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**ADDITION OF INEXPENSIVE SOLAR AIR-HEATERS TO A
PRE-ENGINEERED METAL BUILDING**

Final Report

By
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MASTER

May 1979

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Solar Energy

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Final Report

25 September 1977 - 25 March 1979

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INTRODUCTION

Increases in price and limited availability of fossil fuels have stimulated interest among researchers in energy conservation. The problem of heating industrial buildings in the southeastern states is especially acute. The majority of these industrial buildings are not energy efficient since they were built when fossil fuels were plentiful and relatively inexpensive. Current energy costs have increased sharply for owners of these buildings.

At Mississippi State University a research project was begun in 1976 to investigate the use of site-built solar collectors for heating air in poultry houses. The purpose of this work was to design and test a functional air heater solar collector which would be inexpensive to construct and acceptable to poultry producers. The results reported here are an extension of the original concept. The basic concept is to use a pre-engineered metal building for the structure and incorporate the solar air-heaters as an integral part of the south facing wall of the building. The outer skin of the building is used as the absorber plate for the collectors.

The report will first discuss construction and testing of the solar collectors and heat storage systems and the latter portion of the report will deal with the performance characteristics of the site-built solar collectors.

SFK BUILDING MODIFICATIONS

General Description

The Gulf States Model SKF pre-engineered metal building is normally used as an inexpensive storage facility where the primary concern is to keep the storage dry. The pre-engineered metal building has two alternate plans for construction to suit the consumer's needs. Figure 1 shows the typical cross section of the Model SKF building used at Mississippi State University. Gulf States, Inc. donated this Model SKF pre-engineered metal building for the testing purposes. The building is all steel, which insures stability and promotes low cost. The seventy-degree slanted wall is well suited for a solar collector in this area because the sun's elevation in the winter is about 35 degrees at noon which provides normal solar incidence when it is most critical.

In a solar heated building insulation must be maximized and air leakage must be minimized. To achieve these desired results, corrugated rubber weather-stripping similar to the building corrugated metal was placed in the open air spaces as the building construction progressed. In addition, one inch-thick beaded styro-foam insulation was laid on the outside edge of the 30 by 48 foot slab to reduce the slab edge losses.

The roof is galvanized steel and was constructed with a slight slope for water run-off.

TYPICAL CROSS SECTIONS

Figure 1 Typical Cross-Section of Pre-Engineered Metal Building

The Solar Collectors

Air-type solar collectors are generally more efficient when collecting heat under the receiver plate and allowing for a stagnant air space between the receiver plate and the glazing. The shorter wavelength radiation from the sun incident upon the collector will be transmitted through the glazing to the receiver plate. The longer wavelength radiation is not transmitted through the glazing. As the collector surface receives this thermal energy it gets hotter and begins to re-radiate at a longer wavelength which the glazing will not pass.

The collector system at Mississippi State used a stagnant air space over the receiver with heat collection under the receiver plate. A total of 480 square feet of the south wall were utilized as the collector. Approximately one foot at the top and bottom of the south wall was left unpainted to prevent thermal degradation of the rubber weather-stripping due to high wall temperatures in the summer. A readily available flat black paint (RUSTOLEUM) was used to paint the outer surface of the south facing wall. The paint was spray applied after cleaning the outer surface of the metal wall with tri-sodium-phosphate.

The glazing for the collectors was chosen to be roll type fiberglass (KALWALL, .060 inch thick) for ease of installation on a site-built collector. The KALWALL was attached to the outer skin of the building using 1 by 2 inch fir wood strips as shown in Figure 2. The fir strips were attached to the corrugated metal wall using flat head screws. The KALWALL was then attached to the wooden strips using pan head self-drilling sheet metal

Figure 2. KALWALL Glazing Attachment to Skin of
Pre-Engineered Metal Building.

screws. The self-drilling feature prevented cracking of the KALWALL as the screws were driven with a variable speed electric drill. The KALWALL was applied horizontally in strips and overlapped to prevent leaks as shown in Figure 3. Leaks in the glazing are not critical in this installation since the wall of the building is leak resistant prior to installation of the glazing.

The inner collector wall was constructed of second grade corrugated metal of a pattern similar to the building corrugation. By installing the inner wall in a criss-cross pattern to the outer wall, a one-and-one-half inch deep air flow space was created. This construction technique promotes expected turbulence effects due to the corrugation and thus produces a high heat transfer coefficient which permits a higher heat collection. The 26 gauge sheet metal was purchased in 3 by 10 foot sheets and was easily installed as shown in Figure 4.

The corrugated metal which formed the flow channels was attached to the back side of the skin of the building (Figure 4) by using conventional neoprene gasketed sheet metal screws which were installed from the outer side of the building wall.

The inner wall of the collectors consisted of ten sections, each with one-foot-wide air channels approximately twenty-two feet long connected to the center of the building by a plenum reaching the height of the air channels. All air pulled through the collectors was centralized here before being drawn into the room. The plenum is approximately twenty-one inches wide and twelve inches deep. To ensure a good fit next to the inner wall, the plenum was cut by a jigsaw and caulked to prevent air leak-

Figure 3. Collector Surface on South Wall of Pre-Engineered Metal Building.

Figure 4 Flow Channels in Place on South Wall

age. The back of the plenum was covered by plywood and the common edges were caulked with a butyl compound. Figure 5 shows the completed plenum and the ducting used to transport the heated air out of the collector system.

The Building Interior

Once the building was erected and the collector system finished, the interior of the building had to be modified mainly for insulation purposes. A network of two by four studs were positioned along all four walls and spaced two feet apart so that the inexpensive wood paneling could be easily attached. A froth-in-place type insulation, urea formaldehyde foam (RAPCO), was blown into the wall cavities formed by the wooden studs and adhered readily to the metal. The studs were positioned at a distance of one-half inch away from the metal siding to permit the foam to cover the entire wall area. The manufacturer's specifications indicate the foam has a R value (resistance to heat transfer) of 25 for a three-and-one-half inch thickness. One precaution must be mentioned about this foam because it will "outgas" (emit volatiles from the material) when temperatures exceed 280 degrees Fahrenheit [1]. The foam required several weeks of curing time as a noticeable odor was evident and one's eyes watered within seconds upon entry whenever the building had been shut up overnight. Since the foam was blown in under pressure in all the cavities, it was assumed that any major air leaks not sealed during the earlier construction were now eliminated. Polyethylene was stapled to the two by four studs to prevent the insulation from falling out of the cavities

Figure 5 Plenum and Duct Installed on the South Wall.

after drying. A one-percent shrinkage of this foam was expected as advised by the manufacturer and within two weeks the foam had developed about a one-inch gap along the sides of the studs and about two inches along the top of the stud framework. Figure 6 shows the RAPCO foam in place with shrinkage prior to the completion of the interior wall construction.

In accordance with required building codes, one-half inch conduit was used for running the electrical wiring. A junction box was located immediately inside the building close to an existing exterior switch box. All conduit within the building was run from this box to four 110-volt double receptable boxes, two light switches, and one three-phase 220-volt receptacle for the blower. The light switches were installed so that adequate lighting would be available upon entrance from either side door. The conduit was attached directly to the metal purlins supporting the roof and conduit boxes were spaced at ten-foot intervals for ceiling lighting on each side.

To insulate the ceiling a suspended type of construction was used by bolting wooden one by fours in a criss-cross pattern to the existing metal purlins. The conduit already in place on these purlins posed no major problem, as it acted only to suspend the ceiling further down. Tongue and groove styrofoam insulation sized two by eight feet and two inches thick was fastened to the framework of one by fours with two-and-one-half by one-quarter inch lag bolts using a pneumatic impact wrench. As a precaution, three-quarter inch washers were used with the lag bolts to provide a larger stress distri-

Figure 6 RAPCO Foam Insulation in Place on the South Wall

bution over the foam and to ensure no slippage. Powered by the impact wrench, these bolts were driven about one-quarter of an inch into the styrofoam to assure a tight hold.

For best fitting of the styrofoam and a neat finished appearance, a nichrome wire powered by a Variac was utilized to cut the foam. By setting the Variac to a certain voltage level, the styrofoam could be cut easily in any desired shape. On the north and south walls of the building where the seventy-degree slanted walls posed a problem of close fittings, this apparatus was assembled to pre-cut the ends of the styrofoam at the desired angle which assured little air leakage. Tongue and groove insulation was used primarily to reduce infiltration from the ceiling. Since the lights were already fastened to the purlins, the styrofoam was cut by a soldering iron to fit around the light sockets.

Thermal Storage

Gravel is generally used as the storage medium for an air system and was used in this project. Close [2] has indicated that gravel less than one-quarter inch in diameter should not be used because it induces a very high pressure drop through the storage. A local ready-mix contractor had a one-inch diameter gravel available and this was used after cleaning.

The storage box was positioned directly in front of the blower. A twelve-inch round duct connects the blower box to the heat storage chamber. To permit an evenly distributed air flow through storage, a twelve-inch air space was allowed before the actual rock storage began and to accommodate duct work later to be installed. A network of two by four studs with

one-half inch hardware cloth was built into the storage to restrict the gravel on the ends. No baffles were added to prevent possible air channeling, but from inspection of the air flow at the end of the completed storage, it seemed that an even air flow was occurring.

The size of the storage was based on collector size and typically is 0.17 to $0.26 \text{ M}^3/\text{M}^2$ [2]. Equivalently in English units, it corresponds to 0.56 to $0.85 \text{ FT}^3/\text{FT}^2$. Basing the size on $0.20 \text{ M}^3/\text{M}^2$, the required storage volume was 8.92 M^3 or 315 FT^3 , but the size of storage was physically restrained by the building dimensions. For ease in construction a perimeter of two by four studs, eighteen by eight feet, was fastened to the concrete floor by one-quarter inch tap-ins to facilitate easy storage removal if necessary after completion of this project. An allowance of two one-foot air gaps at either end of the storage reduces the perimeter to sixteen by eight feet. The sides of the storage were formed by cutting three-quarter inch plywood into sheets of two by eight feet. This size made construction easier because the styrofoam insulation size was now compatible; however, this reduced the effective storage volume to about 260 cubic feet. Nonetheless, construction of the storage proceeded with the understanding that a storage based on the minimum requirement for storage volume of $0.56 \text{ FT}^3/\text{FT}^2$ was used. To help prevent swaying and lateral movement of the plywood upon gravel input, four two-by-four studs were placed one inch from the tops of the plywood sides and bolted through the plywood by lag bolts. A one-inch depression of these studs down from the top inside the box was necessary so that insulation could be added later. One-half inch plywood decking was placed over the insulation to stop air

leaks and air channeling over the top of the gravel. The final level of the gravel was to coincide with the tops of the studs. The top layer of insulation was taped to the edges of the storage and at each connecting seam of the insulation to safeguard against air leaks. The top decking also served to protect the top of this storage system.

The Ducting System

The ducting system has been omitted from previous discussion so that it could be explained in one major section. Once the air was drawn through the collectors and centralized in the plenum, it was pulled through a round fourteen-inch duct to the blower and into a centralized blower box. Three modes of operation are possible:

Mode 1. Heating Directly from Collectors

Mode 2. Charging Storage

Mode 3. Heating from Storage

Figure 7 and Table 1 indicate the locations of all important components in the experimental system (dampers, thermocouples, etc.).

Figures 8, 9, and 10 indicate the positions of all dampers for the three modes of operation. All dampers were manually positioned as required during the gathering of experimental data. All ducting leaving the centralized blower box is twelve inch round duct.

Figure 11 shows a view of the duct work and heat storage bed and other portions of the experimental system.

Table 2 shows the various system modes indicating position of the various dampers for the three modes of operation and air flow rates.

Figure 7. System Component Location.

BUILDINGS AND EQUIPMENT - 0

1. TRAILER (DATA SYSTEM)
2. SHED
3. BUNKER
4. COLLECTOR
5. PLENUM (WALL, EAST)
6. PLENUM (WALL, CENTER)
7. PLENUM (WALL, WEST)
8. DAMPER NO.1
9. DAMPER NO.2
10. DAMPER NO.3
11. DAMPER NO.4
12. DAMPER NO.5
13. DAMPER NO.6
14. DAMPER NO.7
15. DAMPER NO.8
16. MAIN BLOWER
17. AUXILLARY BLOWER
18. AUXILLARY HEATER
19. ROCKBED
20. PLENUM (ROCKBED, EAST)
21. PLENUM (ROCKBED, WEST)
22. DELTA T CONTROLLER
23. SWITCH (AUXILLARY SYSTEM)
24. TIMER
25. RECORDER
26. FILTER (RETURN AIR)

SENSORS - A

1. RELATIVE HUMIDITY (INSIDE)
2. RELATIVE HUMIDITY (OUTSIDE)
3. PYRANOMETER (COLLECTOR)
4. PYRANOMETER (HORIZONTAL)
5. THERMOCOUPLE (6")
6. THERMOCOUPLE (30")
7. THERMOCOUPLE (6')
8. THERMOCOUPLE (AMB)
9. THERMOCOUPLE (INL)
10. THERMOCOUPLE (OUTL)
11. THERMOCOUPLE (EPL)
12. THERMOCOUPLE (ERB)
13. THERMOCOUPLE (CRB)
14. THERMOCOUPLE (WRB)
15. THERMOCOUPLE (WPL)
16. THERMOCOUPLE (CLE)
17. THERMOCOUPLE (CLN)
18. THERMOCOUPLE (ΔT CONTROLLER)
19. THERMOCOUPLE (ΔT CONTROLLER)
20. THERMOSTAT (FAN)
21. THERMOSTAT (HEATER)

Table 1. System Nomenclature.

MODE 1 - HEATING ROOM FROM COLLECTOR

Figure 8. Mode 1. Heating from Collectors.

Figure 9. Mode 2. Charging Storage.

Figure 10. Mode 3. Heating Room from Storage.

Figure 11. Photograph of Building Interior.

Mode	Mode Description	Dampers							
		1	2	3	4	5	6	7	8
I	Heating Room from Collector	0	0	0	X	X	0	X	0
II	Charging Storage	0	X	X	0	X	X	0	0
III	Heating Room from Storage	X	0	X	X	0	0	0	X

Table 2. System Modes and damper positions for Heat Collection, Heat Storage and Heating from Storage. 0-open X-closed.

Supplemental heat was available through use of electrical resistance heating which was thermostatically controlled. The heaters were operated when the thermal storage of the rock bed became exhausted. The quantity of auxiliary heat utilized was measured by knowing the KW rating of the heaters and using an electric clock to measure the total time of operation of the heaters.

Instrumentation

A mobile minicomputer-controlled data acquisition system was used during the testing phase of this project. With this system, a teletype terminal was used to communicate with the minicomputer. The minicomputer controlled the scanner which sampled 21 separate channels once each hour. These data were then recorded on magnetic tape and printed on the teletype. The magnetic tape was taken to the Mississippi State University UNIVAC 1106 computer each week where the data were stored for future analysis. When close monitoring was necessary, the period between data sampling was reduced from 1 hour to 15 minutes. Thermocouples, dewprobes, and a pyranometer were used

in obtaining data with this system. Copper-constantan thermocouples were used for temperature evaluations. Data description and sensor location relative to the building are presented in Fig. 7.

In addition to the sensors shown on Figure 7, accumulated solar insolation on the horizontal plane was obtained from an Epply pyranometer approximately 2 km from the building. Instantaneous values of solar insolation at normal incidence to the collector plane were acquired at the test site. Airflow rates for several modes of operation were determined by using a velometer and a hot wire anemometer. A variable speed blower was used to provide air flow through the solar heating system and blower speed was determined with a strobotac.

The pressure drops through the collectors and through the rock storage were measured at various air flow rates by a magnehelic gauge.

TEST PROCEDURE

General Description

In order to determine the performance of a solar collector and storage system, reliable equipment was essential. A variable speed blower was used to induce different air flow rates through the collectors, while the mobile minicomputer registered the air temperature at numerous locations. Figure 7 shows a schematic of sensors used for recording experimental data.

Blower

For those days when collector performance was all that was tested, the blower ran for approximately ten hours per day. A delta "T" control (DDT Model 100, Heliotrope General) was used to actuate the fan when the collector surface temperature exceeded the storage rock bed temperature by 9°F.

Determination of the Air Flow Rates

The air flow rates were determined by a velometer which was inserted into the duct perpendicular to the air flow direction. An opening large enough to admit the probe into the duct was cut at a distance downstream for the plenum to reduce the entrance effects on the velometer's readings. The air traversing through the probe engaged a spring-loaded indicator which read in feet per minute. The probe was marked in one-inch increments to facilitate readings throughout the duct. Time averaged readings were taken at every inch inside the fourteen-inch duct and recorded. These readings were fairly symmetric about the duct

centerline which permitted an easy determination of the average air velocity. Multiplication by the duct cross-sectional area will yield the flow rate in cubic feet per minute (CFM). The accepted standard for rating collector air flow rates is CMF/FT², and this was finally calculated by dividing the CFM measurement by the collector area. The results as reported herein are for an average flow rate of 1010 CFM or 2.1 CFM/FT² collector surface.

Collector Heat Collection

The test to determine how well the particular solar collector was performing was by evaluating its heat collection rate and its efficiency. An average value of heat collection per square foot of collector area was calculated by

$$Q_c = \frac{M C_p \Delta T}{A_c} \quad (60) \quad (1)$$

where

- Q_c = Quantity of heat collection, BTU/HR FT²
- M = Air mass flow rate, LB/MIN
- C_p = Specific heat of air, BTU/LB °F
- ΔT = Temperature difference between collector exit and ambient, °F
- A_c = Collector area, FT²

The value of the air mass flow rate was found by using

$$M = \rho A V, \quad (2)$$

where

ρ = Air bulk density, LB/FT³

A = Duct cross-sectional area, FT²

V = Measured average air velocity, FT/MIN

No attempt was made to correct for moisture content in the air and its effect on the overall heat collection. White [3] has argued that the error involved in omitting moisture consideration is less than 1.5 percent.

The total heat collection per day was reasoned to be the sum of the calculated hourly totals. Collector heat losses were not considered in calculating collector efficiency because the determination of the heat collection was with actual data and not a theoretical approach for design.

Collector Efficiency

The accurate measurement of the solar insolation was most critical in determining the collector efficiency. Two such measuring devices were used during this project's duration. These consisted of measurements made with two LAMDA pyranometers; one mounted to measure total horizontal radiation and the other attached to the building wall to measure total radiation on the sloped wall.

The collector efficiency was determined by

$$\eta = \frac{Q_c}{Q_s} \quad (3)$$

where

η = Collector efficiency

Q_s = Measured solar insolation, BTU/HR FT²

Q_c = Quantity of heat collection, BTU/HR FT²

The Thermal Storage

The thermal storage was built to carry the building heating requirements beyond the daylight operation hours. With the thermocouples placed inside the bed as described previously, sufficient data were taken to determine the amount of heat stored and rejected in twenty-four hour period. The thermocouples at each end of the storage bed indicated the entering and exiting air temperature while one thermocouple located in the geometric center of the rock bed storage registered the actual rock temperature. For the purpose of calculating the amount of heat stored into or rejected out of the storage, equations similar to (1) and (2) were used. The only exception lies with equation (1) specifically, in that the collector area was omitted to obtain storage or rejection of heat in the units of BTU/HR.

A rock storage operates on the principle of sensible heat storage or rejection as opposed to phase change storages where the latent heat of fusion is involved. Thus the amount of heat transferred to or from the system was based on the air entrance and exit temperature difference. The thermocouple in the center of the rock bed was used solely as a monitoring device to indicate how the storage heat was traversing the system.

A further procedure concerned the time of the day when different modes were changed. To keep the system on an hourly basis, the modes were switched immediately after the minicomputer had printed the previous hours data. This method allowed transient effects to be effectively dissipated by the next hourly recording.

SYSTEM PERFORMANCE AND RESULTS

General Discussion

Tests on the solar system were performed during the months of January, February, and March in 1978 and 1979. During the 1978 tests corrugated fiberglass was used as the glazing over the absorber surface. This material is used by Gulf States Manufacturing to construct skylights in the pre-engineered metal buildings. After approximately three years use as glazing, this material began to yellow. During the Fall of 1978 this glazing was removed and was replaced with .060 inch thick KALWALL. Some air leaks in the air flow system were also sealed. Several days with good insolation levels were chosen to demonstrate the capability of the system. Plots are included which show the temperatures at the inlet and outlet of the collector and the outside ambient temperature. The rock bed heat storage chamber performance is shown by plotting the east plenum (entrance during charging mode), center of rock bed, and west plenum (exit during charging mode). In the heating from storage mode the east plenum temperature is the temperature of the air exiting storage. The available insolation and heat collection rate are included on another plot.

The heat collection and collector efficiency are calculated as shown previously. Artificially high efficiencies will be calculated late in the day due to the capacitive effects of the collector temperature after the insolation levels have dropped sharply.

1978 Results

Fig. 12 shows the collector outlet and inlet and the outside ambient temperatures for Julian day 29 (January 29, 1978). The outlet temperature reached a peak of 115°F at 1300 hours. The rock heat storage chamber performance for this day is given in Fig. 13. Fig. 14 contains the insolation, heat collection, and collector efficiency for Julian day 29. Fig. 15 contains the collector temperatures and ambient temperature for Julian day 55 (February 24, 1978). The outlet collector maximum temperature was 126°F at 1330 hours. The heat storage performance is given in Fig. 16 and the insolation and heat collected results are shown in Fig. 17.

1979 Results

Fig. 18 contains the collector outlet and inlet temperatures and the ambient temperature for Julian day 9 (January 9, 1979). The collector outlet reached a peak temperature of 137°F at 1400 hours. The collector temperatures for Julian day 10 (January 10, 1979) are shown in Fig. 19. The collector outlet reached a maximum temperature of 140°F at 1200 hours.

Fig. 20 shows the ambient and collector outlet and inlet temperatures for Julian day 41 (February 10, 1979). The maximum outlet temperature was 135°F and it occurred at 1300 hours. The heat storage performance is given in Fig. 21 and the insolation and heat collection results are included in Fig. 22.

Fig. 23 gives the ambient and collector outlet and inlet temp-

FIG. 12. COLLECTOR TEMPERATURES AND OUTSIDE TEMPERATURE FOR JULIAN DAY 29, JANUARY 29, 1978.

○ -EAST PLENUM TEMP.
 △ -CENTER ROCKBED TEMP.
 □ -WEST PLENUM TEMP.

FIG. 13. HEAT STORAGE CHAMBER TEMPERATURE AT THREE LOCATIONS FOR JULIAN DAY 29, JANUARY 29, 1978.

FIG. 14. AVAILABLE INSOLATION, HEAT COLLECTION RATE, AND COLLECTOR EFFICIENCY FOR JULIAN DAY 29, JANUARY 29, 1978.

FIG. 15. COLLECTOR TEMPERATURES AND OUTSIDE TEMPERATURE FOR JULIAN DAY 55, FEBRUARY 24, 1978.

FIG. 16. HEAT STORAGE CHAMBER TEMPERATURE AT THREE LOCATIONS FOR JULIAN DAY 55, FEBRUARY 24, 1978.

FIG. 17. AVAILABLE INSOLATION, HEAT, COLLECTION RATE, AND COLLECTOR EFFICIENCY FOR JULIAN DAY 55, FEBRUARY 24, 1978.

FIG. 18. COLLECTOR TEMPERATURES AND OUTSIDE TEMPERATURE FOR JULIAN DAY 9, JANUARY 9, 1979.

FIG. 19. COLLECTOR TEMPERATURES AND OUTSIDE TEMPERATURE FOR JULIAN DAY 10, JANUARY 10, 1979.

FIG. 20. COLLECTOR TEMPERATURES AND OUTSIDE TEMPERATURE FOR JULIAN DAY 41, FEBRUARY 10, 1979.

FIG. 21. HEAT STORAGE CHAMBER TEMPERATURE AT THREE LOCATIONS FOR JULIAN DAY 41, FEBRUARY 10, 1979.

○ - INSOLATION
 △ - HEAT COLLECTED
 □ - EFFICIENCY

FIG. 22 AVAILABLE INSOLATION, HEAT COLLECTION RATE, AND COLLECTOR EFFICIENCY FOR JULIAN DAY 41, FEBRUARY 10, 1979.

FIG. 23. COLLECTOR TEMPERATURES AND OUTSIDE TEMPERATURE FOR JULIAN DAY 42, FEBRUARY 11, 1979.

eratures for Julian day 42 (February 11, 1979). The peak outlet temperature reached was 140°F at 1400 hours. The heat storage performance for this day is shown in Fig. 24. The available insolation and heat collection rate is given in Fig. 25.

Supplemental Heating Requirements

The electric resistance heater used as supplemental heat had a power output of 7200 watts. A clock was used to monitor the total amount of time the supplemental heater was used. From this data it was determined that little or no supplemental heat was required for a night following a fair day if the inside room temperature was 68°F or higher at sunset. The solar collector/thermal storage system was adequate even on the coldest nights (minimum temperatures, 10-15°F). Usually there was no supplemental heat used and the highest level was one hour. However, if the room temperature was below 60°F at the time the system was shifted from charging storage to heating from storage, two to four hours of heat were required. In this situation, the heat storage chamber was exhausted before sunrise and supplemental heat was required.

On a night following a partly cloudy or hazy day the system ordinarily used one to two hours of supplemental heat if the inside room temperature was at 68°F at sunset. Following two or more successive fair days, the system was able

△ -EAST PLENUM TEMP.
 ○ -CENTER ROCKBED TEMP.
 □ -WEST PLENUM TEMP.

FIG. 24. HEAT STORAGE CHAMBER TEMPERATURE AT THREE LOCATIONS FOR JULIAN DAY 42, FEBRUARY 11, 1979.

FIG. 25. AVAILABLE INSOLATION, HEAT COLLECTION RATE, AND COLLECTOR EFFICIENCY FOR JULIAN DAY 42, FEBRUARY 11, 1979.

to store enough heat to warm the building throughout a night and partially through the next night even with poor insolation conditions during the interim day.

After the latter part of February when night time minimum temperatures did not fall below 28°F, the heat storage chamber was able to provide essentially all the heating requirements of the building. The only occasion the supplemental heat was needed was when there were several successive days with poor insolation conditions and low minimum temperatures. In summary the thermal storage under proper management of the system would provide adequate heating for the building. An automatically operated damper arrangement to change modes would be a logical extension for this system.

REFERENCES

1. Grimmer, D. P. and Moore, S. W., "Cost Effectiveness and Durability: Two Important Factors in Material Choice," Solar Engineering Magazine, January 1977, Table 3, p. 22.
2. Close, D. J., "Rock Pile Thermal Storage for Comfort Air Condition," Mechanical and Chemical Engineering Transactions, pp. 11-22, May, 1965.
3. White, H. E., "An Investigation of Flat-Plate Heated Air Solar Collector," A Thesis Submitted to Mechanical Engineering Faculty of Mississippi State University for the Degree of Master of Science, August, 1974.