, since less incident radiation is required to induce the specified temperature rise.

From Table 2 it is seen that by increasing the spacing between ET collector tubes, an increase in performance per tube pair is realized, although fewer tubes can be placed in a given area. Decreasing the number of tube pairs from 260 to 194 only decreases the total load carried by solar energy by 5.1%.

Effects of Storage Size on System III Performance

Simulations of System III with flat plate and evacuated tubular collectors have been performed with several storage sizes. Table 3 shows the characteristics of the five sizes of storage units employed and the simulation results. It can be seen from Figure 5 that single storage offpeak systems with flat plate collectors need larger storage units than those with evacuated tubular collectors. Evacuated tubular collector system performance is insensitive to storage size beyond 16 m^3 ; the critical storage size is closer to 22 m^3 for the flat plate system.

Effects of Controls on System III Performance

In solar air heating systems, the collector receives air from either the conditioned space or the cold end of the pebble bed. The collector is usually turned on by comparing the collector temperature to the inlet temperature. Since air can enter the collector from either the conditioned space or storage unit, two differential controllers are required to compare the collector temperature to the room and cold end pebble bed temperatures, respectively. Typical air heating collectors have only one controller because the two possible collector inlet temperatures are nearly identical throughout the winter, while in the spring and fall, the system is over-designed so that collector control is not critical. However, in offpeak auxiliary systems similar to System III, the cold end pebble bed temperature is generally not equal to room temperature, so simulations were done to determine the performance penalty incurred by using one rather than two differential controllers to control the collector.

The offpeak charging of the pebble bed is controlled by comparing the average pebble bed temperature obtained from a thermopile (or several thermocouples) to a set minimum average temperature, which changes each month to account for the variation in maximum space heating load with time of year. In northern climates, the solar system is over-sized in the spring and fall so that the average pebble bed temperature is often higher than that required in the winter. Thus the performance penalty incurred by maintaining the minimum average pebble bed temperature at its maximum monthly value throughout the year was determined.

The results of these simulations appear in Table 4. Using two collector differential controllers results in only a moderate performance increase. Simplifying the control of offpeak pebble bed charging by keeping the minimum average bed temperature ($T_{\min}$) constant over the year results in a small decrease in performance. This decrease is small because in the spring and fall the average pebble bed temperature is generally higher than $T_{\min}$ anyway, while at other times, the higher system temperatures caused by this control simplification have little effect because ET collector performance is nearly insensitive to inlet temperature.

Effect of Service Hot Water Heat Exchanger Position on System III Performance

Table 5 shows the effects of location for the domestic hot water heat exchanger. With the heat exchanger at the collector outlet, more energy is transferred to the domestic water system so that, on the average, the rest of the system operates at a lower temperature. Placing the heat exchanger in front of the collector drives down the collector inlet temperature somewhat, but on the average, not as low as before, since less energy is transferred to the domestic water system. Since ET collector performance is rather insensitive to inlet temperature, the difference between these two cases is small.

CONCLUSIONS

Two basic types of offpeak electric auxiliary solar air heating systems have been studied using simulation methods; Systems I and II, which separate the storage of auxiliary and solar energy, and Systems III and IV, which store all energy in the same pebble bed. Systems I and II are thermally identical to conventional (non-offpeak) solar air heating systems, if losses from the auxiliary storage unit are ignored; Systems III and IV must operate at higher temperatures than Systems I and II because of the single storage unit but are simpler from a mechanical viewpoint. The simulation results presented in Table 1 show the superiority of the separated storage concept. However, combined storage offpeak auxiliary systems (Systems III and IV) perform nearly as well as separated storage systems (Systems I and II) provided that low loss coefficient collectors, such as the evacuated tubular type, are used.

In the flat plate collector systems, system performance remains sensitive to storage size until it is increased beyond approximately 22 m^3 . With evacuated tubular collectors, the asymptotic value of system performance is approached near 16 m^3 . Therefore, smaller storage units can be used in offpeak auxiliary systems with low loss coefficient collectors.

Table 2 shows that system performance is a weak function of collector flowrate, for flowrates high enough to allow energy distribution to the load at comfortable temperatures. Table 2 also indicates that it is always preferable to space a given number of evacuated tubular collectors over as large an area as possible, and that increasing the density of tubes on a given area by packing them closer than approximately one diameter apart will not increase system performance enough to warrant the extra cost. In fact, the economic optimum tube spacing on a given area may be larger than one diameter.

Table 4 indicates that one differential controller comparing the collector outlet temperature to the cold end pebble bed temperature is sufficient to control collector operation. Table 4 also indicates that the minimum average temperature to which the storage unit is heated daily during offpeak hours can remain the same throughout the heating season with only a small performance penalty.

The service hot water crossflow heat exchanger is in the collector to storage air flow loop because this loop is most likely to have consistent air flow during the day when most hot water is used. Simulations summarized in Table 5 show that in offpeak systems such as III and IV, it makes little difference whether the heat exchanger is located at the collector inlet or outlet.

DISCUSSION

Offpeak auxiliary solar systems for buildings are a necessity if the widespread use of solar energy is to become a reality in areas where only utility-supplied auxiliary energy is available. Simulations are useful in comparing basic offpeak auxiliary designs and analyzing the effects of many design variables. This information is useful for designing an experimental offpeak auxiliary system. It is expected that the experimental system will be useful for working out the practical problems involved in building and controlling a real system in the optimum manner. With adequate instrumentation, the experimental system can be used to pinpoint weaknesses in the design which prevent the real system from reproducing the simulated predictions.

NOMENCLATURE

- C - specific heat [$\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$]
- ET - evacuated tubular collector
- FP - flat plate collector
- h_v - volumetric convective heat transfer coefficient [$\text{kJ hr}^{-1} \text{ } ^\circ\text{C}^{-1} \text{ m}^{-3}$]
- $\dot{m}$ - air flowrate through the storage unit [kg hr^{-1}]
- NTU - $h_v V / \dot{m} C_f$ [dimensionless]
- NTU_c - corrected NTU accounting for axial dispersion and finite conductivity of the pebbles [dimensionless]
- $Q_{\min}$ - maximum daily heating load incurred during non-offpeak hours in the month [kJ]
- T - temperature ($^\circ\text{C}$)
- UA - (Building design heat load) (design temperature difference) $^{-1}$ [$\text{kJ hr}^{-1} \text{ } ^\circ\text{C}^{-1}$]
- V - Volume of the pebble bed [m^3]
- ϵ - void fraction of pebble bed [dimensionless]
- ρ - density [kg m^{-3}]

Subscripts

- b - storage unit packing material (pebbles)
- f - fluid (air)
- LD - lowest daily (for the month)
- LH - lowest hourly (for the day)
- MU - minimum useful

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Figure 5 Fraction Supplied by Solar vs. Storage Size For System III

Table 1
Effect of System Configuration and Collector Type

<u>SYSTEM</u>	<u>HR</u>	<u>Q_u</u>	<u>Q_L</u>	<u>Q_{AUX}</u>	<u>Q_{WL}</u>	<u>Q_{WAUX}</u>	<u>% by Solar</u>
I (ET)	128.79	61.85	81.65	28.75	12.16	3.51	65.6
I (FP)	148.11	53.84	81.65	34.80	11.47	4.35	58.0
II (ET)	128.79	60.96	81.65	30.10	12.49	3.35	64.5
II (FP)	148.11	52.66	81.65	36.35	11.55	4.22	56.5
III & IV (ET)	128.79	59.14	81.65	33.90	12.78	1.88	62.1
III & IV (FP)	148.11	46.46	81.65	43.95	11.66	3.35	49.5

where

HR - total radiation incident on 50.6 m² (FP) or 44.0 m² (ET) tilted 59° due south (GJ)

Q_u - useful energy gained by collector (GJ)

Q_L - space heating load (GJ)

Q_{AUX} - space heating auxiliary energy (GJ)

Q_{WL} - domestic water load actually supplied (GJ)

Q_{WAUX} - domestic water auxiliary energy (GJ)

% by Solar - percent of total load (Q_L + Q_{WL}) met by solar

Table 2

Effect of Tube Spacing and Flow Rate on the
Performance of Systems III with ET Collectors

<u>System</u>	<u>Tube Pairs</u>	<u>$\dot{m}_{coll.}$ (kg/hr)</u>	<u>Q_u</u>	<u>Q_L</u>	<u>Q_{AUX}</u>	<u>Q_{WL}</u>	<u>Q_{WAUX}</u>	<u>% by Solar</u>
III(ET)	156	1595.	53.15	81.65	38.85	12.18	2.26	56.2
III(ET)	194	1190.	58.42	81.65	35.05	13.07	1.72	61.2
III(ET)	194	1587.	59.14	81.65	33.90	12.78	1.88	62.1
III(ET)	194	1984.	58.15	81.65	34.60	12.59	2.02	61.1
III(ET)	260	1595.	64.75	81.65	29.60	13.40	1.59	67.2

Table 3

Effect of Storage Size on System III Performance

STORAGE CHARACTERISTICS:

<u>Storage Size</u> <u>(m³)</u>	<u>T_{min} in January</u> <u>(°C)</u>	<u>NTU</u>	<u>NTU_c</u>
6.	104.	21.	14.5
10.	81.	25.	17.5
16.	67.	28.	20.0
22.	61.	31.	22.0
28.	58.	34.	24.0

STORAGE SIZE SIMULATION RESULTS:

<u>System</u>	<u>Storage Size</u> <u>(m³)</u>	<u>HR</u>	<u>Q_U</u>	<u>Q_L</u>	<u>Q_{AUX}</u>	<u>Q_{WL}</u>	<u>Q_{WAUX}</u>	<u>% by Solar</u>
III(ET)	6.	128.79	51.01	81.65	46.5	15.95	.69	51.7
III(ET)	10.	128.79	54.18	81.65	41.8	14.73	.99	55.6
III(ET)	16.	128.79	57.84	81.65	36.4	13.47	1.44	60.2
III(ET)	22.	128.79	59.44	81.65	33.9	12.78	1.88	62.1
III(ET)	28.	128.79	59.95	81.65	32.8	12.50	2.09	62.9
III(FP)	6.	148.11	25.19	81.65	67.75	13.09	2.09	26.3
III(FP)	10.	148.11	35.76	81.65	56.1	12.34	2.49	37.7
III(FP)	16.	148.11	42.9	81.65	48.0	11.86	3.04	45.4
III(FP)	22.	148.11	46.46	81.65	43.95	11.66	3.35	49.3
III(FP)	28.	148.11	47.88	81.65	42.3	11.59	3.49	50.9

Table 4

Effect of Simplified Controls on the Performance of
System III

<u>System</u>	<u>Number of Collector Controllers</u>	<u>T_{min}</u>	<u>Q_u</u>	<u>Q_L</u>	<u>Q_{AUX}</u>	<u>Q_{WL}</u>	<u>Q_{WAUX}</u>	<u>% by Solar</u>
III(ET)	1	constant	57.9	81.65	36.65	13.30	1.60	59.7
III(ET)	1	varies monthly	59.14	81.65	33.90	12.78	1.88	62.1
III(ET)	2	varies monthly	61.04	81.65	32.10	12.83	1.98	63.9

Table 5

Effect of Heat Exchanger Position on the
Performance of System III

<u>System</u>	<u>Ht-x Position</u>	<u>Q_u</u>	<u>Q_L</u>	<u>Q_{AUX}</u>	<u>Q_{WL}</u>	<u>Q_{WAUX}</u>	<u>% by Solar</u>
III(ET)	collector outlet	59.14	81.65	33.90	12.78	1.88	62.1
III(ET)	collector inlet	58.40	81.65	30.60	11.56	4.94	61.9

Appendix A

Parameter Values Used in the Simulations

EVACUATED TUBULAR COLLECTORS

Active tube length	1067.00 mm
Absorber tube outer diameter	43.00 mm
Cover tube outer diameter	53.00 mm
Number of glass covers	1.00
Emittance	0.07
Absorptance	0.86
Effective transmittance - absorptance product	0.78
Backing surface tilt from horizontal	59.00 degrees
Azimuth angle (0° = due south)	0.00 degrees
Backing surface area (w/o manifolds)	44.10 m ²
Total number of tube pairs	
Table 2	156.00
Tables 1-5	194.00
Table 2	260.00
Air flowrate per tube pair	
Table 2	6.1 Kg/hr
Tables 1-5	8.18 Kg/hr
Table 2	10.22 Kg/hr

FLAT PLATE COLLECTORS

Efficiency factor (F')	.80
Number of glass covers	2.00
Emittance	.94
Absorptance	.94
Cover system transmittance	.80
Top loss coefficient	(function of condition)
Bottom and edge loss coefficient	2.00 KJ/hr-m ² -°C
Tilt from horizontal	59.00 degrees
Azimuth angle (0° = due south)	0.00 degrees
Collector area	50.60 m ²
Air flow rate	32.00 Kg/hr-m ²

SERVICE HOT WATER SYSTEM

Pre-heat tank volume	.45 m ³
Tank loss coefficient	1.50 KJ/hr-m ² -°C
Cross-flow heat exch. effectiveness	.52
Water side flow rate	450.00 Kg/hr

Appendix A (Continued)

Parameter Values Used in the Simulations

FAN

Capacity (assumed the same for all modes)

Flat plate collector simulations	1632.00 Kg/hr
Evacuated tubular collector simulations	
Table 2	1190.00 Kg/hr
Tables 1-5	1587.00 Kg/hr
Table 2	1984.00 Kg/hr

CONTROLS

Offpeak hours	10 p.m. - 8 a.m.
Minimum temperature rise across collector	5.00 °C
1st stage heating	T _{ROOM} < 20°C
2nd stage heating	T _{ROOM} < 18.3°C

Appendix A (Continued)

Parameter Values Used in the Simulations

SERVICE HOT WATER SYSTEM (Continued)

Air side flow rate	1190.-1984. Kg/hr
Supply water temperature	60.00 °C
Mains water temperature	11.00 °C
Water consumed, 6 a.m.-7 p.m.	20.00 Kg/hr

PEBBLE BED STORAGE UNITS

Perimeter	14.00 m
Density (including voids)	1600.00 Kg/m ³
Effective axial thermal conductivity	.45 KJ/hr-m-°C
Thermal loss coefficient	1.10 KJ/hr-m ² -°C
Specific heat of gravel	.84 KJ/Kg-°C

System I (Solar storage), III and IV

Volume	22.40 m ³
Height	1.83 m

System II (Solar storage)

Volume	14.90 m ³
Height	1.22 m

System III (Auxiliary storage)

Volume	5.60 m ³
Height	.46 m

SPACE HEATING LOAD

UA	900.00 KJ/hr-°C
Constant internal heat generation rate	1500.00 KJ/hr
Thermal capacitance of building	25000.00 KJ/°C
note - energy losses from pebble beds and pre-heat tank are subcontracted from the load	

AUXILIARY FURNACE

Capacity	200000.00 KJ/hr
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