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REPORT ON THE GROVER CLEVELAND SCHOOL SOLAR HEATING
SYSTEM, BOSTON, MASSACHUSETTS, USA

United States Special Format Report

MASTER

August 1976

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General Electric Company
Philadelphia, Pennsylvania

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Solar Energy

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NATO Committee on the Challenges of Modern Society

CCMS SOLAR ENERGY PILOT STUDY

Solar Heating and Cooling Systems in Buildings

UNITED STATES SPECIAL FORMAT REPORT

REPORT ON THE GROVER CLEVELAND SCHOOL
SOLAR HEATING SYSTEM
BOSTON, MASSACHUSETTS, USA

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For the

Energy Research and Development Administration
Division of Solar Energy
Washington, D.C. 20545

August 1976

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INTRODUCTION

This is a special report covering a solar heating experiment on a school in Boston, Massachusetts. It was prepared for the U. S. Energy Research and Development Administration (ERDA) under contract number E (11-1)-2626.

The content, organization, and format of the report was defined by the Committee on the Challenges of Modern Society (CCMS), a group organized under NATO and the ultimate recipient of this report. Two references exist on the project in the form of reports on the design, installation, and checkout phase and the operational phase. They are:

1. Final Report of the Solar Heating Experiment on the Grover Cleveland School Boston, Massachusetts, 15 July 1974.
2. Annual Report of the Solar Heating Experiment on the Grover Cleveland School Boston, Massachusetts, 15 July 1975.

They provide detail data not included in the CCMS format and additional elaboration of the qualitative data.

I. GENERAL DESCRIPTION OF PROJECT AND ENVIRONMENT

I.A. Program Objectives

The overall objective of this program was to obtain data which would assist in evaluating the applicability of solar heating systems in large metropolitan areas. This data was to be of an "operational" nature, in contrast to theoretical, and encompass the areas of construction, societal interactions, economics, aesthetics, etc., as well as the thermal performance aspects. The data was obtained by constructing and operating a solar heating system of pilot plant scale on a middle school in Boston, Massachusetts.

The detailed objectives for which the data was obtained were as follows:

1. To demonstrate to the general public that solar heating is a viable source of energy for public buildings and homes.
2. To design and manufacture a solar heating system utilizing approximately 4500 square feet of solar collectors.
3. To retrofit this system to the Grover Cleveland School and bring it to an operational status by March, 1974.
4. To gather any manufacturing data applicable to "large" scale systems.
5. To operate the system through May 15, 1975 to augment the existing heating system, analyze the system's performance and prepare applicable reports.

The schedule established in mid-January, 1974 is shown in Figure I-1.

Completion dates are shown with a symbol ▼ . If the planned date is different than the actual completion date it is shown with a symbol ▽ . The work week was established at forty hours for the entire program. Some spot overtime was used to expedite a particular work element only if it became a pacing item in the material/work flow.

I.B Description of Environment

I.B.1 Climate

In terms of the TREWARTHA classification system, the Boston climate is humid continental, cool summer. Three important influences are responsible for the main features of Boston's climate. First, the latitude (42°N) places the city in the zone of prevailing west to east atmospheric flow in which are encompassed the northward and southward movements of large bodies of air from tropical and polar regions. This results in variety and changeability of the weather elements. Secondly, Boston is situated on or near several tracks frequently followed by systems of low air pressure. The consequent fluctuations from fair to cloudy or stormy conditions reinforce the influence of the first factor, while also assuring a rather dependable precipitation supply. The third factor, Boston's east coast location, is a moderating factor affecting temperature extremes of winter and summer.

Hot summer afternoons are frequently relieved by the locally celebrated "sea-breeze", as air flows inland from the cool water surface to displace the warm westerly current. This refreshing east wind is more commonly experienced

along the shore than in the interior of the city or the western suburbs. In winter, under appropriate conditions, the severity of cold waves is reduced by the nearness of the then relatively warm water. The average date of the last occurrence of freezing temperature in spring is April 8; the latest is May 3, 1874 and 1882. The average date of the first occurrence of freezing temperature in autumn is November 7; the earliest on record is October 5, 1881. In suburban areas, especially away from the coast, these dates are later in spring and earlier in autumn by up to one month in the more susceptible localities.

Boston has no dry season. For most years the longest run of days with no measurable precipitation does not extend much more than two weeks. This may occur at any time of year. Most growing seasons have several shorter dry spells during which irrigation for high-value crops may be useful.

Much of the rainfall from June to September comes from showers and thunderstorms. During the rest of the year, low pressure systems pass more or less regularly and produce precipitation on an average of roughly one day in three. Coastal storms, or "northeasters," are prolific producers of rain and snow. The main snow season extends from December through March. The average number of days with 10 centimeters or more of snowfall is 4 per season, and days with 18 centimeters or more come about twice per season. Periods when the ground is bare or nearly bare of snow may occur at any time in the winter.

Relative humidity has been known to fall as low as 5% (May 10, 1962), but such desert dryness is very rare. Heavy fog occurs on an average of about two days per month with its prevalence increasing eastward from the interior of Boston Bay to the open waters beyond.

The greatest number of hours of sunshine recorded in any month was 390, or 86% of possible, in June 1912, while the least was 60 hours, or 21%, in December 1972.

Although winds of 14 M/SEC or higher may be expected at least one day in every month of the year, gales are both more common and more severe in winter.

Average annual water equivalent precipitation for the Boston area is 1055 mm. This is based upon records since 1871. The average annual snowfall, based upon records since 1936, is 1064 mm. For the years 1974 and 1975, the annual water equivalent precipitation values were 1022 and 1163 mm respectively. For the winter of 1974-75, the snowfall was 701 mm.

The Boston area sky conditions result in average annual sunshine hours equal to 57% of the maximum possible, the maximum amounting to 4475 hours.

I.B.2 Location

The solar collector array is located on the roof of a three story building in Boston, Massachusetts. Its geographical location is

Latitude = 42° north

Longitude = 71° west

Altitude = 15 meters above sea level

There are no sun or wind obstructions which would influence the solar collector performance. The surrounding terrain is essentially flat. The site of the building is approximately 0.4 km from Dorchester Bay and 10 km from greater Massachusetts Bay which is essentially open sea.

There is a city incinerator within about 1 km of the site and, in addition, the school is under one of the approaches to Boston International Airport. Both appear to contribute to a significant dust and particulate deposit on the solar collectors. No quantitative data is available to describe the extent of this deposit or its influence upon collector performance. To date, periodic rain has appeared capable of removing the particles.

I.B.3. Solar Radiation

Total solar radiation measurements were made with an Eppley Model 8-48 pyranometer. The pyranometer was positioned so that its sensing surface was parallel to the plane of the solar collectors. Hence, the measurements are in terms of energy incident upon the collectors per unit collector area. The collector orientation as described by azimuth and tilt angles is

Azimuth = 15° east of south

Tilt = 45° .

The azimuth angle is the angle between the projection of the collector normal in the local horizontal plane and the south direction in the local horizontal plane. The tilt angle is measured from the local horizontal plane.

The results of the measurements are given in Table I-1.

Table I-1
Measured Monthly Incident Solar Energy
(Measured on the Plane of the Collectors)

Month/Year	No. of Days over which Energy was Integrated	Incident Energy (MJ/M ²)
April/1974	15	195
May	14	168
September	16	246
October	29	478
November	30	262
December	31	210
January/1975	31	271
February	28	277
March	29	316
April	30	363
May	14	166

I.B.4 Ambient Temperatures

Local weather conditions, i.e., temperatures, relative humidity, and degree days, were taken from the records of the National Oceanic and Atmospheric Administration, Environmental Data Service, National Climatic Center, Asheville, N. C.

Monthly average values are given in Table I-2 for the ambient dry bulb temperature and the relative humidity. The heating and cooling degree day base is set equal to 18.3°C.

I.B.5 Wind

The monthly wind data were taken from the same source as the ambient temperature discussed in Section I.B.4. The data is presented in Table I-3.

I.C Description of System

I.C.1 Qualitative Description

Each absorber panel of a solar collector contains two fluid flow circuits in parallel. This feature requires pairs of inlets and outlets for each collector. The collector network is comprised of basic units consisting of pairs of collectors connected in series, as shown in Figure I-2. The series-pairs are connected to inlet and outlet headers, with a valve at each inlet to the lower absorber panel. Flexible hoses are used to make the header/collector connections. The designations upper and lower panels simply refer to the relative location of the panels when mounted in place.

TABLE I-2

AMBIENT TEMPERATURE/RELATIVE HUMIDITY/DEGREE DAYS

Month/Year	Average Temperature($^{\circ}\text{C}$)	Relative Humidity (%)	Degree Days (Base = 18.3°C)	
			Heating	Cooling
April/1974	10.5	63.0	238	5.6
May	12.7	69.3	186	12.2
September	17.7	75.8	56.7	37.8
October	10.0	62.5	254	0.6
November	7.2	67.5	326	1.7
December	3.3	68.0	464	0.
Jan/1975	1.6	65.5	514	0.
February	0.0	60.8	510	0.
March	2.7	60.8	481	0.
April	7.2	57.5	328	0.
May	16.4	67.0	90	33.3

TABLE I-3

WIND SPEED AND PREVAILING DIRECTION

Month/Year	Average Speed (M/Sec)	Prevailing Direction
April/1974	6.03	WNW
May	5.36	SW
September	5.05	SW
October	5.41	SW
November	5.59	SW
December	5.63	WNW
January/1975	5.95	NW
February	4.96	WNW
March	5.36	NW
April	5.50	WNW
May	4.38	SW

FIGURE 1-2 COLLECTOR FLUID CIRCUIT

The series-pair units are distributed among six collector banks, each bank containing approximately 1/6 of the collectors. Within each bank, the series-pair units are connected in parallel between inlet and outlet headers. The banks themselves are then connected in parallel to form the final solar collector array. A schematic of this arrangement is shown in Figure I-3.

In addition to the solar array, the system includes the thermal energy storage (TES) tank, by-pass heat exchangers, two air heating units, make-up and expansion tanks, and associated pumps and valves.

The thermal energy storage tank consists of a 2000 gallon steel tank, an internal heat exchanger, a vent and a five centimeter layer of thermal insulation completely enclosing the tank. A schematic drawing of the TES tank is shown in Figure I-4.

The collector fluid is passed through the internal heat exchanger during periods of energy storage. When the TES tank is to deliver energy to the school, it is isolated from the collector loop, and a secondary fluid loop is formed including the internal heat exchanger and the heating units.

Unfortunately, the internal heat exchanger was improperly positioned within the TES tank during construction. It was intended that the inlet to the heat exchanger be located at the top of the heat exchanger tube bundle and the outlet at the bottom, as indicated in Figure I-4. In actuality, the heat exchanger assembly was rotated 90° from this position, resulting in inlet and outlet at the same elevation. This resulted in a somewhat decreased useability of the TES tank

Figure I-3 Roof Area Piping Schematic

Figure I-4 Cross Section Pictorial of Thermal Energy Storage Tank

due to increases in the achievable temperature differences between the stagnant TES fluid and the circulating working fluid.

Solar energy transfer to the school air supply was effected by adding solar heating coils (liquid-to-air heat exchangers) to two existing air heaters. The existing air heaters were roof mounted, multizone, heating and cooling units manufactured by ITT-Nesbitt and referred to in this report by their building plan designation, AC-6 and AC-7. A schematic drawing of these units is given in Figure I-5. Briefly, in the heating mode, the units mix building return air and outside air and then split this mixed air between two passages or decks, one of which contains electric heating coils while the second is simply a by-pass duct. The hot and cold streams are proportionally mixed by the control dampers based on a signal from the zone thermostat and then distributed among the school rooms. The ratio of hot deck to cold deck mass flow is then controlled by the building heating loads.

The solar heating coils were added to each Nesbitt unit just upstream from the electric heating coils and downstream from the point at which the air is split between the cold (by-pass) and hot (electric heating) decks. (This location is shown in Figure I-6) The solar coil acts as a preheater for the electric heater which is itself controlled based on hot deck exit air temperature; thus, when sufficient air temperature rise is achieved across the solar coil, the electric heater will not come on. This configuration also provides for load sharing when the solar coil is not capable of supplying the required air temperature rise. In addition, this configuration allowed retention of the existing control system.

Figure IV-4 Side Elevation of Nesbitt Roof Heating/Cooling Unit

Figure I-5 Schematic Rooftop Heating and Cooling Unit at Grover Cleveland School

Figure I-6. Modification Concept - Hot Deck Preheating

The by-pass heat exchangers were utilized in this system to provide both heat recovery and heat dump functions. They originated due to anticipated need for a means of dumping heat should an "overttemperature" condition of any kind occur. Various types and locations for such a heat dump heat exchanger were available; one type being simply a fan/coil unit of the appropriate capacity. However, an observation made during the initial inspection tour led to a dual function unit. This observation was a large area of melted snow around two of the roof mounted ventilators during a morning when the roof ambient was about -13°C with almost no wind and the exhausting warm school air had both melted the previous day's 15 cm snowfall and, in spots, dried the roof. These ventilators were found to shut off only at night and provide a steady flow of approximately 22°C air with a total flow of 1.8 scc/sec. The ventilators represent a significant heat removal from the school which is not unusual since schools by design intent have large rates of air exchange.

The dual function concept then is to form a heat exchanger around these ventilators, use the steady source of air to cool the loop for the heat dump mode, and also use the steady source of warm air to accelerate the morning warm up transient. Since it is reasonable to expect the loop working fluid to start out the morning at temperatures ranging from 0 to 30°F in winter, this warm air supply represents a significant boost. The use of bypass coils was then attractive to the system in that:

1. They provide a means to preheat the air and accelerate the fluid's morning warm up transient.
2. They provide a heat dump which could be utilized for the contemplated spring and summer operation when the school heating load is at a minimum.
3. They made the system more flexible and could be useful for experimentation purposes.
4. They provide additional system safety.

A drawing of the bypass heat exchangers is shown in Figure I-7.

A schematic drawing of the complete solar system is shown in Figure I-8. The bypass heat exchangers, the AC-6 and AC-7 heating coils and the TES tank are piped in parallel, permitting the flow to pass thru any single one of these elements or thru any combination of them, if desired. In addition, the TES tank, the TES pump and the AC-6 and AC-7 heating coils can be completely isolated from the remainder of the system and function as a heating subsystem, with the TES tank acting as the heat source.

A complete discussion of the various operating modes will be found below in Section I.C.2.

I.C.2 Quantitative Description

The collector array consists of 144 solar panels, each 1.22 by 2.44 meters in size. The total collector area is 427.5 square meters. The working fluid is a solution of Boston city water and a commercial, automotive grade, ethylene glycol

FIGURE I-7. BYPASS HEAT EXCHANGER SECTIONAL DIAGRAM

FIGURE I-8. SOLAR HEATING SYSTEM FUNCTIONAL SCHEMATIC

containing corrosion inhibitors. The solution, by volume, is 30% glycol. The total loop volume unfortunately is not known precisely, but is somewhere between 940 and 1020 liters.

The positioning of the solar collectors can be described by their orientation and inclination. The orientation is 15° east, where orientation is defined here as the angle between the projection of the sun's rays at solar noon on the horizontal plane, and the projection of the normal to the collector on the horizontal plane. The inclination is 45° , where inclination is defined as the angle between the horizontal and the normal to the collector.

The overall system performance from mid-September, 1974 to mid-May, 1975 is summarized as follows:

Incident solar energy = 118.6×10^4 MJ

Solar energy collected = 42.1×10^4 MJ

Solar energy delivered = 21.0×10^4 MJ

Total Energy delivered = 40.0×10^4 MJ

Of the total energy delivered to that section of the building serviced by solar energy, 52.5 percent was solar energy. The solar energy collection efficiency was 35.5 percent. (The total energy delivered was for a period of time only solar energy due to a malfunction of the AC-6 and AC-7 electrical heaters. This is discussed in some detail in Section II-A below.)

The main pump is a 3.75 kw pump and based upon an average of 12 hours of operation per day, the total pump energy expenditure for the mid-September, 1974 to mid-May, 1975 time period was 3.9×10^4 MJ.

It was observed that the electrical heating required of the AC-6 heating unit was considerably greater than that of the AC-7 unit. During the initial days of operation, it was noted that the solar heating system could satisfy the heating requirements of AC-7 rather easily; however, solar heating could not satisfy AC-6 requirements until several hours after it had done so for AC-7. Consequently, the distribution of the collector loop fluid through the solar coils of these units was intentionally imbalanced. When the fluid is passing through both solar coils simultaneously, the AC-6 flow rate is approximately three times that of the AC-7 unit. With this flow distribution, the total heating load of AC-6 was satisfied by solar heating typically 10-20 minutes after AC-7 was satisfied. This also caused a delay in satisfying AC-7, but it appeared small.

The flow distribution through the collector array was adjusted in order to ensure a uniform flow rate per individual collector.

As will be discussed below, there are eleven distinct flow path configurations for the system. These can be described by indicating the position (open or closed) of each of the six motorized valves shown in Figure I-9. A given set of valve positions corresponds to one of five basic operating modes. These modes are described below in the discussion of the control system. For the present, it will suffice to say that in three of the five modes, valves 2A and 2B, located at the exits of units AC-6 and AC-7 respectively, are normally both open. However, if one of these heating units either goes into an air conditioning mode or into an overtemperature condition (over 74°C), the corresponding valve (2A or 2B) will automatically close.

Figure I-9. BOSTON SCHOOL CONTROL & INSTRUMENTATION LAYOUT

Flow rates and pump inlet and outlet pressures are given for the eleven flow paths in Table I-4. Each flow path is described by stating the valve positions. Also noted are the operating modes corresponding to each flow path.

More detailed discussion of performance characteristics of the collectors, TES system and the Nesbitt units will be found below in Section IV, Subsystem Performance.

Control of the system is effected through several elements, all shown in Figure I-9. These elements consist of:

- main pump
- TES pump
- temperature sensor (main pump inlet)
- temperature sensor (TES tank)
- valve 1A (to bypass heat exchangers)
- valve 1C (to collector banks A, B, C)
- valve 2A (exit from AC-6 Nesbitt unit)
- valve 2B (exit from AC-7 Nesbitt unit)
- valve 3 (to TES tank from collectors)
- valve 4 (to collectors from Nesbitt units).

All valves are motorized and are either fully opened or fully closed.

Emphasis on simplicity and a minimum of active elements resulted in a system which carries out all of the required functions with five basic operating modes.

These modes are described in Table I-5. There are additional operating modes.

TABLE I-4
FLOW RATES AND PUMP PRESSURES

Operating Mode	Control Position								Flow Rates (l/sec)			Pressures (Kpa)			
	Main Pump	TES Pump	Valve Number						Nesbitt Units		Main Pump	Main Pump		TES Pump	
			1A	1C	2A	2B	3	4	AC-6	AC-7		Out	In	Out	In
1	On	Off	0	0	C	C	C	0	0	0	4.41	453	162	302	302
2	On	On	0	0	0	0	C	C	1.2	3.78	4.41	446	160	536	440
2 AC	On	On	0	0	C	0	C	C	0	0.725	4.41	446	160	530	440
2 AC	On	On	0	0	0	C	C	C	1.4	0	4.41	446	160	522	429
3	On	Off	C	0	0	0	C	0	3.01	0.977	4.04	453	162	295	295
3 AC	On	Off	C	0	C	0	C	0	0	1.34	1.51	488	167	205	205
3 AC	On	Off	C	0	0	C	C	0	3.41	0	3.6	460	164	274	274
4	On	Off	C	0	0	0	0	0	2.33	0.725	4.85	440	158	419	419
4 AC	On	Off	C	0	C	0	0	0	0	1.09	3.66	453	160	453	453
4 AC	On	Off	C	0	0	C	0	0	2.6	0	4.67	440	157	426	426
5	On	Off	0	0	C	C	0	0	0	0	5.1	433	158	419	419

AC denotes either AC-6 or AC-7 on air conditioning.

TABLE I-5.
SOLAR HEATING SYSTEM BASIC OPERATING MODES

Mode	Current Condition Existing	Control Position								Physical Description of Condition
		Main Pump	TES Pump	Valve Number						
				1A	1C	2A	2B	3	4	
1.	Collector outlet below 27°C and thermal energy storage tank below 54°C	On	Off	Open	Open	Close	Close	Close	Open	System too cold to provide heat.
2.	Collector outlet below 27°C but thermal energy storage tank above 54°C	On	On	Open	Open	Open	Open	Close	Close	Collector loop too cold to provide heat but stored heat adequate.
3.	Collector outlet between 27°C and 63°C	On	Off	Close	Open	Open	Open	Close	Open	Usable to more than adequate heat supplied from collectors.
4.	Collector outlet above 63°C	On	Off	Close	Open	Open	Open	Open	Open	Significant extra heat being supplied by collectors.
5.	Collector outlet above 107°C	On	Off	Open	Open	Close	Close	Open	Open	Excessive heat being supplied by collectors.

which arose due to the philosophy of not providing solar heat to a heating unit (either AC-6 or AC-7) which is operating in the refrigeration mode of air conditioning in which case the appropriate valve 2 closes. In addition, there are two "failure" modes; one in the event of an overtemperature safety relay closure in either heating unit and the other in the event valves 1A, 2A, 2B and 3 would normally all be closed (mode 3 with both AC-6 and AC-7 on air conditioning). In either case, the system reverts back to the configuration of Mode 1.

The system operates off of only two basic input signals; fluid temperature at the main pump inlet and the TES fluid temperature. When the main loop is too cold to be useful (below 27°C) the fluid is routed through the bypass heat exchangers (Mode 1). If concurrently the TES fluid is hot enough to heat recirculated fluid to useful temperatures, then the TES sub-loop is circulated simultaneously but isolated from the main loop (Mode 2). The bypass heat exchangers are in a steady stream of 21 to 24°C air being exhausted from the building and, when a combination of the exhaust air and sun on the solar collectors have warmed the loop fluid to a usable temperature range, the flow through the bypass heat exchanger is stopped and flow is routed through the solar heating coils (Mode 3). As the main loop temperature exceeds the level required to carry the total heating load of AC-6 and 7, valve 3 opens, and a parallel fluid flow begins to store energy as sensible heat in the TES tank (Mode 4). Should a temperature (107°C) be reached which is high enough to be beyond usefulness and perhaps be foreshortening operational lifetimes, i.e., main pump seals, then the system goes into a heat dump mode with flow through

the TES tank and the bypass heat exchangers (Mode 5). These five basic modes are modified by two additional binary signals which are the only control interface with the heating units. Two relay closures were added to each heating unit, one to occur whenever the unit goes into a refrigeration air conditioning mode and the other to occur if the unit's hot deck air ever reaches the lowest of three existing internal overtemperature limits (74°C). Either relay closure within a heating unit results in a closure of the appropriate valve 2.

The controls are housed in an autonomous, semiportable two-bay console located in a small control room at the top of a stairwell header leading to the school roof. The console is actually divided into two groupings of components; those devoted to system control and those devoted to instrumentation. The console is powered by a 120 vac circuit which is connected to the school's emergency generator and thus would function in the event of a power outage in the school's locality. The console, and consequently the system, operation is governed by a 24-hour time clock which turns the system on near sunrise or 7:00 am (whichever is earlier) and off at 7:00 pm. This was done to conserve power consumption and because, with the night setback temperature levels in use at the school, there was a nearly negligible nighttime heating demand.

The motorized control valves are driven by 120 vac power supplied by the console. The control console also provides the valve control signal (and in the event of any signal failure the corresponding valve reverts to an open condition).

The console portion of the control system is shown in Figure I-10 and is comprised of the following components:

1. Energy Flow Panel. Pictorially illustrates system status.
2. Temperature Control Meters. Panel mounted adjustable controllers used to control system operating modes.
3. Control Panel. Provides on/off, auto/manual, the various component switches (operable in the manual mode only), and indicator lights.
4. Alarm Buzzer. Sounds if pressure differential across main pump is not maintained or the dc power supply fails.
5. Time Clock. Turns control console off at night.
6. DC Power Supply. Primary source of signal power for control valves.
7. Back-up dc Power Supply. A back-up dc source which switches in automatically if the primary one fails.
8. Rack Blower. Provides cooling air to the control system electronics.
9. Power Control Panel. Provides circuit breakers for entire console.

The system normally operates in a fully automatic mode with the 24-hour time clock shutting the system down during nighttime.

The instrumentation system is independent of the control system. The instrumentation consists of thermometers, thermocouples, flow meters, a solar flux sensor, weather instruments, and a data acquisition subsystem. The locations of the various sensing elements was shown in Figure I-9.

FIGURE I-10. CONTROL PORTION OF CONSOLE

The data acquisition subsystem is housed in the console bay not occupied by the control system and is shown pictorially in Figure I-11. It was designed to provide three types of data; continuously recorded, recorded sample, and instantaneous display. The continuously recorded data consists of six strip charts recording weather data, and "events" which are of a random occurrence nature. The sampled data is recorded by a Doric 210 Datalogger which scans 100 channels every thirty minutes. The instantaneous data displays provide visual indications of the current operating condition of the system. Power to drive the recorders comes from both the power control panel and the dc power supply as required by the particular device.

The continuously recorded data is obtained by "Rustrac" recorders, utilizing five centimeter wide, pressure sensitive paper driven at 2.5 centimeters per hour for the following functions:

1. Wind speed
2. Wind direction
3. Humidity
4. Ambient temperature
5. Events in Zone 1
 - a. AC-6 first stage heat on/off
 - b. AC-6 second stage heat on/off
 - c. AC-6 third stage heat on/off
 - d. Valve 2A open/close
 - e. Valve 1A open/close
 - f. Valve 1C open/close
 - g. Spare channel

FIGURE I-11. DATA ACQUISITION PORTION OF CONSOLE

6. Events in Zone 2:

- a. AC-7 first stage heat on/off
- b. AC-7 second stage heat on/off
- c. AC-7 third stage heat on/off
- d. Valve 2B open/close
- e. Main pump on/off
- f. TES pump on/off
- g. Valve 3B open/close
- h. Valve 4B open/close

There is approximately a five week supply of paper in each recorder.

The sampled data is the primary data source for analysis of the system.

It consists of 90 channels of copper constantan thermocouple data, nine channels of millivolt analog voltages and one calibration reference voltage for a total of 100 channels. These data are recorded sequentially on printed paper tape every thirty minutes and there is approximately a two-day supply of paper in the data logger. The first two millivolt channels are utilized for solar flux and loop flow rate and channels 3 through 9 are spares. Channels 10 through 75 are various system temperatures and channels 76 through 99 are detail temperatures obtained from within four instrumented collector panels.

The instantaneous data displays are not recorded and are intended primarily as visual aids to ascertain system conditions. These displays consist of thermometers, pressure gauges, and eight visual flowmeters in the main loop; a panel mounted electronic flowmeter and three panel mounted "thermometers" in the control console. Each panel mounted thermometer is coupled to a ten position switch to enable a selection of a total of 30 iron/constantan thermocouples.

II. SYSTEM THERMAL PERFORMANCE

II.A Monthly Energy Transfers

The various monthly energy transfers were summed from values calculated each half hour and are given below in Table II-1. The "Total Energy Required" column is the conventional plus solar energy input to the air by both AC-6 and AC-7. This would normally be reflective of the heating load but was not because of two related malfunctions of the conventional electric heating system.

There are three relays which were added to each of AC-6 and 7, to indicate which of the three stages of conventional electrical heating were "on". While reducing data in the late fall of 1974, it was noticed that all three stages of electrical heat were indicating as cycling on together and staying on nearly continuously in the mornings and yet the measurable effect was zero and the solar heat utilization was relatively large, which together was incredible. A site visitation the second week in December 1974 coincided with a service visit by the heating service contractor. During the service call the custodians related that they had lately been unable to get the two air handlers to heat the classrooms to a comfortable level for 8:00 A.M. classes no matter what they did with the thermostats. However, the rooms would generally become warm enough by 9:30 or 10:00 A.M. and would remain so the rest of the day and for the evening classes. The data system readings were explained to the serviceman and a joint examination of the air handler revealed that no electricity was getting to the actual heating elements. As a consequence, the solar heat was the only heat source in the air handler. In tracing back, it was found that a serviceman made a maintenance visit in June 1974 at which time it appeared

he rewired the heating stage sensing relays for some unknown reason. The result was whenever the unit first called for conventional heating, all three sensing relays were energized simultaneously and locked in until no heat was required, but the actual heating elements were not energized. The electric circuit to the heating elements was restored in mid-December 1974 which eliminated the problem of cold classrooms at 8:00 A.M. However the temporary fix utilized left unremedied the problem of all electric heating stages switching on together at the first call for electric heat and, as was subsequently discovered, during refrigeration air conditioning operating modes (in which heat, if required is supposed to be supplied via a condensate reheat coil). These phenomena together with some minor operating discrepancies lead to excessive use of the conventional electric heat source during the mid-December 1974 thru April 1975 time frame. This makes a quantitative measurement of the true heating load impossible based on available data.

In this system the supplemental energy is electric resistance heat which is normally switched on in three progressive stages as required to satisfy a hot deck exit plenum air temperature requirement. The set point value of exit air temperature is variable and controlled by each heating unit based on ambient temperature and exit air mixing damper positions (which reflect heat load on the unit). Thus the supplemental energy category is the energy delivered by the electrical heating coils in AC-6 and AC-7. No data was available for the months of April and May, 1974 and, as stated above, the electrical energy delivered was zero for the months of September through November and for the first half of December, 1974.

The Solar Energy Incident category gives the solar energy incident upon the solar collectors while the Solar Energy Collected category gives the solar energy transferred to the solar loop fluid. Finally, the Solar Energy Used category gives the solar energy transferred to the air stream at the solar heating coils installed in AC-6 and AC-7.

The main pump in the solar collector fluid loop requires approximately 161 MJ/day of energy. This amounts to 0.48×10^4 MJ for a thirty day period and for the entire period of operation it amounts to 4.36×10^4 MJ. This can be compared to the total solar energy used which amounts to 23.4×10^4 MJ. The main pump energy requirement is approximately 19% of the total solar energy used. The comparatively high pumping energy is a result of an intentionally high pressure piping network (to minimize fluid inventory and system response time) and an overly simplistic pump control approach resulting in excessive running time.

II.B Quality of the Thermal Performance of the System

The thermal performance of the system was in general quite good, although somewhat less effective as a system than expected due to the malfunctions of the conventional heater discussed in the foregoing section. For those months for which complete data was available and the electric heater was operating, January through mid-May 1975, it can be seen that of all energy delivered, 42% was solar energy. From mid-September to mid-December, 1975, the electric heating coils of AC-6 and AC-7 were inoperative and 100% of the supplied energy was solar. The yearly average of the fraction of supplied energy which was solar was 63%.

One of the more germane evaluations of the quality of system thermal performance is obtained by noting that the solar heating system was able to meet all the heating requirements for the 21,000 ft² section of the school from June to early December 1974. The heating requirements were of course low through the summer. However, the failure of the conventional heat source went totally undiscovered and the condition only became physically noticeable when sunrises became later, temperatures colder, and the sky more overcast, as occurs when Boston approaches mid-winter.

II.C Solar Contribution to Energy Requirements

The solar contribution to energy requirements are given in Table II-2. As pointed out above (see Section II-A) electrical heat was not available for the period September through mid-December 1974. Hence, the solar contribution data in Table II-2 are given in terms of the solar energy delivered as a percentage of the total energy delivered, solar plus electrical.

II.D Monthly And Annual Savings

Based upon an average electrical energy cost of 4 cents per kw-hr, the savings due to the use of solar energy have been computed and the data are given in Table II-3. The category "Solar Energy Savings" is the cost of electrical energy equivalent to the amount of solar energy delivered. The "Net Savings" is the "Solar Energy Savings" less the main pump electrical energy costs. The "Total Cost" is the cost of electrical energy equivalent to the amount of total energy delivered, the summation of both solar and electrical.

TABLE II-1
MONTHLY ENERGY TRANSFERS

Month/Year	No. of Days	Total Energy Required (MJX10 ⁻⁴)	Supplemental Energy Req'd (MJX10 ⁻⁴)	Solar Energy Incident (MJX10 ⁻⁴)	Solar Energy Collected (MJX10 ⁻⁴)	Solar Energy Used (MJX10 ⁻⁴)
April/1974	15	---	---	7.84	3.15	1.40
May	14	---	---	6.76	2.46	.962
September	16	1.16	0.	9.90	2.05	1.16
October	31	2.85	0.	19.20	5.02	2.85
November	30	2.11	0.	10.55	3.38	2.11
December	31	3.34	1.23	8.43	3.33	2.11
January/'75	31	7.95	5.01	10.90	4.58	2.94
February	28	6.90	3.80	11.14	4.94	3.10
March	31	7.66	4.44	12.67	5.20	3.22
April	30	6.94	3.83	14.58	5.49	3.11
May	14	1.09	0.68	6.67	2.50	0.41

TABLE II-2

SOLAR CONTRIBUTION TO ENERGY DELIVERED

MONTH/YEAR	NO. OF DAYS	PERCENT SOLAR ENERGY DELIVERED
September/1974	16	100
October	31	100
November	30	100
December	31	63
January/1975	31	37
February	28	45
March	31	42
April	30	45
May	14	38

TABLE II-3

SAVINGS

MONTH/YEAR	NO. OF DAYS	SOLAR ENERGY SAVINGS (\$)	NET SAVINGS (\$)	TOTAL COST (\$)
April/1974	15	155	128	---
May	14	107	82	---
September	16	129	100	129
October	31	316	264	316
November	30	234	180	234
December	31	234	179	371
Jan/1975	31	326	271	882
February	28	344	294	766
March	31	357	305	850
April	30	345	291	770
May	14	46	21	121

II.E Energy and Mass Balances

As an illustration of the system's daily performance, the data collected on April 16, 1974 was chosen as a basis for discussion. During this day, only heating unit AC-6 was called upon to supply heat (AC-7 being on air conditioning). As can be seen in Figure II-1, initially both the collector outlet temperature and the TES temperature were less than the transition temperature levels at which either source was used to supply heat. The two prior days had been nearly sunless and thus the TES tank heat was depleted. This condition persisted till about 8:30 A.M., hence at earlier times the heating demand was answered by the three electrical heating stages. All three of these heaters were on till approximately 7:30 A.M. at which time Heater No. 3 cycled once and shut-off. Just before 8:00 A.M. heater number 2 began to cycle and by 8:30 A.M. heater number 1 also began to cycle. At this time, 8:30 A.M., the collector outlet temperature had reached the 27°C transition point and, as can be seen in Figure II-1, the electrical heaters were off or cycling and valve no. 2a was opened, permitting the hot fluid to flow through the solar coil in AC-6. At 9:30 A.M. the electrical heating ceased for the day and the solar system carried the heating load.

FIGURE II-1. SYSTEM DAILY PERFORMANCE

This mode of operation then persisted till about 10:30 A.M. at which time the collector fluid reached its second transition temperature, 63°C , causing valve number 3 to open and permitting the collector fluid to transfer some of its energy to the TES tank. As can be seen in Figure II-1, at 10:30 A.M. the TES temperature began to rise.

At shortly after 1:00 P.M., Figure II-1 shows valve number 2a alternately opening and closing till about 5:00 P.M. This intermittent type of operation was caused by unit AC-6 cycling on/off of the refrigeration air conditioning mode during this time period.

At approximately 3:30 P.M. the collector outlet temperature has again passed through its 63°C transition point. The solar insolation has been decreasing and its angle of incidence upon the collectors has been increasing. Both of these factors led to a lowering of the collector outlet fluid temperature. As can be seen in Figure II-1, this results in the closing of valve number 3 and a rather constant TES tank temperature thereafter.

From 5:00 P.M. till 7:00 P.M., valve number 2a is constantly open. During this time interval the collector outlet temperature is initially high enough (greater than 27°C) to supply the heating demand. However, by about 6:00 P.M. the collector outlet temperature has reduced to its 27°C transition point and is no longer used to supply heat. Nevertheless, the TES temperature is above its transition temperature of 54°C and consequently valve number 2a remains open and the TES pump comes on, permitting the TES fluid to meet the heating demand for the remainder of the heating period.

Another feature of the system's performance can be seen in Figure II-1. Under certain conditions, valves 2a and 3 will be open or closed as the collector outlet temperature passes through one or another of its transition point temperatures. This raises the possibility of the system passing into a cyclical

mode of operation. For instance, if the collector outlet temperature is increasing and passes through its 27°C point, valve number 2a will open, assuming that the TES tank temperature is less than 54°C . One might imagine that now the collector fluid temperature could be reduced as it passes through the solar coil to such an extent that at the collector outlet it would again fall below 27°C . This would result in valve number 2a being closed and an increase in the collector fluid temperature, which would again cause valve number 2a to open. Such cyclical behavior obviously did not occur in the performance shown in Figure II-1.

During numerous instances of observing system response during a mode transition no cyclic behavior has been seen except as a result of refrigeration air conditioning or the 63°C mode 3/4 transition point. The mode 3/4 transition (on the rising phase) usually produces one or two cycles since it introduces a significant new heat load into the flow path. These cycles normally have about a 20 minute period and are quite orderly in nature.

Further data for this typical day is given in Figure II-2. Five performance parameters are plotted as a function of time, i.e.,

1. Collector outlet temperature
2. Collector fluid loop temperature rise across the collector array
3. Solar insolation on the collectors
4. Collector loop flow rate
5. TES fluid temperature.

FIGURE II-2
TYPICAL DAY PERFORMANCE

III. SYSTEM ECONOMIC ANALYSIS

An economic analysis of this project is meaningful only in terms of relative costs of various elements of the installation; for example, support structure costs compared to piping costs. An economic analysis of this project is invalid in the conventional sense of return on investment, break-even point, etc. because of the circumstances applicable to the project, specifically:

- Primary objectives of the project were learning to fabricate and install systems, experimentation, and data acquisition rather than economic functional performance.
- This was the first sizeable solar energy system installation for everyone concerned with the project and the first exposure to solar energy applications for all of GE's subcontractors.
- A heavy emphasis was placed on an accelerated schedule.
- Over-design to speed approvals.
- Time and material subcontracts to avoid bidding delays.
- Part load shipments when required to hold schedule.
- Use of "available" rather than "optimum" components
- The system utilized a solar collector which was then in the early phase of development, had not been "product" engineered, and for which there was no collector assembly line. Consequently, each collector was hand built one at a time.

- A "wildcat" trucking strike which seriously disrupted transportation of both raw and finished materials related to the project and increased effort required to meet schedule.

III.A Total Cost of Solar Portion

Since this project was a retrofit system to an existing building and HVAC system, essentially all the costs were related to the solar portion of the total HVAC system. A summary of all the costs related to the project are provided in Table III-1. It can be seen from Table III-1 that the items related directly to the physical installation of the solar heating system totaled \$197,400.

It is interesting to note that the majority of the physical installation costs relate to conventional construction activities and also that steel support structure and piping are the major items and comparable to the solar collector costs.

It could be argued that some of the items such as "roofing" (B.8) could have been significantly reduced or omitted from the above table since only about twenty percent of the cost was related directly to the solar installation (resealing the roof penetrations required by the supporting structure). In this case, the remaining majority of roofing costs were to refurbish small places on the roof following construction activities. While this was not a direct solar related cost, these costs were included in the table since the

TABLE III-1
PROJECT TOTAL COST SUMMARY

PROJECT ITEM	Cost ~ \$ K
<u>A. Heating System Design</u>	
1. System Design	≈ 50*
2. Architectural Services	19.5
Subtotal	<u>69.5</u>
<u>B. Physical Installation - Heating System</u>	
1. Solar Collectors (material & mfg. labor for 4608 ft ² of collectors)	75.6
2. General Contractor (VAPPI Co.)	22.0
3. Steel Fabrication	36.2
4. Steel Erection	8.6
5. Piping	41.2
6. Electrical	7.0
7. Existing Heater Modification	3.5
8. Roofing	4.3
Subtotal	<u>197.4</u>
<u>C. Experimental Installation</u>	
1. Instrumentation Design & Components	≈ 70*
2. Instrumentation Installation & Checkout	≈ 20*
Subtotal	<u>90</u>
<u>D. Support & Sustaining Operations</u>	
1. On-site Operations	≈ 20.7*
2. Experimentation, Data Analysis & Reports	≈ 140*
3. Project Management, Coordination, & Travel & Living	≈ 52*
Subtotal	<u>212.7</u>
Grand Total	<u>569.6</u>

*Best Estimate Available.

work would likely not have been required had the roof been untrafficked. Consequently, the data in Table III-1 includes some judgement factors so as to accurately reflect the incurred costs applicable to the physical installation, operation and evaluation of the solar heating system.

Similarly, this project required a considerable coordination and interfacing effort both to achieve the required schedular efficiencies and to carry out the public information functions associated with the project. These costs were larger than would be incurred in a "normal" HVAC project and are included in the support effort, area D.

III.B Labor Costs

Approximate installation labor costs (as opposed to shop fabricated or purchased material) are shown in Table III-2.

TABLE III-2
APPROXIMATE INSTALLATION SITE LABOR COSTS

Cost Source	Man-Hours	\$ K
General Contractor	1200	15.0
Steel Fabrication	24	0.3
Steel Erection	410	8.6
Piping	1390	24.7
Electrical	330	6.3
Existing Heater Modification	110	2.5
Roofing	190	3.6

It must be remembered that the above costs are also based on 1974 rates and include union benefit factors.

III.C Material Costs

The data in this section is corollary to the preceding data and is given in Table III-3.

TABLE III-3
APPROXIMATE INSTALLATION MATERIAL COSTS

Cost Source	Type of Materials	Cost ~ \$ K
Solar Collectors	Components & shop fabrication	75.6
General Contractor	Security, truck & crane rental, scaffolding rental	7.0
Steel Fabrication	110,000 lbs. of steel & shop fabrication	35.9
Piping	TES tank with heat exchanger, pipe, valves & insulation	16.5
Electrical	Conduit, boxes & wire	0.7
Existing Heater Modification	Air Heating Coils	1.0
Roofing	Stone, tar, decking & flashing	0.7

About 50 percent of the steel fabrication material cost shown above is actually labor as is about 20 percent of the piping cost. However, this is shop labor required to fabricate components which are in turn delivered to the job site for installation. Since there is a fabrication labor component common to all purchased hardware, e.g. valves, this off-site portion of the subcontractor's labor cost was treated as a purchased material cost required for the installation.

III.D Operational Cost

The normal operational costs associated with this system are the following:

- a. Electricity for pump operation
- b. Electricity for control subsystem operation
- c. Changes of glycol/water working fluid once every two years
- d. Changes of system hoses once every four to six years
- e. Miscellaneous labor for route inspections, pump lubrication, etc.

On an annual basis, these costs are calculated as shown in Table III-4. The assumed labor cost of \$20/hour may at first appear high; however, that is a reasonable figure allowing for administrative burdens and/or benefit packages which are applicable. Thus, the hourly rate is nearly independent of whether Boston utilizes their own custodial personnel or contracts the work out to more specialized tradesmen, e.g. for hose replacement.

TABLE III-4
ANNUAL OPERATING COSTS

Cost/Item	Frequency ~ Years	Calculation Basis	Annualized Cost ~ 1974 \$
Electricity	1	15,841 Kw-hr/yr	65
Glycol	2	\$4/gal for 120 gal	240
Glycol labor	2	8 hrs @ \$20/hr	80
Hoses	4	\$.70 for 337 ft.	59
Hose Labor	4	90 hrs @ \$20/hr	450
Miscellaneous Labor	1	4 hrs @ \$20/hr	80

III.E Local Economic Factors

The prevailing economic factors applicable at the time this system was installed were an annual overall national inflation rate of about 10 percent and rates applicable to construction labor and materials of about 6 percent and 12 percent respectively but which are currently both approaching 8 percent. Mortgage interest rates were approximately 8 percent. This was an experimental system utilizing undeveloped collectors and an accurate lifetime could not be predicted for it. However, matured solar heating systems have 15 to 20 year lifetimes.

III.F Expected Selling Price or Costs

The solar collector design utilized for this project was experimental and has not and will not be offered for sale. However, it is reasonable to expect developed solar collectors of this general type to be sold at about \$10/ft².

It is significant to observe that in Table III-1 the cost of the "conventional" equipment was considerably more than the solar collectors. On an areal basis, the "conventional" portion of the physical installation was \$26/ft² of collector. While this cost is somewhat higher than would normally occur due to the schedular and "first time" factors already mentioned, it is still a major factor. More significantly, this cost is less susceptible to reduction by further development effort.

The major contribution of "conventional" elements to the total cost of a solar HVAC system was one of the significant lessons learned in this project. The result has been a major thrust of the development effort at the General Electric Company toward producing collectors which are reasonable in cost themselves and have features which also reduce the conventional cost elements so as to result in the lowest cost total system.

III.G Maintenance Frequency and Costs

The expected normal maintenance items are covered in the Operational Costs Description in subsection III.D above. In actuality, this system required more than the normal amount of site activities and maintenance as a result of the experimental nature of the system and poor performance of some of

the commercial items; particularly, the main pump and two of the mororized valves. The complete discussion of the activities undertaken are extensive and are covered in paragraphs 6.2.5 and 6.3 of Reference 1 and paragraph 4.3 of Reference 2. Normally, maintenance, modification and experimentation activities as well as public information functions were all performed on any one site visit. True maintenance operations were a small fraction of the on-site labor.

A total of approximately 1000 hours of on-site labor and \$750 were consumed in the first fifteen months of operation. It is estimated that over 90 percent of this effort is directly a result of the experimental status of the system and approximately 20 percent of it is directly instrumentation/data acquisition subsystem related. As a consequence of minor system modifications, the required level of effort reduced with time to the point that 22 hrs/mo was the average for the last five months and this included two major periods of on-site experimentation.

III.H User Reactions and Comments

At the inception of the project, there appeared to be a general disbelief that a solar heating system would work in Boston, and few believed a system of the magnitude described could be built within six weeks. February and March in Boston are usually cold and snowy months. During the construction from February 13 to system operation on March 6, the weather was relatively mild with very little snow. However, the chill factor was extremely low since there was always a wind blowing on the school rooftop. The acceptance and enthusiasm

of the construction work force changed dramatically on the morning of March 7, 1974 as they found they could warm their hands on the pipes which were still uninsulated. From that moment on, the construction force was sure solar heat would work in Boston and appeared proud to be on the team that installed the first major solar heating installation in a public building.

Interaction with the Grover Cleveland School Principal and others was very friendly and helpful. In the early days the interaction was primarily that of providing access and help. They were periodically briefed on the progress and system operation and occasionally a teacher would come up and onto the roof. Interest increased on March 7 when the Principal was told that heat is now being applied from the Solar Heating system. She, the Principal, was given a tour of the system and a demonstration. Again the qualitative test of feeling the pipes on a very cold day was proof positive that solar energy could be used in the Northern latitudes.

Visitation on the roof area was generally off limits while construction was still in process. The school custodians became interested in the system since they could see that the system worked and was likely to ultimately be turned over to them for operation. As the system became debugged, the normal day to day responsibilities were assumed by the lead school custodians on the first and second shift.

The supervisor of HVAC for the Boston School Department was originally skeptical of the project. However, after a year and a half he was quoted in the Boston Globe newspaper as follows:

"I just didn't think it was feasible," he said, shaking his head.

"But when you come up here on the school roof in an overcoat on a day when the temperature is 10 degrees and find water that's 190 degrees hot, you believe. Really you do."

The pupils at the Grover Cleveland School became aware of something special happening at their school. The depth of understanding and acceptance was best portrayed by the poster contest conducted by the Art Department at General Electric's request. Their only guidelines were to portray their understanding of solar heating. Seventeen posters were submitted. The winner, an 8th grade girl's poster, is shown in Figure III-1. Mr. A. Furnace, a tired old man, is retiring as the new solar heat is being applied.

Protection from vandalism was a prime consideration in the system and collector design. The collector windows were made from Lexan to prevent breakage in the event that the neighborhood youths threw rocks at the collectors. This did occur on numerous occasions. No significant damage to the system has occurred from items thrown; however, loss of one school window per week was typical. Usage of glass level indicators and flow meters were minimized or valved to lessen the possibility for breakage and subsequent system drain.

Figure III-1 Winning Poster

Visitors from all parts of the world have telephoned, visited and asked questions. This includes college professors, power company executives, architects, college students, competitors and a few blue collar workers from the Dorchester area. The visitor traffic was and still is composed primarily of technically oriented personnel; the average Dorchester citizen seems to accept solar energy as a thing to read about in the newspaper or watch on the evening TV news. Press coverage peaked in early January 1974 after contract award and again in early March 1974 when the system went operational.

IV. SUBSYSTEM PERFORMANCE

IV.A Solar Collectors

IV.A.1 Description of Physical Configuration

The solar heating system utilizes the GE P3 prototype collector module.

Each module is comprised of three major components.

1. The absorber plate, insulation and frame pan, which are molded into an integral structure
2. An inner window
3. An outer window, with sealant

The arrangement and interrelationship of these components is shown in Figures IV-1 and IV-2.

Combining the absorber plate, foam insulation and lightweight frame pan into a single molded assembly provides a number of unique performance enhancing and cost saving advantages. The resultant absorber assembly is a rigid foam insulation-cored panel having the sheet aluminum frame pan as one "skin" and the absorber plate as the other. Foam or honeycomb cored panels are widely used in the aerospace and building industries to produce high strength, lightweight panels for a variety of uses. In this application the "sandwich" construction provides a very stiff, self-supporting panel which weighs only three pounds per square foot with the windows installed.

The two inches of polyurethane insulation provides a calculated rearward conductance of approximately $0.4 \text{ W/M}^2\text{-}^\circ\text{C}$. The insulation is completely sealed by the aluminum pan, the absorber plate, and the Kydex (acrylic-polyvinylchloride)

Figure IV-1 GE P3 Prototype Solar Collector Configuration

Figure IV-2 - GE Solar Collector Cross Section

profile section which forms the inner window support. RTV silicones seal all joints, effectively preventing long term degradation of the polyurethane due to moisture infiltration; gradual replacement of the fluorocarbon gas blowing agent with other atmospheric constituents, particularly water vapor, in unprotected urethane insulations not only lowers the insulating value significantly, but also may adversely affect strength and dimensional stability. (Absorption of water and water vapor also degrades glass fiber and mineral insulations.) In addition, direct exposure to UV is recognized as a significant cause of degradation of urethane foam insulations. The fully sealed insulation of the GE design is believed to eliminate these problems, providing this design with a high potential for durability.

The inner and outer windows are made of Lexan UV-inhibited polycarbonate plastic. This material was selected for its durability, desirable thermal, optical, mechanical, and lightweight properties. Both windows have integral formed stiffening ribs which serve to accurately control the spacing of the windows in order to minimize conductive and convective heat losses. The point contacts where the ribs cross also minimize outward thermal losses through the low thermal conductivity plastic. UV resistant polycarbonate plastic, with its high heat deflection temperature (140°C), high impact resistance and formability, is considered to be particularly suitable for use as solar collector windows. Examination of Figure IV-3 shows that the spectral transmission characteristics of clear Lexan sheet are well matched to the solar radiation spectrum. The integrated solar transmittance and reflectance of 0.203 cm Lexan sheet are .87 and .093 respectively. Beyond three microns, the measured transmittance of

0.203 cm inch clear Lexan sheet is less than one percent in any one micron spectral interval.

While glass offers good transmittance, abrasion resistance, long term stability, weather resistance and low thermal expansion, its weight and relatively fragile nature may limit its usefulness for low cost, lightweight applications. To withstand the 122 to 171 kg per square meter peak wind loads experienced in most of the 48 contiguous states, .635 cm thick plate glass or .478 cm thick tempered glass must be used for 1.22 by 2.44 m collector panels. The approximate weight of .478 cm tempered glass desirable for large collectors is 12.2 kg per square meter. This must be compared to the 1.5 to 2.4 kg per square meter weight of the Lexan cover sheet materials of interest.

Figure IV-3. SPECTRAL TRANSMITTANCE OF WINDOW MATERIALS

While normal 0.228 cm window glass is relatively low in cost (on the order of \$2.15 per square meter in large quantities) tempering, greater thicknesses, and low iron formulations all add significantly to the cost. Quotes made in 1974 to GE from major glass manufacturers for large quantities of tempered normal and low iron glass ranged from \$5.00 per square meter for normal 0.318 cm (DS) tempered to \$21.10 per square meter for 0.55 cm, tempered low iron glass. The 0.318 cm thick tempered glass is of questionable suitability for the outer surface of collectors larger than 0.9 by 1.8 m because of wind loading considerations. Some manufacturers are hesitant to quote large sizes of 0.318 or 0.396 tempered glass because of handling difficulties.

Long term exposure to ultraviolet radiation has effects of varying severity on various plastics. The transmittance of acrylic sheet is not affected to any very significant degree by UV; however, loss of strength and impact resistance has been observed in long term outdoor weathering tests in sunlight. Polycarbonate sheet with an early UV inhibitor system has evidenced a loss of approximately six percentage points in transmission over five years exposure in Florida weathering tests, but no significant loss in strength or impact resistance has occurred (Reference 3). More recently developed UV inhibitors for Lexan have provided significant improvements in the resistance to transmission degradation. These are now being carefully evaluated for solar collector applications.

Acrylic sheet plastic, or heat strengthened or tempered glass are significantly more susceptible to breakage than the polycarbonate material. (It is interesting to note that among all the collectors built for the four completed NSF school solar heating systems, all of the three collector arrays using glass windows have experienced breakage due to handling, thermally induced stresses, or missile impact - or combinations of these causes. Only the GE collectors have remained intact, in spite of their being subjected to bombardment with a few baseballs, and rocks up to the size of railroad ballast).

A clear advantage of this window design is that in addition to providing a large clear aperture, edge shadowing is significantly reduced by the window mounting technique and the sloping Kydex edge. This design offers approximately 4 to 6 percent gain in total energy capture potential over one having a more conventional 1.9 to 2.5 cm glazing border.

Another significant advantage of the formable plastic window is that it provides a continuous, weather tight surface with a sealing lip which is unbroken, even at the corners of the panel. Figures IV-1 and IV-2 illustrated the use of the transverse ribs and the sealing lip around the edge.

This type of weather proof sealing arrangement also makes it possible to remove and replace windows without removing the collector from its installed position and without draining or disconnecting the attached fluid piping. A butyl strip architectural glazing sealant under the outer window forms a fully weathertight seal, protecting the panel from moisture infiltration. This type of construction

offers the ultimate potential for sealing arrays of collectors to form weather tight roof surfaces.

The absorber heat exchanger plate of this solar collector is Alloy 1100 aluminum, with integral fluid passages formed using the OLIN roll-bond process. The resulting panel has high thermal efficiency, is light in weight and low in both material and production cost. When used in conjunction with corrosion inhibitor systems developed for automotive applications, the durability of this material is excellent; OLIN reports outstanding durability of aluminum roll-bond used as heat recovery panels in commercial lighting fixtures.

Unlike spot or seam welded absorber panels which have many narrow capillary interstices in which non-flowing concentrations of corrosion producing materials may be deposited from the working fluid, roll-bond sheets are fully diffusion bonded in all areas where fluid flow is not desired, thus reducing the potential of confined corrosion sites.

OLIN's existing roll-bond manufacturing equipment limits the width of panels they can produce to 0.9 meters. Because of this manufacturing limitation it was decided to make the absorber panel as a 0.61 x 2.44 m module and assemble two of these in mirror image orientation in the collector; a mechanical and thermal bond between the two plates results in a full 1.22 x 2.44 m absorber plate assembly. Since a reliable, low cost intrapanel fluid connection between the two 0.61 x 2.44 m sections could not be devised within the available time, it was decided to provide a fluid inlet and outlet on each section.

These connections are made by welding internally threaded adapters to the roll-bond panels, then at collector assembly threading short aluminum pipe nipples into the absorber adapters through appropriate clearance holes in the pan ends. These penetrations are then sealed with RTV silicone rubber to provide a flexible weather tight seal between the pan and each fluid connection.

The solar collectors are coated with the 3M 301-C10 Black Velvet paint, baked at 175°C. Measured properties of this coating, as used in this application, are:

$$\frac{\text{Solar Absorptivity}}{\text{Infrared Emissivity}} = \frac{a}{\epsilon} = \frac{.975}{.907} = 1.075$$

This coating is durable and abrasion resistant in normal handling.

3M's published weathering data for direct outdoor exposure indicates a three-year minimum life for this product, and a maximum continuous service temperature of 150°C.

The long term effects of exposure in the collector environment - low relative humidity air at elevated substrate temperatures, in the absence of UV - must be determined; it is expected that a significantly longer life will be realized with this product since it is protected by collector covers and operates at temperatures significantly below 150°C.

General Electric is currently evaluating selective coatings for collector applications; however, at the time of this project the durability and retention of selective properties and costs of these coatings were not adequately established, and for this reason, they were not selected for use in this application.

Porous plugs are provided to vent the cavity between the absorber and the outer window, allowing for air expansion and the expulsion of water vapor on heating. These plugs are protected by the window lips from direct weather exposure.

Recessed threaded inserts are provided along both 2.44m edges of the back of the collector modules to permit bolting to their supporting structure. Twelve 1/4-20 bolts provide adequate retention margin (5:1) against the 2.1 kg per square m maximum design wind load.

IV.A.2 Thermal Performance Characteristics

The thermal performance of the collectors is displayed in Figures IV-4 through IV-10. The collector efficiency is given in Figures IV-4 through IV-6 as a function of the average collector plate temperature, the air temperature, the total insolation per unit collector area, and the wind speed.

The remaining figures, Figures IV-7 through IV-10, give the absorptivity - transmissivity factor and the upwards loss coefficient. The loss coefficient is given as a function of the same parameters as is the collector efficiency.

The definitions of the thermal performance parameters given in the figures are presented in the following paragraphs.

Consider first only the direct component of the solar radiation. Let I_D denote the direct radiation and let θ denote the angle of incidence of the radiation on the collector. Then, the rate at which direct solar radiation is incident upon unit area of the collector is

$$E_i = I_D \cos \theta \quad (1)$$

The fraction of this energy which is absorbed at the collector plate of the solar collector is given by the absorptivity-transmissivity factor. The energy absorption rate is then

$$Q_{\text{abs}} = (\alpha \tau) I_D \cos \theta \quad (2)$$

where $(\alpha \tau)$ = absorptivity-transmissivity factor.

Some of this absorbed energy is lost by conduction, convection and thermal radiation and is given by the expression

$$Q_{\text{Loss}} = U_{\text{Loss}} (T_p - T_{\text{Air}}) \quad (3)$$

where

U_{Loss} = loss coefficient

T_p = average collector plate temperature

T_{Air} = air temperature

The loss coefficient is the sum of the back and side loss coefficient and the upward loss coefficient. The back and side loss coefficient is 0.495 watts per square meter per $^{\circ}\text{C}$. The upward loss coefficient is given in Figures IV-8 through IV-10.

Now let I_F denote the rate at which diffuse radiation is incident per unit collector area, and let $(\alpha \tau)_F$ be a suitably averaged value of $(\alpha \tau)$ which describes the fraction of diffuse radiation absorbed at the collector plate. The rate at which solar energy is transferred to the collector fluid loop can now be written as:

$$Q_u = (\alpha \tau) I_D \cos \theta + (\alpha \tau)_F I_F - U_{\text{Loss}} (T_p - T_{\text{Air}}) \quad (4)$$

where of course $(\alpha \tau)$ is to correspond to the angle θ .

FIGURE IV-4

FIGURE IV-5

FIGURE IV-6

FIGURE IV-7

FIGURE IV-8

74
UPWARD LOSS COEFFICIENT ($W/M^2-^{\circ}C$)

FIGURE IV-9

FIGURE IV-10

The collector efficiency is defined as the ratio of the collected, or useful, energy Q_u to the total incident solar energy, i.e.,

$$\text{Efficiency} = Q_u / (I_D \cos \theta + I_F) \quad (5)$$

IV.A.3 Lifetime Performance Characteristics

As mentioned earlier, when discussing lifetime aspects it must be remembered that the solar collectors utilized on this project were in an undeveloped, experimental status when installed. In addition, a significant output of the project was to be the collector/system interactions and the effect on the design of each.

IV.A.3.1 Long Term Thermal Performance

An investigation was made of what performance degradation, if any, occurred with the collectors over an approximately 15 month operational period. This was done by searching out days with "matching" conditions in the spring of 1974 and 1975 and then comparing collector performance. The days chosen for comparison exhibited essentially cloudless skies which tended to minimize collector transients. Furthermore, the performance at midday was analyzed, a choice which also tended to minimize transients. The criteria of cloudless skies and noontime data also minimized variations in the distribution of the insolation between the direct and diffuse components and variations in the incidence angle of the direct component. Not all variations could be eliminated, of course, especially in view of the large number of significant parameters.

In addition to those already mentioned, the air and collector plate temperatures the wind speed and the magnitude of the insolation all play a role in determining collector performance at any given time.

The results of the efficiency calculations and the values of the more significant parameters are given in Figure IV-11. The efficiency is plotted as a function of $\Delta T/I$, where:

ΔT = difference between collector plate and air temperatures.

I = total insolation incident upon the collectors (direct plus diffuse)

Using $\Delta T/I$ as the independent variable tends to reduce the scatter in data since, to a first approximation, the efficiency is a linear function of $\Delta T/I$.

A straight line was passed through the 1974 data to serve as a basis for expected initial performance. The 1975 data agree with the 1974 data within experimental error. On the whole, the comparison suggests that there has been no apparent degradation in collector performance.

The collector pressure drop at operating conditions is defined by the following equation

$$\Delta P = .0548 G$$

where

ΔP = Collector pressure difference $\sim$ k Pa

G = Collector flow rate $\sim$ cc/sec

For all credible operating modes, flow through the collector will be laminar and a nominal operating point is 2.76kPa at 50.3 cc/sec.

FIGURE IV-11
LONG TERM THERMAL PERFORMANCE

IV.A.3.2 Long Term Optical Characteristics

A collector, serial number 028, was removed from the array after nine months operation and dissected. The quantitative data in this section was taken from this collector.

Optical properties of the S/N 028 absorber plate coating were measured. The values found were 0.975 and 0.925 for solar absorptivity and for 100⁰C infrared emissivity, respectively. This compares with 0.975 and 0.907 which were measured beginning-of-life values.

There was significant discussion during the planning stages of the project as to how often and what type of window cleaning procedures might need to be employed on the collectors. Since cleaning a 4600 square foot array is a formidable task, it was expected that developed "tricks of the trade" would be a valuable output of this project. The matter was complicated somewhat by the scratch susceptibility of Lexan relative to glass. Cleaning equipment representative of various types of commercially used techniques were purchased.

The array is west of an incinerator and falls underneath one of the approaches to Boston's Logan Airport. As a consequence, there is a more than average supply of particulate contamination which falls on the windows. The prevailing winds are west and during the approximately 30 percent time frame when the wind is not out of the west, it usually blows from the east. Because of the height and the direction, the windows are nearly always wind swept. This was a concern due to the possibility of building up a static charge which would enhance particulate adherence.

Bank B collectors were cleaned after approximately two weeks exposure and 5 days without rain. Two cleaning techniques were used (detergent/water and pure water with a soft rag). That night it rained and the following day all collector windows appeared equally clean, the "cleaned" collectors having been water spotted and the "uncleaned" collectors having been rinsed clear of particulate. The conclusion was that while the panel performance is temporarily improved somewhat by cleaning, it is not worth doing because:

1. The improvement is short lived (hours).
2. Rain is frequent and effective enough to do an adequate job (at least in Boston).

This experiment has been repeated several times since with the same conclusion resulting each time.

Three Lexan window samples were tested for solar spectrum transmission, specifically, 1) uncleaned outer window from S/N 028; 2) uncleaned inner window from S/N 028; and 3) a virgin piece of Lexan from the same batch but which had not been exposed. Following the test of sample #1, it was carefully cleaned with alcohol to remove the "Boston dirt film" which had accumulated and was retested. The results are as follows:

<u>Sample</u>	<u>Transmissivity</u>
1. Outer window as removed from S/N 028	.810
2. Inner window as removed from S/N 028	.841
3. Unexposed Lexan from S/N 028 batch	.843
4. Sample #1 cleaned with alcohol	.837

The outer window showed no signs of yellowing or discoloration of any kind. The collector was removed in the rain, so it is probably safe to assume loose dirt which would normally be removed by rain was mostly absent.

IV.A.3.3 Corrosion/Fluid History

This is a large subject and a thorough investigation was beyond the scope of this project. However the work which was done is reported here and consists basically of two evaluations, fluid chemistry and metalographic inspection of the dissected collector S/N 028.

The desire to minimize costs with the compressed construction schedule dictated the use of copper piping for the fluid loop. The TES tank and the internal heat exchanger had to be steel for the same reasons. Since the collectors utilized aluminum roll-bond, the wetted surface areas were approximately 144 M² aluminum, 45 M² copper, and 42 M² mild steel.

It is common knowledge that in aqueous solutions heavy metal ions such as copper will produce a corrosive attack and pitting on aluminum unless the solution is adequately inhibited. In addition, galvanic attack is possible where copper is coupled to aluminum. Considerable work has been done in developing inhibitors for copper, aluminum and steel systems, largely related to the automotive industry. The most common types of inhibitors are the following:

1. Sodium mercaptobenzothiozole
2. Borax with various additives
3. Sodium benzoate-sodium nitrate

Most commercial automotive antifreeze solutions contain a combination of these inhibitors.

Discussions with personnel at General Electric's Corporate Research Center and Betz Laboratories revealed that maintenance of a solution pH value in the 7 to 9 range was highly desirable from the system standpoint. Higher pH values would be better for the steel and the copper was insensitive over practical pH ranges. Since the steel component wall thicknesses were 5 to 10 times the aluminum wall thicknesses, priority was placed on protecting the aluminum.

Commercial automotive antifreeze was purchased for use in this system, and while its chemistry was proprietary with the manufacturer, it appears that the first two types of inhibitors mentioned above are embodied in this product. Two additives were selected which would be compatible with the antifreeze, its existing inhibitors, and the fluid loop materials; sodium mercaptobenzothiozole (MBT) and sodium acid phosphate. The former's role is primarily to stabilize the copper ions and thus reduce their attack on the aluminum, and the latter is utilized as a buffer for pH control and to help inhibit the aluminum surface. The amount added was 0.2% by weight of MBT (which produces a total MBT content above 0.2%) and enough sodium phosphate to maintain pH levels at 7 to 9, approximately 0.5% by weight.

At various times during the year fluid samples were taken from the circulating loop and returned to Valley Forge for chemical analysis. One of the initial samples (4/22/74) was evaporated and the residue put through an emission spectrographic analysis. The major elemental constituents were identified as aluminum, boron, and sodium with submajor elements being tin and silicon; magnesium was a minor element, and trace quantities of manganese, iron and lead

were also found. It was about as expected with aluminum, iron, tin and lead being fluid loop materials and the rest being constituents of the commercial glycol or Boston water. All of the other samples taken were analyzed for pH and resistivity only.

The history of the system fluid's pH value is plotted in Figure IV-12. A sample of Boston water was measured to have a pH of 6.5. When a solution is produced consisting of approximately 30% of the glycol utilized in the project, the pH value produced rises to the 10.0 - 10.5 range. This was deemed too high for longevity of the aluminum and a buffer to control pH was included as one of the solution inhibitors. The inhibitors were added to the solution the first part of June and the last of September 1974. During the mid to late summer 1974 there were fluid loop hardware problems which resulted in a large solution depletion rate due to the frequent addition of make up water. This situation was stabilized in September and the abrupt rise in pH is attributable to the addition of glycol with some overshoot until the buffer became effective. The loop pH remained stable after that.

Resistivity of the fluid was measured to provide an indication of the total anion content of the working fluid. While it does not distinguish between aluminum and copper ions, for instance, it does provide some indication of the rate of metallic ionization. The resistivity history is shown in Figure IV-13. Again, a Boston water sample was measured and found to have a resistivity of 14,000 Ohm cm. The effects of the summer depletion/clear water make up mentioned above are quite noticeable in Figure IV-13. Since the resistivity

Figure IV-12. History of Liquid pH Value

Figure IV-13. History of Liquid Resistivity

value is inversely related to the anion concentration, the dilution appears as a large rise to 12,000 Ohm cm, almost the pure water value. Addition of the glycol and inhibitors brought the value down to the 300 - 350 Ohm cm range the first of October 1974. The resistivity value was nearly constant after that with a slight upward slope which implies that ions were being removed from solution.

A piece of the S/N 028 absorber plate was sectioned and the interior (wetted) surfaces examined. A beige colored deposit was rather uniformly present and is typical of the effect expected with the corrosion inhibitor utilized. One qualification on uniformity was that the deposit was rough or furrowed in some passages and appeared nearly smooth and fine grained in other passages. However, the surface texture of the deposit appeared uniform in each passage. (A 15 cm length was examined.) There was no definite pattern; however, most passage upper surfaces were rougher than the lower ones and the area near the joint between the two roll-bonded sheets appears rougher than the more planar passage areas (an implication being that slower flow areas correspond to rougher deposits). The deposit was scraped away and the underlying aluminum surface examined in several locations. It was found to be free from pits or any visible signs of corrosion attack.

Various section of the flow passages were also analyzed metallographically. Figures IV-14 and IV-15 show typical cross section photomicrographs, both made at 63 X magnification. Figure IV-14 shows a semi-polished, unetched section under polarized light to enhance the surface coating geometry, (which appears as the cloudy area along the top surface of the metal). An under-

standing of the coating thickness can be obtained by realizing the aluminum is approximately .075 cm thick, i.e., the coating varies from .0075 to .020 cm thick. Figure IV-15 is a polished, etched section which shows the aluminum surface to be clean and with no evidence of corrosion. Another view of the wetted surface at a higher power (460 X) is provided by Figure IV-16 and also shows no evidence of corrosion.

The coating was also analyzed chemically. The coating structure was found to be primarily crystals in an amorphous layer. X-ray diffraction measurements identified the crystals as a unit cell, hydrated alumina chloride, $\text{Al}_{45}\text{O}_{45}\cdot\text{Cl}$. The major elements identified by emission spectrograph are listed in Table IV-1. Essentially identical results were obtained from coating samples from channels 8 and 11. The relatively high concentrations of calcium, silicon and magnesium are likely from the Boston water, while iron and copper are most likely attributable to the piping materials.

This system is young from a corrosion standpoint (with the exception of galvanic corrosion which would ruin an absorber plate in a month or two). While it is too early to be confident, the examinations performed on the absorber plate of collector S/N 028 and discussed above imply that corrosion in this system is not a problem. A definitive statement as to which additives are best or even that those added were optimum is not possible, since there were no "control" tests. It does seem, however, that the combination and amounts used did not harm the aluminum and probably helped.

INHIBITOR
COATING

WETTED SURFACE

ALUMINUM THICKNESS

63 X MAGNIFICATION

FIGURE IV-14

WETTED SURFACE

ALUMINUM THICKNESS

63 X MAGNIFICATION

FIGURE IV-15

WETTED SURFACE

ALUMINUM
ROLLBOND

0
0.0254MM
0.0508MM
SCALE

460 X MAGNIFICATION

FIGURE IV-16

TABLE IV-1

EMISSION SPECTROGRAPHIC* ANALYSIS OF COATING SAMPLES

ELEMENT ppm	Channel 11 Specimen	Channel 8 Specimen
Boron	600	850
Copper	>1 K	>1 K
Titanium	200	280
Magnesium	>1 K	>1 K
Manganese	>1 K	>1 K
Silver	27	28
Chromium	20	17
Lead	200	230
Tin	>1 K	>1 K
Silicon	>1 K	>1 K
Iron	>1 K	>1 K
Calcium	300	280
Sodium	>1 K	>1 K

*Note that very light, volatile, or non metallic elements do not register well by emission spectrograph.

IV.A.3.4 Working Fluid Leakage

It would be nice to be able to say that the system's operation was without problems; however, there were some. One of the major objectives of this pilot plant scale experimental project was to identify problems so that they are not repeated in the future. The leakage problems occurred in two areas; the collector's hydraulic interface and the main pump shaft seal.

The collector hydraulic interface appeared to be a straightforward area which became a problem due to subtleties. Two components are involved, the nipple, which is the interface to the absorber plate and protrudes through the collector case, and the rubber hose which connects the nipple to the rest of the system. The absorber plate nipple is an aluminum tube approximately 5 cm long, 1.28 cm O.D., and having an .15 cm wall thickness. Pipe threads are cut on one end which mate with the female threaded adapter welded to the absorber plate. The problem which develops is that with time and thermal cycling some of these joints begin to seep very slightly. The one instance in which the leak rate was measured, a value of 3×10^{-4} scc/sec was recorded. This is not significant from a fluid loss standpoint but is sufficient to cause visible condensation on the interior surfaces of the Lexan windows. This is undesirable from the aesthetics standpoint and, if the condensation is sufficiently heavy, from a performance standpoint. Initially, the nipple threads were coated with a room temperature vulcanizing silicone compound (RTV) prior to insertion but approximately halfway through the fabrication run of collectors, TFE teflon tape was applied to the nipple threads as a joint sealant. This change was

made as a result of leaks experienced while bringing collectors on line in February/March 1974. Most of the TFE sealed nipples found their way into Banks A and D and these banks have been, historically, the most troublefree. Some collectors did develop seepage to the point of accumulating droplets within the collector. However, the incidence of nipple/absorber seepage to the point of visible condensation was not large and occurred on perhaps 40 out of the nearly 600 such joints existing in the system.

Initially, a workable cure for the problem was to loosen the connecting hose, tighten the nipple into the absorber fitting and retighten the hoses. After six to nine months, the coating of the corrosion preventative on the female adapter threads became hard enough to preclude advancing the nipple threads.

A more elaborate procedure entailing nipple removal and thread cleaning would probably be successful and could be worked out but was effort beyond the scope of the current project. An improvement for future absorbers would be to utilize only metallurgically bonded connections within the collector envelope.

Rubber hoses of 1.28 cm I.D. are utilized between the tandem mounted collectors and to connect the collectors to the system. Their function is to provide a hydraulic connection which electrically isolates the absorber and accommodates the significant relative motion which occurs with varying system temperatures. The susceptibility of many types of rubber to degradation as a result of exposure to ultraviolet light (UV) and ozone is well known. Consequently, a particular rubber hose was selected which was reputed to provide years of service on heavy construction equipment exposed to all kinds of climatic

extremes. Unfortunately, the hose delivered utilized a Buna-N rubber compound rather than the desired neoprene. The difference is not readily obvious, and no problems were apparent until surface cracking became visible after eight weeks' exposure. Investigation of the problem led to a conclusion that further degradation could be substantially eliminated by wrapping the hose with an opaque tape. This was done in August/September 1974.

The major problem that exists is that the degraded hose walls have softened, and the original clamps do not exert enough force to preclude leaks at the hose/nipple interface. It has been found that leakage is more likely to occur upon cooldown from high temperature (over 200°F) and, in fact, the smaller leaks could only be found after 9:00 P.M. on a summer night. While the individual leak rates never exceeded a drop every few seconds, they were so widespread that the total liquid loss was sufficient to depressurize the system in a few days. The lowered pressurization level would in turn lead to pump cavitation and flow cessation. In extreme cases, air would be drawn into the top headers via the outlet hoses during night cooldown and again produce pump cavitation due to entrained air.

Approximately 700 of the 900 crimp type clamps originally in the system were replaced with worm screw aircraft type clamps and retightened several times before the leakage was effectively stopped. The tighter hose clamps have led to another problem, however. The daily temperature swings, many of which exceed 150°F, result in significant motions of the absorber plates, headers, and hose nipples relative to the locating steel. It appears that the replacement hose

clamps are tight enough such that a sliding/seizing cycle between the hose and nipple exists for inter-collector hoses which corresponds to the daily heating/cooling cycle. The effect is to "ratchet" one end of an inter-collector hose off the end of a nipple. The solution is to utilize hoses which are slightly longer and thus trapped from excessive axial movement by interference with the collector cases.

The unit replacement of degraded hoses was not implemented due to the success of the above fixes and the labor costs required. The lower header hoses are easily replaced, but the inter-collector hoses cannot be easily replaced without loosening and shifting either the upper or lower collector. The upper header hose connections occur within the insulation which requires de/reinsulating the upper header. Any future projects using rubber hoses should provide good serviceability access to the hoses; they are likely the weak link in any such system.

The main pump utilized in this system was obtained by default rather than selection. This occurred because of the construction schedule and a temporary dearth of pumps with acceptable performance characteristics available in the northeastern part of the country. The pump obtained was of the universal type, motor and pump individually mounted to a common base plate and joined by a flexible coupling. The type of seal utilized on the pump was a five ring, high temperature, impregnated, packing which is pressed into a stuffing box by a gland piece. Adjusting the force exerted by the gland nuts varies the degree to which the packing is squeezed between the rotating shaft and the stationary stuffing box. If the force is too low, the seal leaks

excessively. If too high the seals heat and the seals and shaft wear. A pump with this type of seal is not a zero leak device and was not what was desired but rather what was available.

The system operated for several months with a tolerable seal seepage rate of about 20 drops a minute (this type seepage rate was recommended). A drain tube was added to the pump's seepage catch box to provide a gallon or so reservoir. This both reduced the likelihood of an overflow onto the roof and provided a means to monitor the rate of liquid loss.

In June 1974 the seepage had increased to the point that the drain tube could be emptied more than once a day. The seal repacking operation was performed and found to be difficult and only partially successful, since the shaft was somewhat worn and the seepage rate did not remain low with the new packing. The recommended packing tools were very inconvenient in the restrictive geometry of this particular pump and only with modification did they work at all. Different type tools might have made considerable difference. An additional complication was the fact that the pump had to, of course, be hydraulically isolated from the loop and the loop circulation maintained by the TES pump operating in its backup mode. To ensure that excessive loop temperatures were not experienced the repacking operation was not begun until approximately 3:00 P.M. which resulted in the work being done in a darkening environment.

Because of increasing seepage rates, inquiries were made in July 1974 as to the feasibility of converting the main pump to a mechanical type seal. The result was the removal of the main pump in September, at which time some minor machining modifications were done and a mechanical seal was inserted. This seal operated with zero seepage for about 8 months and eliminated an unsightliness in the pump area. Two significant system benefits were that: 1) the absence of seal leakage kept the need for make up water sufficiently low through the winter that the more complicated addition of glycol was not required; and 2) the mechanical seal eliminated the pump's tendency to draw air into the fluid loop through the shaft packing seal. Unfortunately, in March 1975, the mechanical seal was noticed to drip slightly with fluid temperatures over 180°F. The reason for this is not known, but it is not due to excessive temperatures since the capability of this seal exceeds 300°F.

It is reasonable to expect that fewer seepage and air ingestion problems would have occurred had the pump been factory equipped with a mechanical seal. For comparison, the mechanically sealed TES pump has produced absolutely no problems.

IV.A.3.5 Breakage/Thrown Objects

The initial response of the neighborhood youths to the expanse of "glass" on top of the school was to throw things at it. The number of rocks per day was not fantastic, but virtually every rock reaching the roof hit a collector. Picking up the debris once a week led to the belief that 20-30 rocks/week was about normal. Of course, only the larger rocks and foreign objects are

noticeable since the roofing material is stones on mastic. Most of the thrown objects hit Bank C since it is on the front of the school and closest to the edge. To date, no visible damage has occurred to a collector. One flowmeter window was almost certainly broken by a rock, and two others showed evidence of having been hit (all were on Bank C and removed after the initial flow distribution assessment due to their susceptibility to rocks). For comparisons, the school typically loses one window a week to missiles.

The novelty of throwing rocks wore off after a few months, probably because nothing broke. It was resurrected again during the summer of 1974 when there were more youths with idle time and less observers, and the spectrum of objects thrown increased. We have picked up a few shoes, parts of toy cars, and a piece of a hockey stick in addition to the normal debris. The record rock found to date is about 8 cm in diameter.

To date no worker has been hit by anything thrown. However, on at least three instances an object has come in the general direction of a GE worker (probably without the thrower knowing the man was there). Two classes of objects are of particular worry, the glass bottle and the flattened can; the former because it shatters against the steel, producing flying shards and the latter because it "sails", normally arriving on the roof with a high rotational velocity and sharp edges.

It is credible to assume that glass glazed collectors (using practical types of glass) would not survive this environment.

IV.B Heat Transfer Subsystem

IV.B.1 Description of Physical Configuration

As was pointed out above (see Section I.C.1) water-to-air finned tube heat exchangers were added to the Nesbitt Roof Heating and Cooling units. Considerations of achievable delivery schedule as well as air side pressure drop restrictions and required heat transfer rates led to the selection of a Trane Company two row, type W, water coil as the heat exchanger. The face of this coil is 61 x 152 cm. The tube spacing within each row is 3.81 cm and there are approximately 3 1/2 fins per cm of tube length.

The fins are aluminum and are mechanically bound to the copper tubes. The headers are constructed of cast iron and the casing of galvanized steel.

IV.B.2 Thermal Performance Characteristics

Figure IV-17 provides the basic operating performance predictions for the system in terms of measurable parameters, liquid flow rate and inlet temperature. This figure is based on a 16°C entering air temperature which appears reasonable since a majority fraction of the air entering the hot deck will be building return air and the fan work will have raised the air temperature some. If it is ascertained that the entering air (which is also cold deck air) differs markedly from 16°C, the curve is still valid with the modification that liquid temperature should be replaced by entering liquid to air temperature difference; thus the four curves are for ΔT 's of 44, 33, 22 and 11°C moving from top down on the figure. The 60°C pair of curves is an extrapolated set. The sensitivity to air flow within the operating ranges is shown as the approximately 7 percent change in air temperature rise for a 470 l/sec variation in air flow rate. Some actually experienced operating points are also shown on

Figure IV-17 for comparison. The generally "high" values of air temperature rise are the result of less than the rating value of 3540 l/sec of air actually flowing through the hot deck.

Figures IV-18 and IV-19 provide coil heat transfer characteristics based respectively on water and air side data. Figure IV-20 presents liquid and air side pressure drop predictions. It is seen that water side pressure drops will run in the 7 Kpa range and liquid temperature variations will have a negligible effect. The air side pressure drops are above Nesbitt's nominal value of 0.09 Kpa for all flow rates above about 2850 l/sec which means that approximately 60 percent of the units total 4580 l/sec normally goes through the hot deck. The face area of the normal Nesbitt hot water coil is not significantly larger than that of the "solar" coil.

The nominal design point for the coils in the heating system is 1.9 l/sec each, with a 9.5°C drop at which point they will deliver approximately 69 KW each assuming 16°C inlet air and 49°C inlet water. Increases in inlet water temperature will significantly increase the heat transfer capability.

IV.C Thermal Energy Storage Subsystems

IV.C.1 Description of Physical Configuration

As mentioned earlier, the solar heating system was originally configured without a Thermal Energy Storage (TES) capability because of an inability to find a usable location capable of supporting a concentrated load on the order of 23 to 27,000 Kg. In addition, the Boston Public Facilities Department had

FIGURE IV-18

TRANE, SERIES 16, TYPE W, TWO ROW COIL

FIGURE IV-19

TRANE, SERIES 16, TYPE W, TWO ROW COIL

FIGURE IV-20

expressed considerable concern that glycol from the main fluid loop would leak onto and degrade the roof and the thought of possibly dumping a very large volume onto the roof as a result of vandalism was less than appealing.

From a system performance standpoint, a small TES capability, even just large enough to provide morning heat until the main loop could take over, would be useful. A location on the north side of the east end of Bank E was identified which could readily accommodate a 9,000 Kg load and a search was begun to find a usable tank in the 8,000 liter range. This last proved to be a problem because the late 1973/early 1974 oil shortage had created an unusual demand for storage tanks in this size range; however, eventually a 7570 liter steel storage tank was located.

A normal TES application is to circulate the hot loop working fluid through a large, well insulated tank with the system's thermal load being either in parallel or downstream from the tank. Whenever the main loop is cold, the TES tank is isolated from the main loop and the thermal load is supplied from the TES tank. The TES mechanism is often simply a massive amount of thermal inertia with the energy stored as sensible heat in water, steel, stones, etc. Although materials which change phase offer significant promise, this simple thermal inertia approach using water was chosen for the TES tank.

The design of the tank had to consider that its rated working pressure was 49 Kpa which was considerably below the expected main loop pressure levels. The resulting design utilized an internal heat exchanger ("coil") which both solved the discrepancy in pressure requirements and also put to rest fears of discharging a really large volume of solution onto the roof. As a result, the main loop is circulated within the relatively high pressure coil and the coil is in turn submerged in a stagnant tank of liquid. A schematic of the general configuration is shown in Figure IV-21. The stagnant layer of liquid surrounding the coil will thermally stratify but the consequences of this are somewhat negated in the design by routing the main loop fluid in through the top and out the bottom of the tank. As mentioned in the foregoing, when energy is being withdrawn from the TES tank, the flow through the coil is reversed; entering in the warm bottom region and leaving from the hot upper region.

The principle design problem is to minimize the so called approach temperature. This is defined in this case as the temperature differential between the main loop and the stagnant TES fluid. While it is a bit of an oversimplification, the significance of the approach temperature is that it limits the maximum temperature available when heating the school from the TES tank. This occurs because there is a temperature drop from the main loop to the TES fluid during the storage mode and there is also a drop from the TES fluid to the circulating fluid in the energy withdrawal mode. Since the heat transfer rates are likely similar and the two temperature drops are additive, the maximum temperature available to heat using TES is the maximum main loop temperature less twice the approach temperature.

Figure IV-21 Cross Section Pictorial of Thermal Energy Storage Tank

The approach temperature is a function of heat transfer area and rate and 88 KW was selected as a nominal rate which was likely representative of both the storage and withdrawal modes. Calculations were made which indicated that approximately 18.6 square meters of area would be required to obtain approach temperatures in the range which was deemed to be acceptable (2.7 to 3.9°C). This was accomplished by sizing the tube bundle and water boxes shown in Figure IV-21, to have 18.1 square meters of heat transfer area.

A secondary design consideration was the venting of the TES tank to allow for expansion/contraction of the TES fluid with maintenance of acceptably low pressures. The result, also shown in Figure IV-21, was to utilize a trapped air bubble with a vent pipe. The vent pipe is normally filled to some level which precludes fresh air from entering the tank, thus minimizing corrosion at the waterline. As the TES fluid warms initially, the lower end of the vent pipe is first covered; further expansion compresses the 25.4 cm high air bubble with the resulting air pressure pushing water up the vent pipe. The total height from the bottom of the tank to the open top end of the vent pipe is 3.6 m and therefore the maximum pressure possible in the TES tank is between 35 and 38 Kpa depending on TES fluid density. A 114 liter catch tank was placed on top of the TES tank and in series with the vent pipe to minimize the spillage during the initial TES warm up cycles.

The storage media was water; however, 100 percent ethylene glycol was pumped into the exposed sight glass standpipe to preclude its freezing. In addition, approximately 250 liters of glycol were gravity fed into the bottom of the tank to promote a slushing action rather than abrupt freeze in the event the bottom of the tank did ever approach freezing temperatures (which it never has to date).

IV.C.2 Thermal Performance Characteristics

The basic tank had a capacity of 7570 liters; the volume occupied by the air bubble and the TES coil is 1150 liters and the TES coil and tank are steel and weigh 1360 kg and 545 kg respectively. If the tank itself is discounted, the thermal storage capacity is $1.9 \text{ MJ}/^{\circ}\text{C}$. The tank was insulated with fiberglass insulation and weather-proofed. An insulating mounting interface was achieved by use of wood bearing blocks to support the tank.

The maximum heat loss rate was conservatively calculated at 18.4 watts for every degree centigrade of temperature difference between the average TES fluid and ambient. This translates into a TES fluid temperature loss of about 2.2°C over an average winter night.

Unfortunately, an error occurred during the construction phase and the TES coil was rotated 90 degrees out of position which greatly increased the attainable approach temperature to approximately 11°C. As a partial consequence of this, the useability of TES heat at the design withdrawal rate of 88 kW assuming nominal temperature conditions, is only 3 hours. Fortunately this rate is rarely experienced for three continuous hours and the TES tank has proved useful to the system.

IV.D Air Conditioning Subsystem

This report section is not applicable to this heating only system.

RECOMMENDED

CCMS SOLAR ENERGY PILOT STUDY REPORTING FORMAT FOR HEATING AND COOLING SYSTEMS IN BUILDINGS

August 1975

The objective of this special reporting format is to assure that sufficient information is provided to enable the reader to make his own assessment of the performance of a solar heating and/or cooling system and to relate that performance, which was carried out in one particular climate and economic environment, to a different climate and economic environment.

All details of the format are to be followed as completely as possible. In addition, information on all related back-up reports is requested, including specific instructions on how they may be obtained.

FORMAT FOR REPORTING SYSTEM PERFORMANCE

I. General Description of System Project and Environment

A. Objective of Project

- o Brief description of objective and strategy of project, including duration and major milestones.

B. Description of the Environment - each section to be included if appropriate

1. Climate

- o Brief description of type of climate, according to the Trewartha* worldwide classification system.
- o Annual rain and snow fall (mm per year).

* G. T. Trewartha, An Introduction to Climate (McGraw Hill: New York, 1968).

- o Description of typical sky conditions relative to "clear sky"; either average daily sunshine hours, number of sunshine hours per year, the percentage of maximum possible sunshine hours or annual average cloud cover fraction may be used.

2. Location

- o Latitude, longitude, and altitude (in m) of system.
- o Description of the configuration of the location and distance from solar or wind obstructions or significant geographic features (sea, mountains, etc., in km).
- o Comment on air quality, i.e. dust precipitation.

3. Solar Radiation

- o Mean monthly global (total) and, if relevant, diffuse insolation on a surface whose orientation is described. The number of years over which this mean is defined should be specified, as well as the time intervals of the data.
- o Description of the measurement equipment.

4. Ambient Temperatures

- o Mean monthly dry and wet bulb temperatures (relative humidity may be used in place of wet bulb temperature).
- o Number and basis of degree-days of location.
- o Description of the measurement equipment.

5. Wind

- o Average monthly wind speed and prevailing direction (0 - 360° from North towards East).
- o Description of measuring equipment.

C. Description of System

1. Qualitative Description

- o Description of the entire system, as well as the solar system, by narrative, photographs, or drawings.

2. Quantitative Description

- o Description of the system performance characteristics, including schematic drawings.
- o Orientation* and inclination⁺ of collectors.
- o Control system description, performance characteristics, and location within the system. The operating modes should be described.
- o Measurement system description, performance characteristics (such as precision and repeatability), and location within the system.

II. System Thermal Performance - The information in sections A, B, C and D is essential and therefore should be as complete as possible.

A. Daily, Monthly and Annual Values** of the Mean Daily (Tabular or Graphical Form)

- o Total energy required (thermal load, heating or cooling, on system).
- o Supplemental energy required (amount, kind, and purpose).
- o Solar energy incident on collectors.⁺⁺

* Angle between the projection of the sun's rays, at solar noon, on the horizontal plane and the projection of the normal to the collector on the horizontal plane.

+ Angle between horizontal and normal to collector.

** The monthly value of the mean daily quantities is the most important of the three. Daily values may be provided as optional information.

++ It is suggested that this be based on (at least) hourly values of the global (and/or direct, if appropriate) insolation measured in the plane of the collectors. If the global insolation is only measured on a horizontal surface, it should be so provided and the method used to determine the amount incident on the plane of the collectors should be described.

- o Solar energy collected.
- o Solar energy used.

The criteria for the use of supplemental energy must be described.

- B. Record of the Quality of Thermal Performance of the System
(e.g. departure from the design temperature over reporting period)
- C. Solar Contribution to Energy Requirements - daily, monthly and annual values* of percent solar contribution to the energy requirements.
- D. Monthly and Annual Energy or Fuel Savings - based on primary fuel (state type).
- E. Energy and Mass Balances

This information is of secondary importance in that it is this information that is used to determine the quantities reported in II A. If possible, it is suggested (optional) that a typical day be used to show:

- o Significant energy flow rates - additions and losses.
- o Significant mass flow rates - additions and losses.
- o Temperature and pressure at critical locations.
- o Temperature drop and pressure drop across major components.

III. System Economic Analysis

The following costs and factors should relate to the solar portion of the project but could also be specified for the entire project.

* The monthly value of the mean daily quantities is the most important of the three. Daily values may be provided as optional information.

- A. Total Cost of the Solar Portion of the System - with a specific definition made of the interface between the solar and non-solar portions of the system. If possible, separate design costs from component and installation costs.
- B. Labor Costs - in man-hours and in local currency, for the installation of the system.
- C. Materials Costs - in weight or volume as appropriate and in local currency.
- D. Operational Costs - including supplemental energy costs, in local currency.

Since operational costs depend on the assumed system lifetime, it is suggested that the assumed system lifetime be stated along with the depreciation rate.
- E. Local Economic Factors - such as inflation, interest rates and amortization periods.
- F. Expected Selling Price or Costs - assuming that the system or solar components are mass produced.
- G. Maintenance Frequency and Costs - in hours and material.
- H. User Reactions and Comments

FORMAT FOR REPORTING SUB-SYSTEM PERFORMANCE

A. Solar Collectors

1. Description of Physical Configuration

- o Description of solar collectors by narrative, photographs, and drawings, including collector materials, design, dimension, and construction.

2. Thermal Performance Characteristics

- o Collector efficiency curves (efficiency as a function of average fluid temperature or inlet coolant temperature, ambient air temperature, solar radiation normal to the collector, and wind speed) or equivalent collector performance indication (such as heat production) for several days that typify the full range of operation of the system.
- o Pressure drop through collectors.
- o Optical efficiency vs. incident angle, daily, monthly, and annual optical efficiency.
- o Thermal loss coefficient as a function of the difference between the ambient* and the mean plate temperature, for known wind speeds.

3. Lifetime Performance Characteristics

- o Corrosion
- o Leakage
- o Hot spots
- o Breakage
- o Stability of collector working fluid

B. Heat Transfer Sub-system

1. Description of Physical Configuration

- o Description of heat transfer sub-system by narrative, photographs, and drawings. Specify construction materials and working fluids.

* Optional information to be included if known.

2. Thermal Performance Characteristics*

- o Inlet and outlet temperatures on both sides of exchanger.
- o Inlet and outlet pressures on both sides of exchanger.
- o Mass flow rates on both sides of exchanger.
- o Pumping power.

C. Thermal Energy Storage Sub-systems

1. Description of Physical Configuration

- o Description of thermal energy storage sub-system by narrative, photographs, and drawings.
- o Specify construction materials and working fluids, location within system, insulation details (material and construction), mass and volume of storage sub-system, storage duration and/or energy stored at same temperature.

2. Thermal Performance Characteristics*

- o Mean temperature, hourly and daily, of the immediate surroundings.
- o Thermal loss or gain, hourly and daily.
- o Storage capacity.
- o Inlet and outlet temperatures and pressures.
- o Flow rates and pumping power.
- o If phase change materials are used, specify compound and thermal characteristics.

* This information is of secondary importance in that it is this information that is used to determine the quantities reported in II A. If possible, it is suggested (optional) that a typical day be used to show:

- o Significant energy flow rates - additions and losses.
- o Significant mass flow rates - additions and losses.
- o Temperature and pressure at critical locations.
- o Temperature drop and pressure drop across major components.

D. Air-Conditioning Sub-system

1. Description of Physical Configuration

- o Description of air-conditioning unit by narrative, photographs and drawings.
- o Type of sub-system - heat pump, absorption, passive, etc.
- o Heat rejection method.

2. Thermal Performance Characteristics

- o Capacity at design inlet (to air-conditioning unit) temperature.*
- o Capacity⁺ and coefficient of performance COP curves (inlet temperature as variable).*
- o Sensitivity of the capacity and COP to variations in inlet temperature, evaporation temperature, wet and dry bulb temperature.

* Condenser, absorber and evaporator temperatures should be stated.

⁺ Including the ratio of sensible to latent heat removal.

The international System (S.I.) will be used exclusively* with the following recommendations:

Pressure - given in Kpa.

Temperature - °C

Energy - MJ and/or Kwh

Energy Flow Rate - Kw, w

Solar Radiation - the intensity will be given in W/m^2 , the hourly, daily, monthly or annual totals will be given in MJ/m^2 day averaged over a day, month, or year.

Wind Speed - m/sec

Mass Flow Rate - l/sec or kg/sec

* According to the resolutions of the Convergence Générale des Poids et Mesures, 1960.