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ABSTRACT

General Electric Company was one of four contractors who received a contract in early January 1974 to design, build, and install a solar heating experiment in a public school. The overall objective of this program was to obtain data that would assist in evaluating the applicability of solar heating systems in large metropolitan areas. This data was to be an "operational" nature, in contrast to theoretical, and to encompass the areas of construction, societal interactions, economics, and aesthetics, as well as the thermal performance aspects. The data was obtained by constructng and operating a solar heating system of pilot plant scale on a middle school in Boston, Massachusetts. The Grover Cleveland School was the first solar heating experiment to come on line for continuous operation when heat was supplied at 4:10 p.m. on March 6, 1974. The system was operated through May 15, 1974. The experimental data collected during this period is presented in this report. The report describes the system in detail, presents the analysis of operation, and discusses recommendations and conclusions based on the results of the experiment. (Author/MLF)

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15 JULY 1974

Final Report of the SOLAR HEATING EXPERIMENT on the GROVER CLEVELAND SCHOOL BOSTON, MASSACHUSETTS

Conducted for

THE NATIONAL SCIENCE FOUNDATION

WASHINGTON, D.C. 20550

GENERAL ELECTRIC

SPACE DIVISION

Valley Forge Space Center

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SECTION I

INTRODUCTION

General Electric Company, Space Division, was one of four contractors who received a contract from the National Science Foundation, Washington, D. C. in early January 1974 to design, build and install a solar heating experiment on a public school. The experiment was to become operational in March 1974 and obtain performance data during the 1973/1974 heating season.

System design was started immediately. Vendors were sought out who could respond to the short delivery requirements. Contractors and subcontractors were brought on board in less than one week.

Installation of the 104,000 pounds of prefabricated steel started on February 13 and was completed on February 20. Solar collectors and the control console were delivered to Boston on February 25. Installation proceeded rapidly and smoothly; material continued to flow to the construction site in time to keep the construction crew working. The Grover Cleveland School was the first solar heating experiment to come on line for continuous operation when heat was supplied at 4:10 pm on March 6 (41 days after contract go-ahead).

Solar heating is feasible in Boston and other northern latitudes. Summary performance data is as follows for the 144 collector system installed on the Grover Cleveland School.

• Peak solar flux measured (via Epply meter on May 4)	294 BTU/Hr sq ft
• Maximum loop temperature recorded (April 29)	$224^{o}F$
• Maximum heat collected in one day (April 11)	4,523,000 BTU's
• Solar energy collected in April*	45,800,000 BTU's
• Heat loss through insulation in April*	1,500,000 BTU's
• Electric power consumed by system in April	2,500,000 BTU's
• Maximum daily collection efficiency integrated over the sunlit period (April 16)	54%

*These values are extrapolated for the month of April and based on 15 days of actual data.

The solar heating experiments were to demonstrate to the average citizen that solar energy is a viable part of this nation's plan to become "energy independent." Based on the press coverage and the many inquiries from across the nation the public did become aware of the solar heating demonstration. A large percentage of the visitors and inquiries were from people in allied fields such as architecture, power companies, gas companies, private companies and individuals who are interested in solar heating.

This report covers the time frame from the first week in January to May 15, 1974. A summary of the conclusions is given in Section 3.

SECTION 2

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, 1974 to augment the existing heating system, analyze the system's performance and prepare a final report

These objectives were all accomplished, and the following sections of this report present the results.

The Schedule established in mid-January is shown in Figure 2-1. 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 40 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. The schedule is discussed in more detail in the appropriate section of this report.

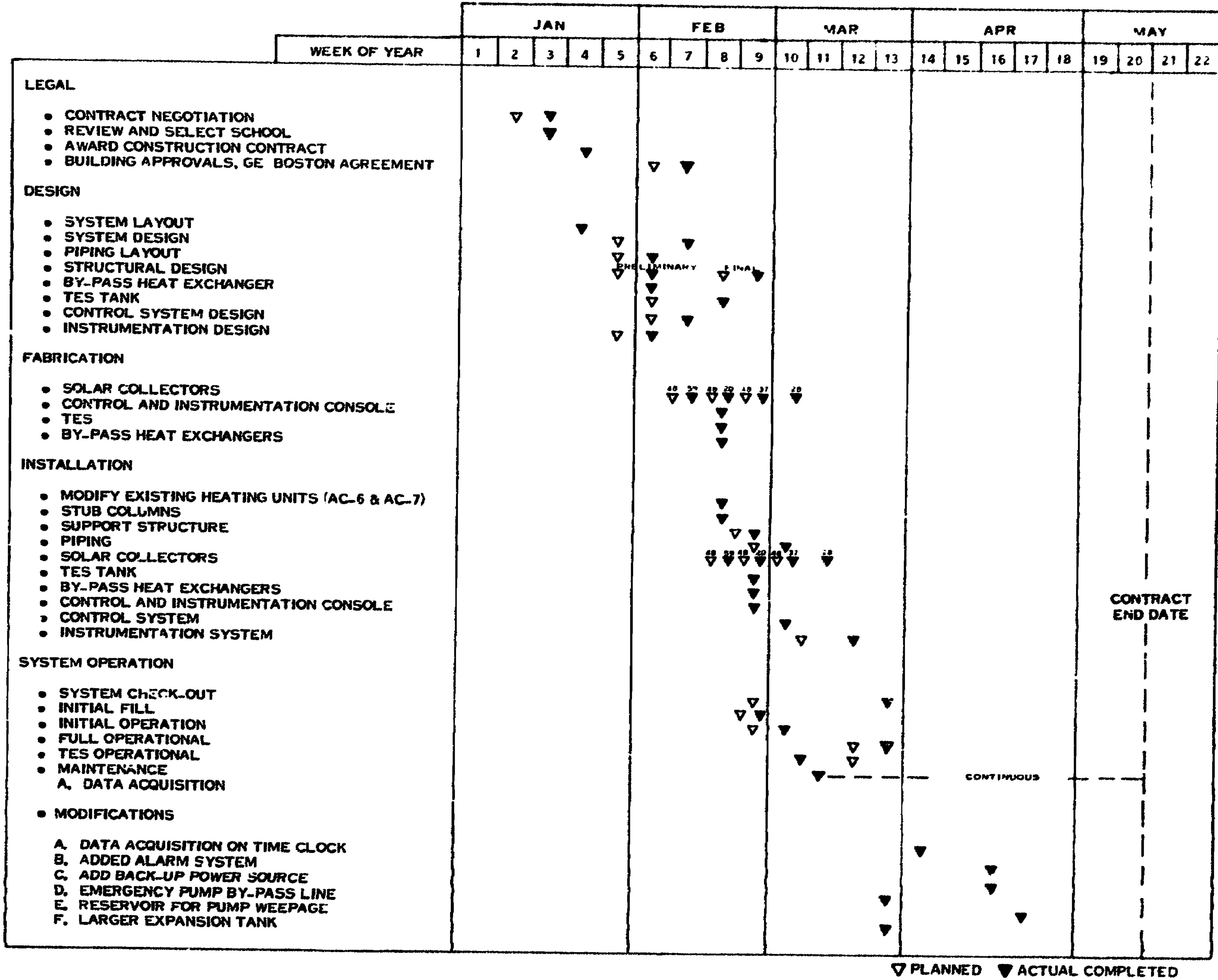

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Figure 2-1. Summary Schedule for Solar Heating Experimental Program

SECTION 3

PROJECT BACKGROUND

Application of solar energy for heating purposes goes back in time virtually to the beginning of civilization. The usage of devices specifically to collect or focus solar energy to produce useful heat, while not ancient, goes back many decades. In the past decade numerous individual experimenters and even some commercial institutions have produced solar collectors which have acceptable performance for specialized applications. Events of the recent past have focused attention on the need to extend or augment our energy supplies nationally. To this end several organizations, the General Electric Company among them, are developing solar collector panels. These devices show promise of becoming an economical and efficient means of capturing solar energy as sensible heat which can be applied to heating of buildings and hot water supplies or, with the proper equipment, to air conditioning of buildings. Since a substantial portion of our national energy consumption occurs in these areas, successful application of solar energy could significantly reduce conventional energy consumption.

3.1 WHY HEAT A SCHOOL?

There are three major characteristics which should be kept in mind when considering a solar heating system:

1. An array of solar panels will exist which faces approximately south, has an area 25 to 75 percent of the floor area to be heated, and is located for minimum shadowing.

2. A thermal energy storage tank will exist which will constitute a concentrated structural load of 5 to 12 pounds per square foot of panel array, be highly insulated, and be located as close as practical to the thermal load.

3. The system will gather energy only during daylight hours with stored heat being utilized during nights or totally overcast days.

The overall effect of these system characteristics is that buildings which are most ideally suited for solar heat will have the following general characteristics:

1. Principal heat load during sunlit hours

2. Principal energy consumption during heating season

3. Low rise construction

4. Lack of shadowing obstructions

5. A "conventional" heating system will exist to augment the solar system in extended sunless periods.

As can be seen from above, a school is well suited generically to the characteristics of a solar heating system. In addition, the use of a school for solar heating feasibility/ demonstration purposes provides a degree of public visibility and awareness not obtainable with homes, factories, etc. The resulting public understanding could assist in determining the acceptability of similar systems in the future.

There is one disadvantage to schools from a general heating standpoint; in most localities there are definite legal requirements to achieve ventilation rates which are higher than an "average" building would have. The net result is increased heating costs due to the intake of large quanities of cold air.

3.2 SUITABILITY OF BOSTON DATA

It is good practice to conduct an experiment in a manner such that the data has the widest possible applicability. This was done in part by the National Science Foundation with their specification of four separate localities for construction of solar heating experiments; one of which was Boston, Massachusetts.

Boston is also representative of a large number of communities in which substantial fuel savings are potentially possible through the use of solar heat. In fact, a study by General Electric which paralleled this project concluded that Boston was typical of a climatic/population grouping wherein usage of solar heating in new construction, for instance, offered a very large potential fuel savings (three times that of the group with the next largest savings). Some cities whose climates are typified by Boston are Hartford, New York, Pittsburgh, Cleveland, Chicago, etc. The major reason for this conclusion was the two fold effect, first that there is a significant fraction of the northeastern part of the country that has a generally uniform climate suitable for solar heating, and, second, that same fraction of the country has a very high population density; hence, the potential total fuel savings is high.

Boston has numerous characteristics both quantitative and qualitative which are representative of potential solar heating sites. Some or all of these characteristics will appear in future solar heating projects assuming utilization of sites offering the largest potential fuel savings. The characteristics/considerations are summarized as follows:

1. Heating season average of 6000 degree days

2. High cost labor

3. Established, strong, interrelating, and protective labor unions

4. Established, elaborate administrative structures in both municipal and school areas.

5. Large metropolitan area

6. Proximity to a large body of water

7. Moderate air pollution

8. Relatively pure, soft municipal water supply

The particular locality in which the subject school was located, Dorchester, is a blue collar community of mixed nationality groups, and the school student body is multi-racial. The school is basically a "middle" school but is operating on a two shift basis to accommodate more than twice its normal pupil load and substitute for a neighboring school which was destroyed by fire. There is a large general incidence of vandalism in the area and this, combined with large numbers of students (approximately 1150 students per day) moving about the school, provides a large exposure to vandalism. In this regard the experiment site is more representative of an "inner city" school than either an "average" or "suburban" school.

3.3 SCHOOL SELECTION PROCESS

The Public Facilities Department of the City of Boston both builds and controls the operation of schools through a few year probationary period. As a consequence the approval cycles (and lost time) could be minimized by limiting school selection to those schools which were still under the aegis of the Public Facilities Department. Two schools were offered, the Richard Murphy Elementary School and the Grover Cleveland Middle School, and an inspection tour of both schools was conducted to form the basis for selection.

3.3.1 RICHARD MURPHY ELEMENTARY SCHOOL

The Richard Murphy school is a new, modern, brick and masonry structure built in 1972. The school is multi-level ranging from one to four stories in height with a staggered, basically unobstructed roof. It contains 137,000 square feet and utilizes a hot water heating system with centrally located, gas fired boilers. There are four different areas and types of heat loads within the school:

1. Classrooms. Wall mounted, unit heater/ventilators, approximately one per 3000 square feet of classroom space.

2. Cafetorium. A large, high ceiling, multi-purpose room which is utilized regularly at lunchtime and on a random schedule basis for assemblies, movies, etc. Forced air heating is supplied from an interior mechanical equipment room. Rated heating capacity, 580,000 BTU/hr.

3. Gymnasium. Very similar to the cafetorium except utilized on a regular and frequent basis and served by a separate mechanical equipment room. Rated heating capacity, 700,000 BTU/hr.

4. Swimming Pool Room. Similar to the gym in size and utilizing a common mechanical equipment room. Major room heat comes from the pool itself and lights; consequently, main heating load is fresh air supply utilized for humidity control. Pool water is heated to 80 to 85°F by gas and air temperatures are kept near 80°F in contrast to the 70°F level in the rest of the school. Rated heating capacity, 515,000 BTU/hr.

The examination of the school led to the conclusion that the classrooms not be considered as an application since extensive work and disruption would be required in the active areas of the school. The other three areas are serviced by two mechanical equipment rooms housing air handlers which utilize hot water heating coils. Access to the rooms would require significant penetrations in the existing building structure as well as significant movement of workmen and equipment through the school. The equipment rooms were small and rather full. Figure 3-1 is a simplified schematic of the heating system.

The exterior of the school was clean, contemporary and aesthetically appealing. The roofs were flat and virtually unobstructed and the primary building line of the school lay in a NW-SE direction. There was no easy access to the roof and there also appeared to be little school yard area usable for collectors, thermal storage tanks, etc.

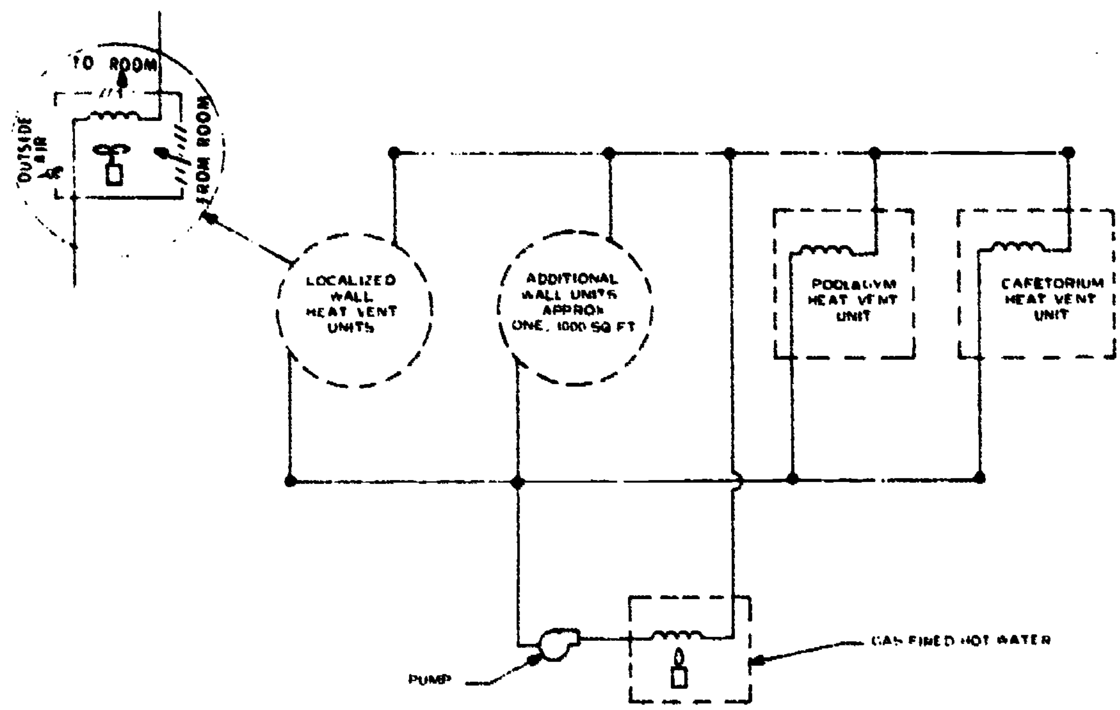

Figure 3-1. Heating System Schematic for Richard Murphy School

Based on the above, the best application of a solar heating experiment to this school was to mount the array on the roof of the four story section of the building and heat the gymnasium. This location would eliminate any consideration of self shadowing by other levels of the building, be reasonably near the heat load, and provide the maximum protection from vandalism. The control/instrumentation console would be housed in the mechanical equipment room. Construction drawings were obtained and a preliminary feasibility layout was completed. Figure 3-2 is a sketch of the general configuration.

3.3.2 GROVER CLEVELAND MIDDLE SCHOOL

The Grover Cleveland School currently consists of an addition onto an older school building. The older portion is in the process of being renovated and is not presently utilized. The new section is a 61,000 square foot, three story high brick and masonry structural "addition" completed in 1972. Most of the building actually consists of only two floors (plus basement) since the first floor is significantly above grade and is made up of

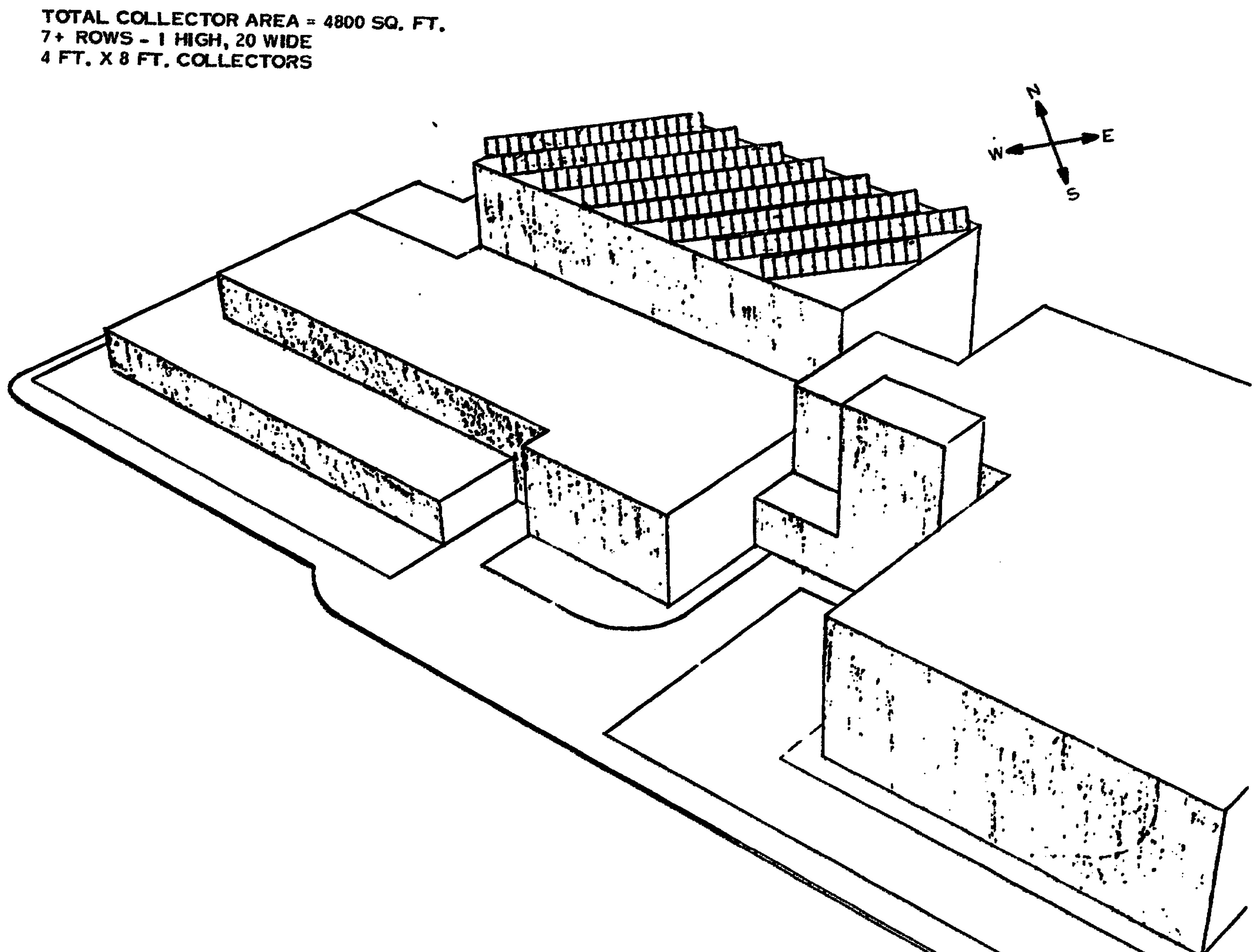

Figure 3-2. Richard Murphy Elementary School

principally high ceiling facilities; i.e., gymnasium, metal shop, etc. The heating system is zone controlled, forced air which is provided by ten, roof mounted, combined function air handling units. These units are manufactured by the Nesbitt Division of ITT and provide the following functions in one cabinet measuring approximately 20 ft long, 7 ft wide and 5 ft high:

1. Exhaust of building return air
2. Intake and controlled addition of fresh air
3. Filtration
4. Air conditioning
5. Pressurizing (via blowers)
6. Heating
7. Air distribution to multiple heating zones

The units are generally set in pairs with one serving a section of the upper story and the other a similar area of the first floor. The units all utilize electric resistance coils for the air heating function and vary in capacity; the largest having 120 kW and 32 ton respective heating and cooling capacities. As a consequence of these units, virtually the entire "heating system" is externally mounted on the roof with only ductwork and electric cables penetrating the roof.

The exterior of the building is very straightforward, utilitarian in appearance, and virtually without frills. There is no school yard, and vandalism has been a problem. The major building line is east-west and the building faces due magnetic south. The roof is basically flat and unshadowed but broken up by stairwell headers, the heating units mentioned previously, and numerous large skylights which admit north light into the upper story classrooms. The skylights were particularly interesting since they were large (approximately 12 ft wide by 12 ft high), rather substantial looking, masonry structures, the south face of which sloped at 45 degrees to the horizontal. In addition, two rows, containing three skylights each, paralleled the front of the school and straddled two of the largest capacity heating units. The visual implication was that each row of skylights could form the support for a fairly simple collector mounting trusswork. The nominally 4 ft by 8 ft collector panels could then be mounted in two high tandem fashion to take advantage of the long sloping face of the skylight and to preclude wasting the nominally 50 foot separation between the rows of skylights.

The preliminary conclusion was that the best application of a solar heating experiment to this school was to mount banks of tandem collectors on the roof over the sloping, south faces of the two rows of skylights. Hot water could then be routed to coils which could be added to the two heating units located between the banks of collectors. There was also space available for a third parallel row of collectors toward the rear of the roof should that be deemed desirable. In addition, a stairwell landing/roof access area was available for an instrumentation console and was adjacent to where the front bank of panels would be located. As a result, the entire system could be installed virtually without building penetrations and disruption to the normal school activities. The school construction drawings were obtained and brief layout study made. A sketch of the resulting configuration is shown in Figure 3-3 and incorporated a third row of collectors.

3.3.3 SCHOOL SELECTION

The actual selection was a difficult choice. The Murphy School was more attractive, had a lower incidence of vandalism, and required more surgery and disruption to be done within the building. The Cleveland School lent itself to isolating the construction activities from the occupied school areas. In addition it faced south so that the collector banks could parallel a building line which was an aesthetic benefit.

Both the City of Boston and school personnel were highly cooperative and stated no strong preferences. For instance, the Public Facilities Department provided construction drawings and energy consumption and costs for 1972 in the schools they were monitoring. This data is given in Table 3-1 and shows that the electrically heated Cleveland School is the most expensive on a cost per square foot basis.

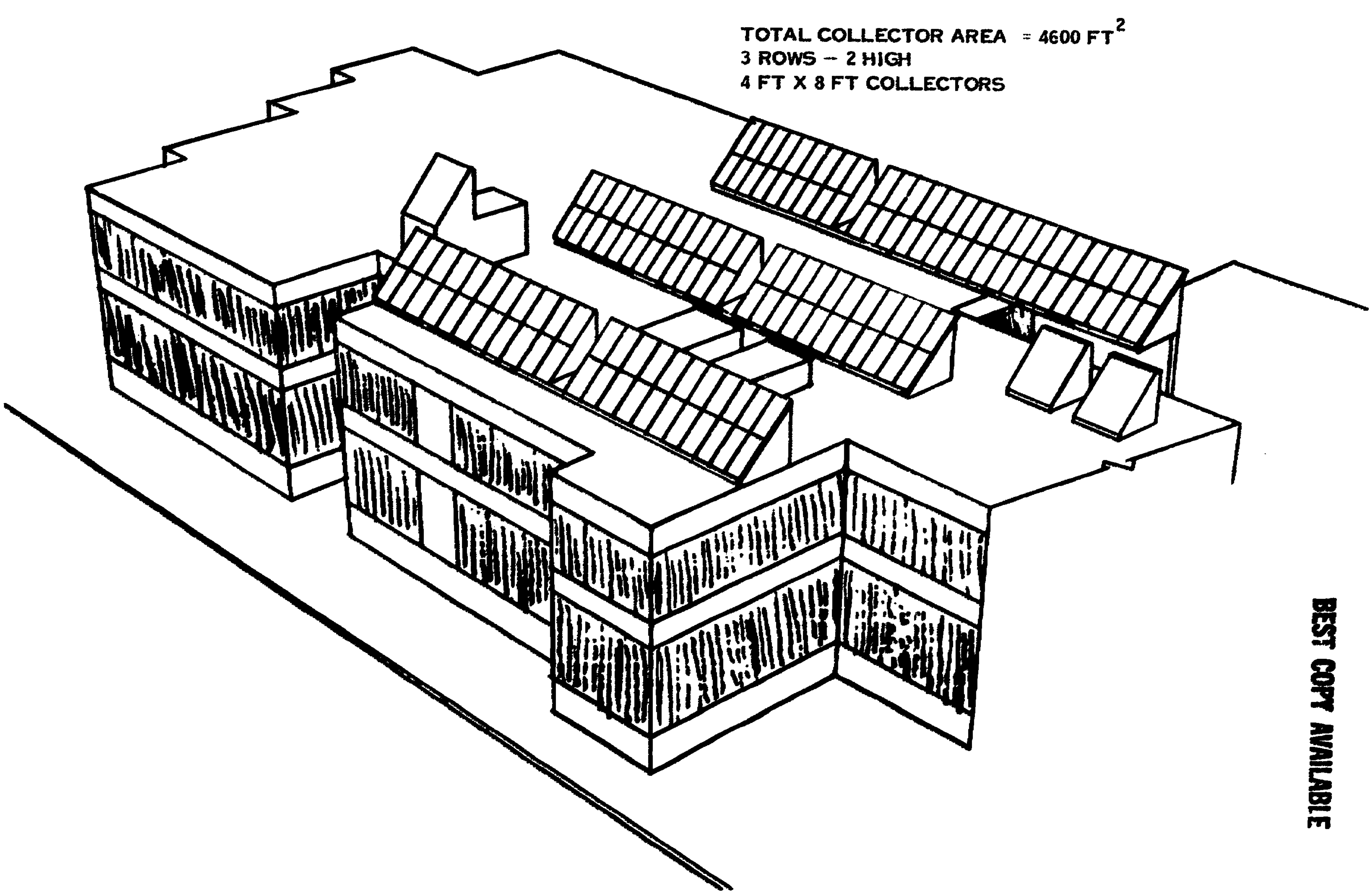

Figure 3-3. Grover Cleveland School

Both schools were adaptable to solar heating and a summary comparison of the more salient aspects of both schools is given in Table 3-2. Consideration of all the above attributes both on their own merit and in light of the required extremely tight construction schedule led to the selection of the Grover Cleveland School. A summary of the basis for selection is given in Table 3-3 and a brief description of the planned solar heating experimental system is given in Table 3-4.

Table 3-1. School Fuel Costs for Calendar Year 1972

Community School	Total Sq. Ft.	Electricity	Gas	Total	Cost/Sq. Ft.
Hennigan	137,800	$ 37,645	$ 25,557	$ 63,202	$ 0.46
Holland	137,125	45,500	40,841	86,341	0.63
Lee	163,360	90,015	5,220	95,235	0.62
Marshall	130,935	69,411	548	69,959	0.54
Trotter	82,250	18,716	1,329	20,045	0.24
Ohrenberger	110,000	33,440	15,566	49,006	0.45
Kent	93,350	17,589	14,587	32,176	0.34
Hernandez	17,000	6,588	173	6,761	0.40
Grover Cleveland	61,000	46,130	1,440	47,570	0.78
Agassiz	110,000	62,548	119	62,667	0.57
Tynan	84,600	24,000	15,871	39,871	0.47
Murphy	137,000	Unavail.	Unavail.	~63,000	~0.46

Table 3-2. Summary Comparison of Richard Murphy and Grover Cleveland Schools

Characteristic	Grover Cleveland	Richard Murphy
1. Heating System	Electric heat/forced air	Gas/hot water/forced air
2. Location of best interface to existing heating system	On roof - modification to Nesbitt heating unit	In mechanical equipment room - modification to air handler
3. Area to be heated and capacity of current heater	A section of the first and second floor - 820,000 BTU/hr	Gymnasium or possibly pool (700,000 or 515,000 BTU/hr)
4. Building penetrations	None required except possibly for supports (skylight based panel supports)	Required for liquid lines, controls instrumentation, and supports
5. Best location for collectors	Roof parallel to front wall	Gym roof at angle to front wall
6. Collector array size	4600 sq. ft., 3 rows, each approximately 16 ft. by 100 ft.	4800 sq. ft., 7 + rows, each approximately 8 ft. by 80 ft.
7. School appearance and environment	Utilitarian and in an older, blue collar area. Vandalism expected to be a problem	Attractive but in an older neighborhood. Vandalism judged a potential problem
8. School student body	Grades 6 to 8, very crowded apparently due to double shifting to accommodate students from a school which burned	Grades 0 to 6
9. Utilities cost in 1972	78¢/sq. ft.	Approximately 46¢/sq. ft.

Table 3-3. Basis for Selection,Grover Cleveland School

- No additional piping or venting penetrations
- Easy integration of solar system (more options, several interface possibilities)
- More working room and "add-ons" area adjacent to heating units
- Easy access to roof area
- Existing skylights to provide some support
- Probably opportunity to demonstrate bigger operating cost savings
- Possible test of resistance to vandalism

Table 3-4. Integrated Solar Heating System Experiment Planned for the Grover Cleveland School

Integrated System Description
• 144 - 4' by 8' solar panels
• 3 - two panel high rows
• Partially supported by existing skylights
• Insulated copper piping
• Glycol water transport fluid
• Time or temperature actuated fluid pump
• Make-up air preheater and/or coil just ahead of existing heating unit

SECTION 4

SOLAR HEATING SYSTEM DESIGN

In January 1974 when this project began, virtually no experience existed inside or outside of General Electric in the design, erection, or operation of large solar collector arrays in the million BTU/hr class. In addition, General Electric's "second generation" of solar collector panels was still in the design stage with testing not yet completed on the first generation. The priorities for the project were:

1. Produce a system which works
2. Deliver heat as early in March as possible
3. Stay within budget

While these statements in some respects appeared mutually exclusive, they set the tone for the project and had a large influence on the design philosophy.

Under normal circumstances when developing a new product, one body of information originates from theoretical studies; a second body from experiments on sub-scale samples; a third from prototype products or systems; and the final body from operational experience with production products or systems. In addition, there is normally a considerable iteration process between the four modes of information development. However, this project required entering the third mode with the first body of information in a somewhat immature state and the second nearly non-existent. As a consequence of all of the above factors, the following design philosophy was employed:

1. Keep the system as simple as possible.
2. Provide those features which would provide maximum capability to:
    a. Compensate for unexpected component performance
    b. Diagnose an impending problem
    c. Recover from a disaster
    d. Incorporate future modifications

3. Design using those components and processes which could be obtained within the required schedule

4. Maximize the capability for unattended operation of the installed system

Due to the site's location being remote from the Space Division's main facility at Valley Forge, Pennsylvania, and particular components' local availabilities, some of the design work was actually done in Boston by both General Electric and Ballinger personnel. A summary of the design schedule is shown in Figure 4-1.

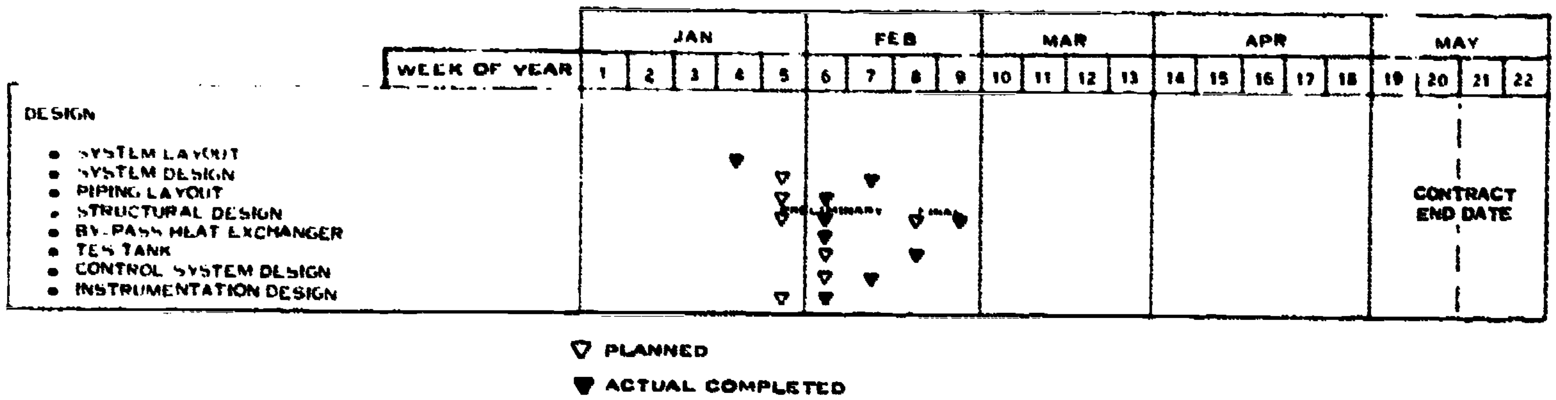

Figure 4-1. System Design Schedule

4.1 COLLECTOR DESIGN

The solar heating system design is described in Subsection 4.2 and utilized GE P3 prototype collector modules (Drawing 47E312004-A). A group of these collector modules, installed on the school, is shown in Figure 4-2. The overall dimensions and configuration of the collector module are shown in GE Drawing 47D312008, External Envelope, P3 Solar Collector.

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 4-3 and 4-4.

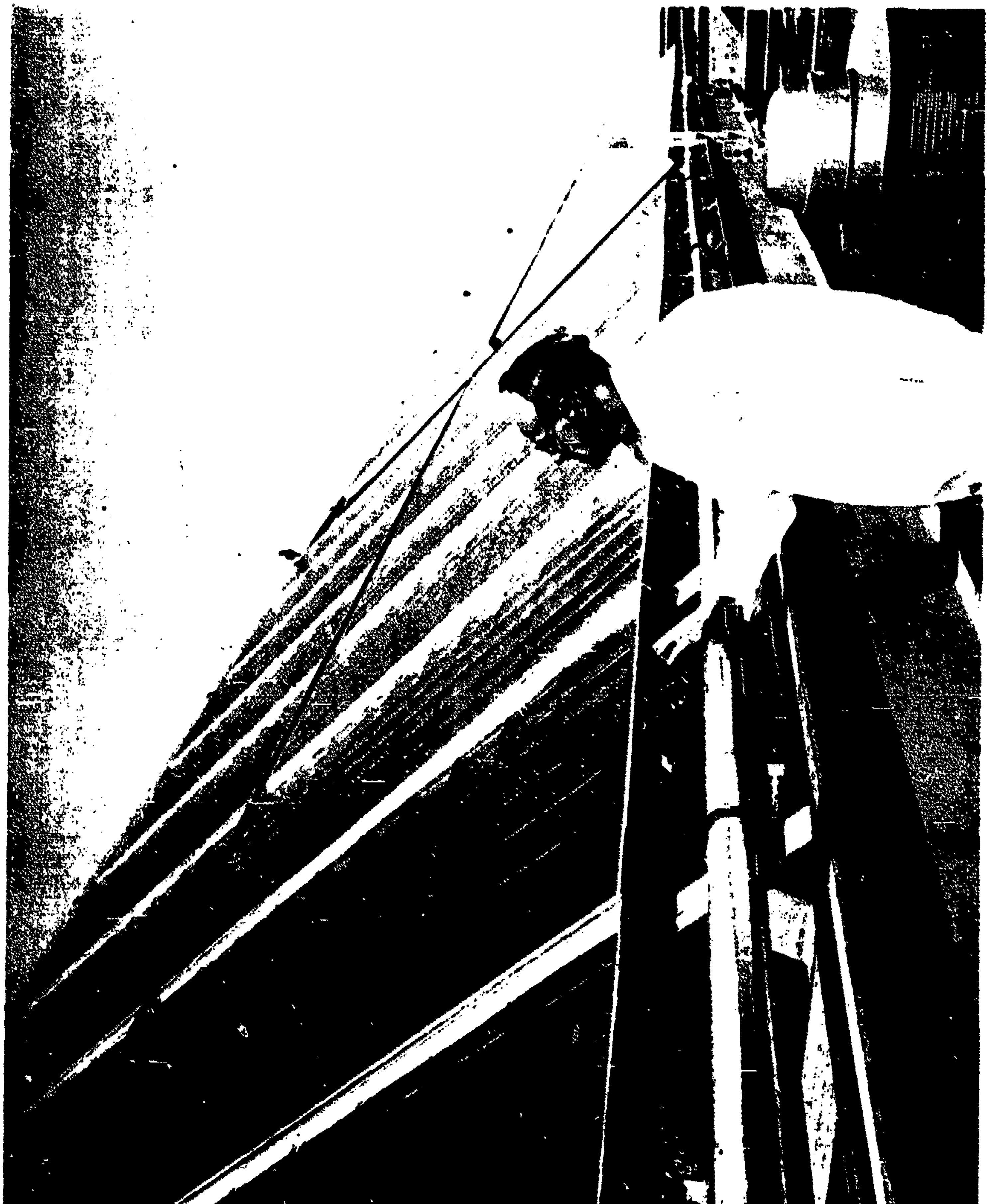

Figure 4-2. GE Prototype Solar Collectors Modules

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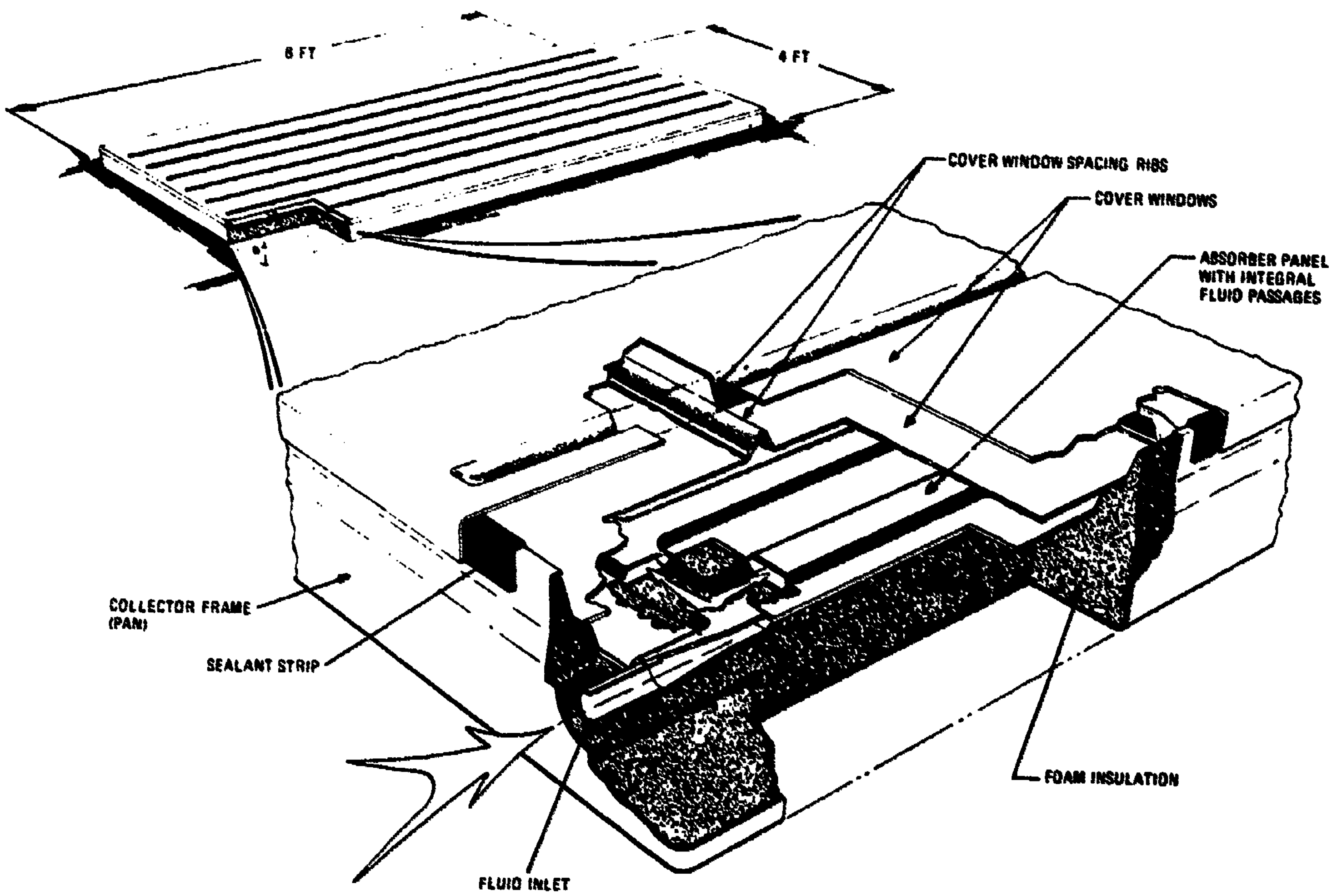


Figure 4-3. GE P3 Prototype Solar Collector Configuration

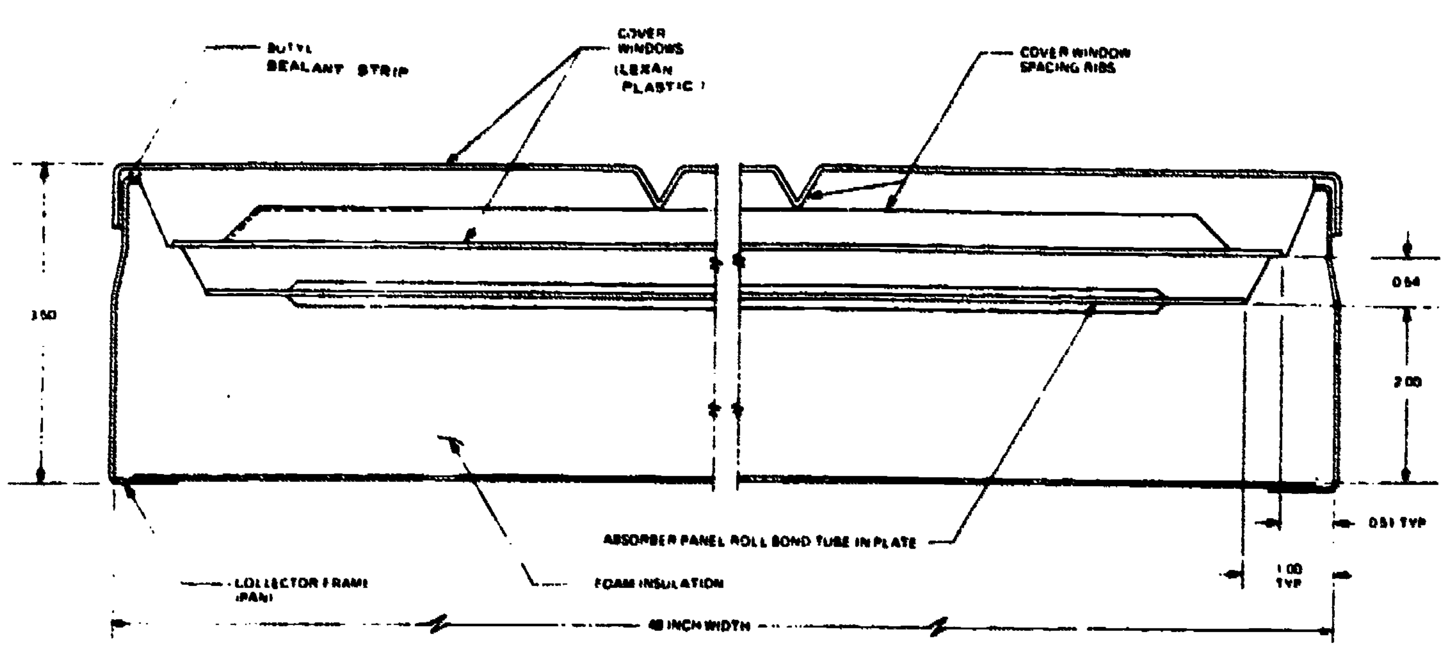


Figure 4-4. GE Solar Collector Cross Section

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 .07 BTU/hr ^{o}F ft^{2}. The insulation is completely sealed by the aluminum pan, the absorber plate, and the Kydex (acrylic-polyvinylchloride) 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 (285° F), high impact resistance and formability, is considered to be particularly suitable for use as solar collector windows. Examination of

Figures 4-5 and 4-6 show that the spectral transmission characteristics of clear Lexan sheet are well-matched to the solar radiation spectrum. The integrated solar transmittance and reflectance of 0.08 inch Lexan sheet are .87 and .05 respectively. Beyond three microns, the measured transmittance of 0.08 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 25 to 35 pound per square foot peak wind loads experienced in most of the 48 contiguous states, 1/4 inch thick plate-glass or 3/16 inch thick tempered glass must be used for 4 by 8 ft collector panels. The approximate weight of 3/16 inch tempered glass desirable for large collectors is 2.5 pounds per square foot. This must be compared to the 0.3 to 0.5 pound per square foot weight of plastic cover sheet materials of interest.

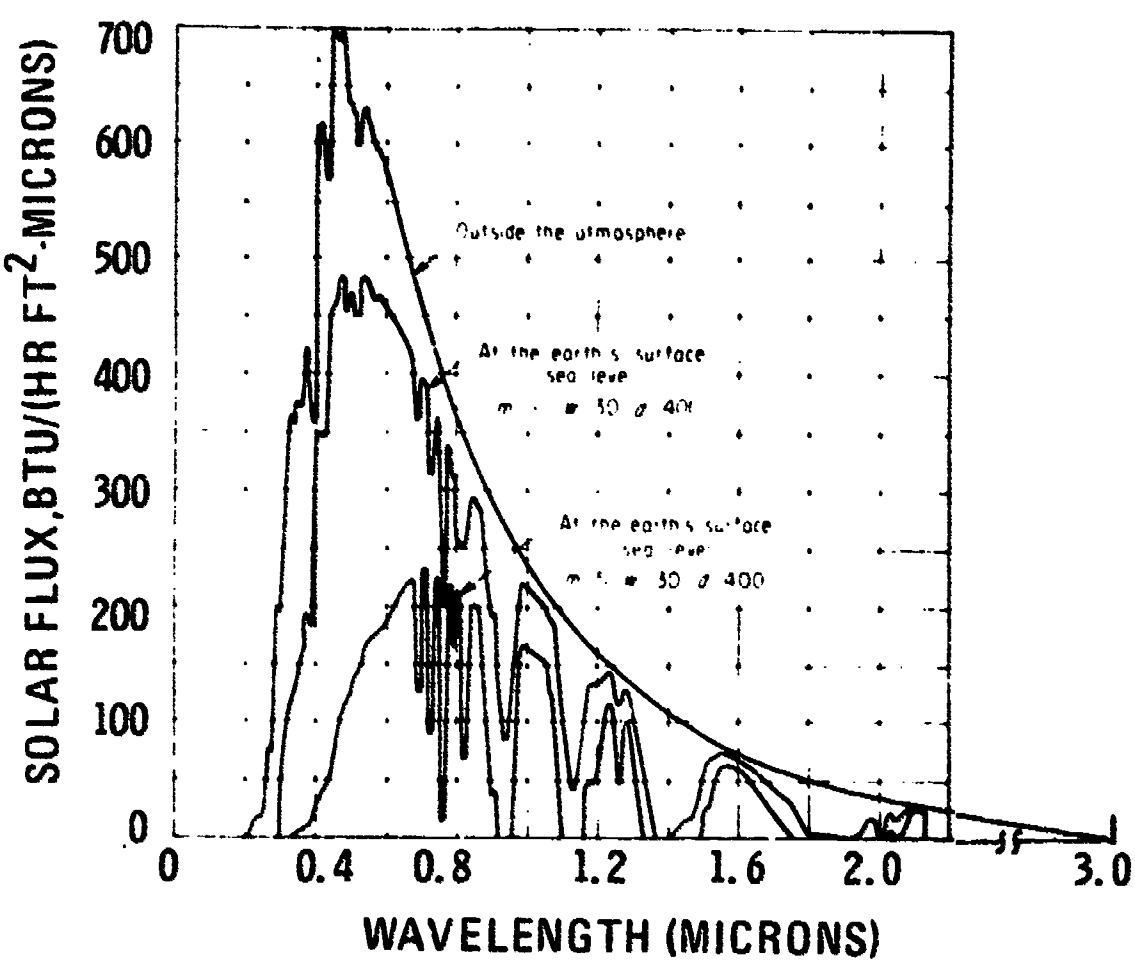


Figure 4-5. Solar Radiation Spectrum

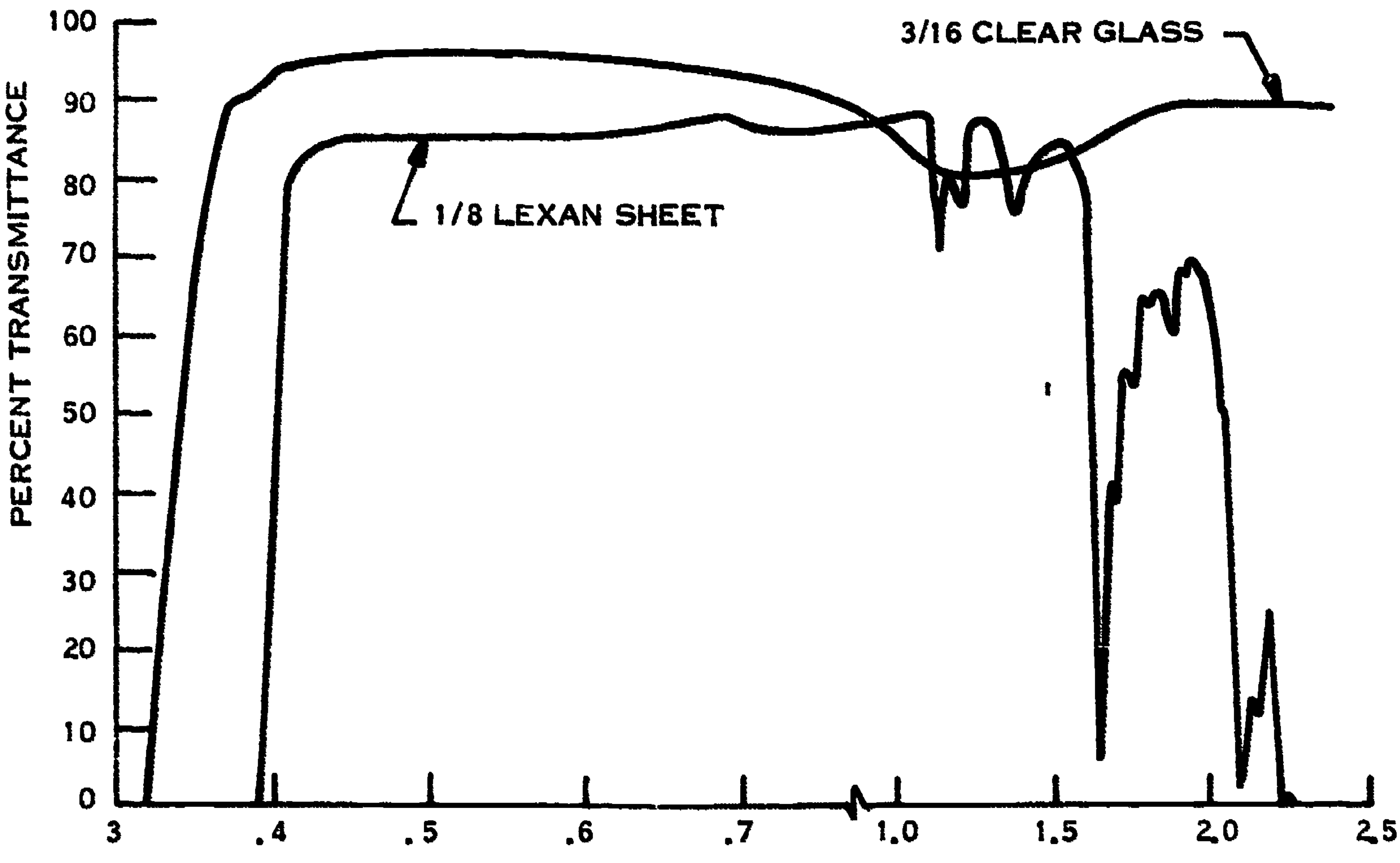


Figure 4-6. Spectral Transmittance of Window Materials

While normal 0.09 inch window glass is relatively low in cost (on the order of $0.20 per square foot in large quantities) tempering, greater thicknesses, and low iron formulations all add significantly to the cost. Recent quotes to GE from major glass manufacturers for large quantities of tempered normal and low iron glass range from $0.46 per square foot for normal 1/8 inch (DS) tempered to $1.96 per square foot for 7/32 inch tempered low iron glass. One eighth inch thick tempered glass is of questionable suitability for the outer surface of collectors larger than 3 by 6 ft because of wind loading considerations. Some manufacturers are hesitant to quote large sizes of 1/8 or 5/32 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 1). 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 recently 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, notwithstanding their being subjected to bombardment with a baseball, 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 3/4 to 1 inch 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 4-2, 4-3, and 4-4 illustrate 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.

Reference 1. Weatherability and UV Resistance, General Electric Lexan Technical Marketing Brochure, Table 2. Lexan Resin Business Section, Plastics Department, Pittsfield, Mass.

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, eliminating the potential of confined corrosion sites.

OLIN's existing roll-bond manufacturing equipment limits the width of panels they can produce to 36 inches. Because of this manufacturing limitation it was decided to make the absorber panel as a 2 ft x 8 ft 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 4 ft x 8 ft absorber plate assembly. Since a reliable, low cost intrapanel fluid connection between the two 2 ft x 8 ft 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 350° F. Measured properties of this coating, as used in this application, are:

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

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 300° F.

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 300° F.

General Electric is currently evaluating selective coatings for collector applications; however, the durability and retention of selective properties of these coatings have not been 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 8 ft 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 30 psf maximum design wind load.

4.2 SYSTEM DESIGN

The City of Boston Public Facilities Department provided invaluable assistance in both providing information/drawings of the school and guidance as to what would be required to obtain necessary approvals. They also materially contributed to the project by constructing a masonry wall to inhibit vandal access to the roof and enclosing part of a stair landing to provide an enclosure to house the control instrumentation console.

The initiation point is shown in Figures 4-7 through 4-9 which are the photographs taken during the school selection tour during the second week of January; Figure 4-7 is a general view of the roof looking east. The "second" row of three skylights is in the central area of the photograph. The AC-6 heating unit and one of the first (front) row of skylights can be

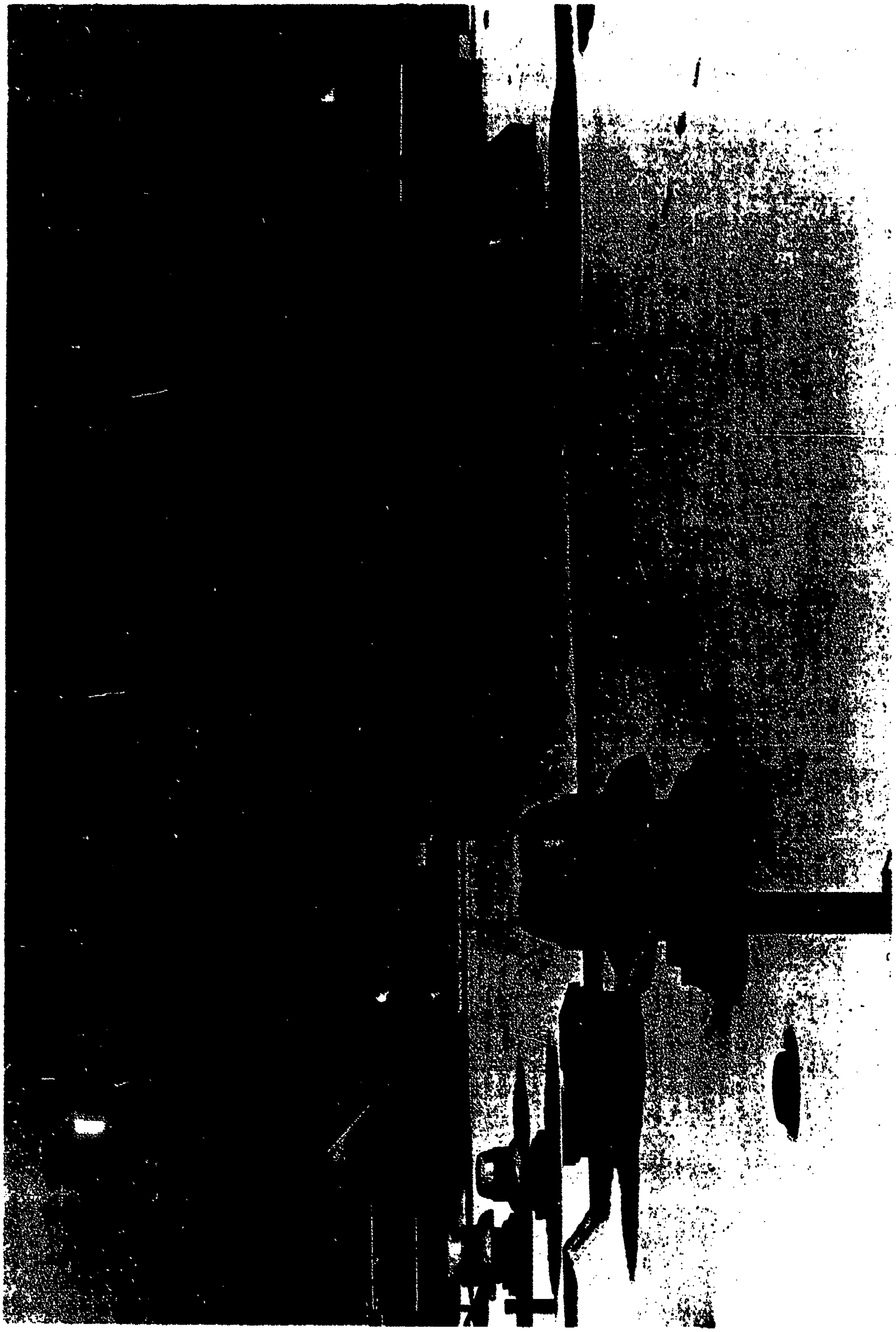


Figure 4-7. General View of the Cleveland School Roof

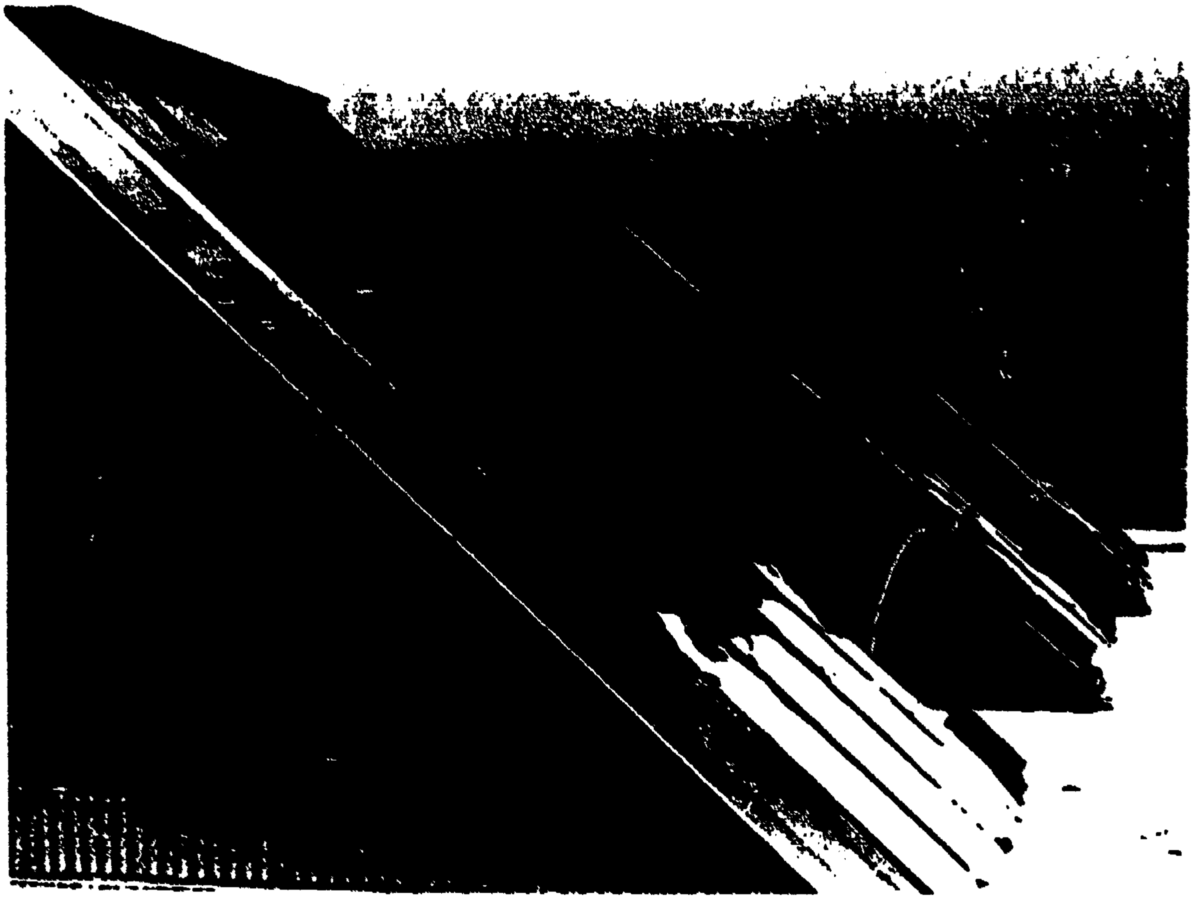


Figure 4-8. Row of Skylights Viewed from Southwest (top). General View from East (bottom).

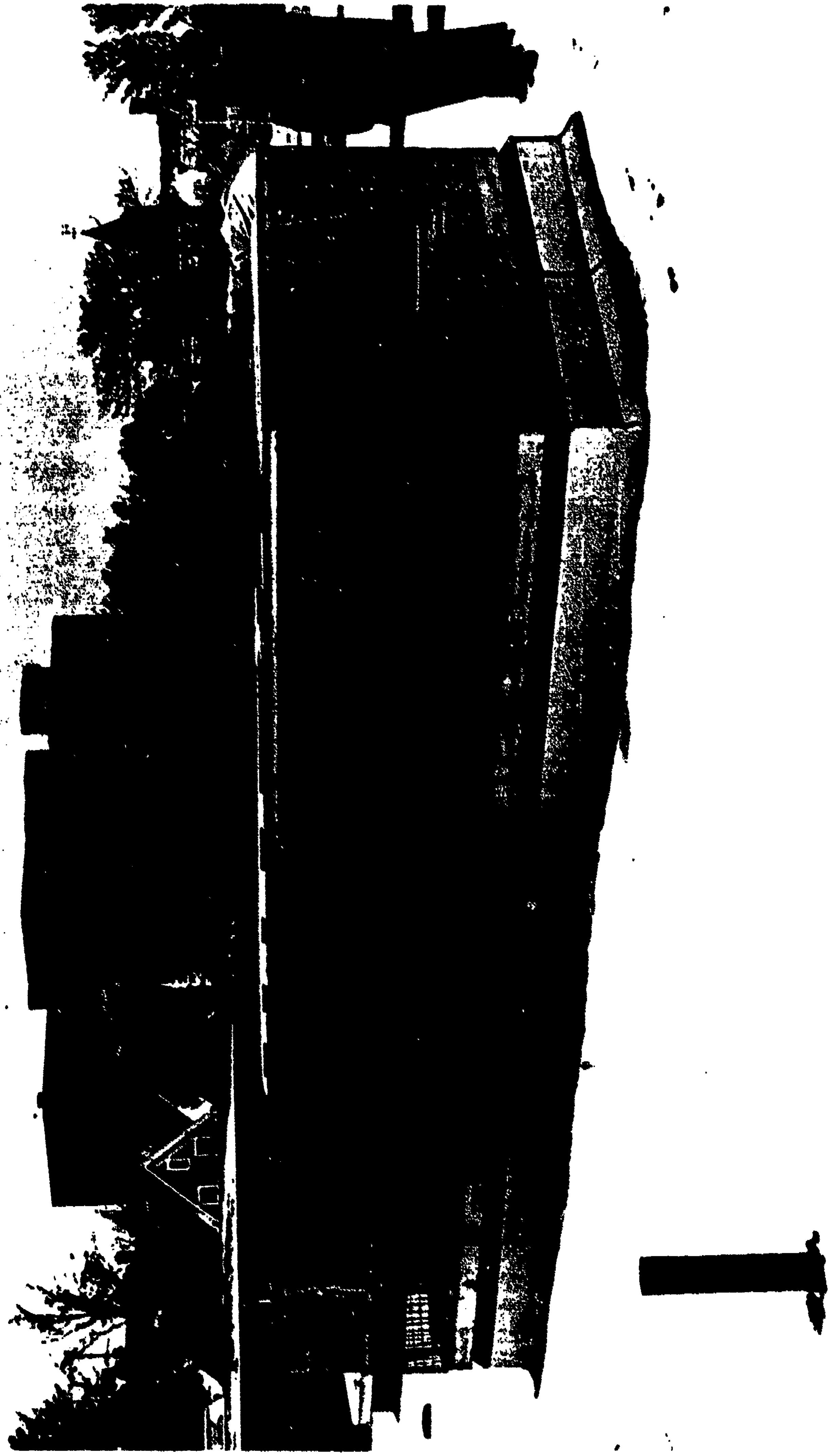


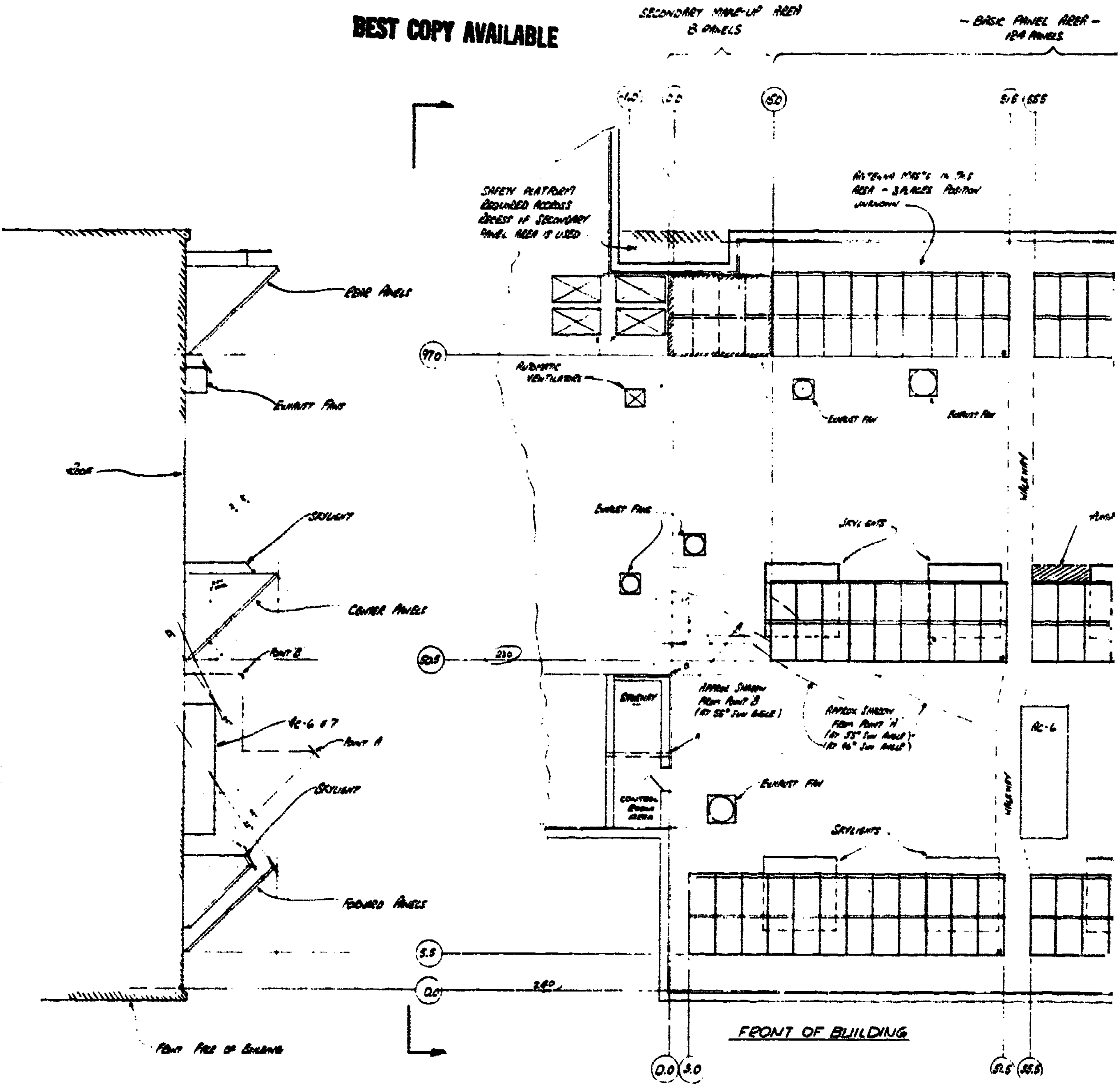
Figure 4-9. Nesbitt Roof Mounted Heating Unit

seen near the right edge of the photograph. Three roof mounted exhaust ventilators which represent a significant heat dump can be identified by the amount of melted snow and appear adjacent to the "near" end of the second row of skylights and the two ventilators nearest the left edge of the photograph. Figure 4-8 shows the "second" row of skylights and a general view looking West, the two rows of skylights, two heating units, the stairway header and roof access door adjacent to the front row of skylights. Figure 4-9 shows one of the combined function, roof mounted Nesbitt heating units.

A subcontracted architectural engineering firm, The Ballinger Company, was utilized in the system design task. They provided consultation, structural design, and produced the engineering drawings which were required for both construction and approvals by both the City of Boston and the State of Massachusetts. Their principal inputs came from the system layout, piping design, and control design tasks. This entire effort required considerable interaction and the tasks were essentially accomplished in a parallel rather than serial fashion.

4.2.1 SYSTEM LAYOUT

The general concept of the system layout had been chosen during the school selection process. At this point the school's construction drawings were used to produce layouts with which to study various array configurations. The initial estimates had concluded that due to the duty cycle of the existing heating units, the solar heating system could likely carry most of the load even if sized to deliver significantly below 820,000 BTU/hr. Consequently, 450-500,000 BTU/hr was selected as a target for the system size. The space readily available on the roof was approximately 100 ft east/west by 115 ft north/south. The centerlines of two rows of skylights were 45 ft apart with two, 20 ft by 7 ft by 5 ft heating units (designated AC-6 and AC-7), located approximately midway between the two skylight rows. There was also an area of useable roof extending approximately 45 ft behind the second row of skylights. Analytical estimates of average heat output integrated over the sunlit period for optimum tilt angles and mean winter conditions were 80 to 100 BTU/Hr FT^2 of collector and so the system layout became a task of placing 140 to 160 collector panels in two or three rows. A decision was also made to divide the rows hydraulically into banks of approximately equal heat output to maximize system flexibility, commonality of piping sizes, and ease of flow balancing. Figure 4-10 is the layout sketch which became the basis for the system.


SECONDARY MAKE-UP AREA
8 PANELS
– BASIC PANEL AREA –
124 PANELS
REAR PANELS
EXHAUST FANS
SKYLIGHT
CENTER PANELS
POINT B
POINT A
FORWARD PANELS
EXHAUST FAN
SKYLIGHTS
WALKWAY
FRONT OF BUILDING

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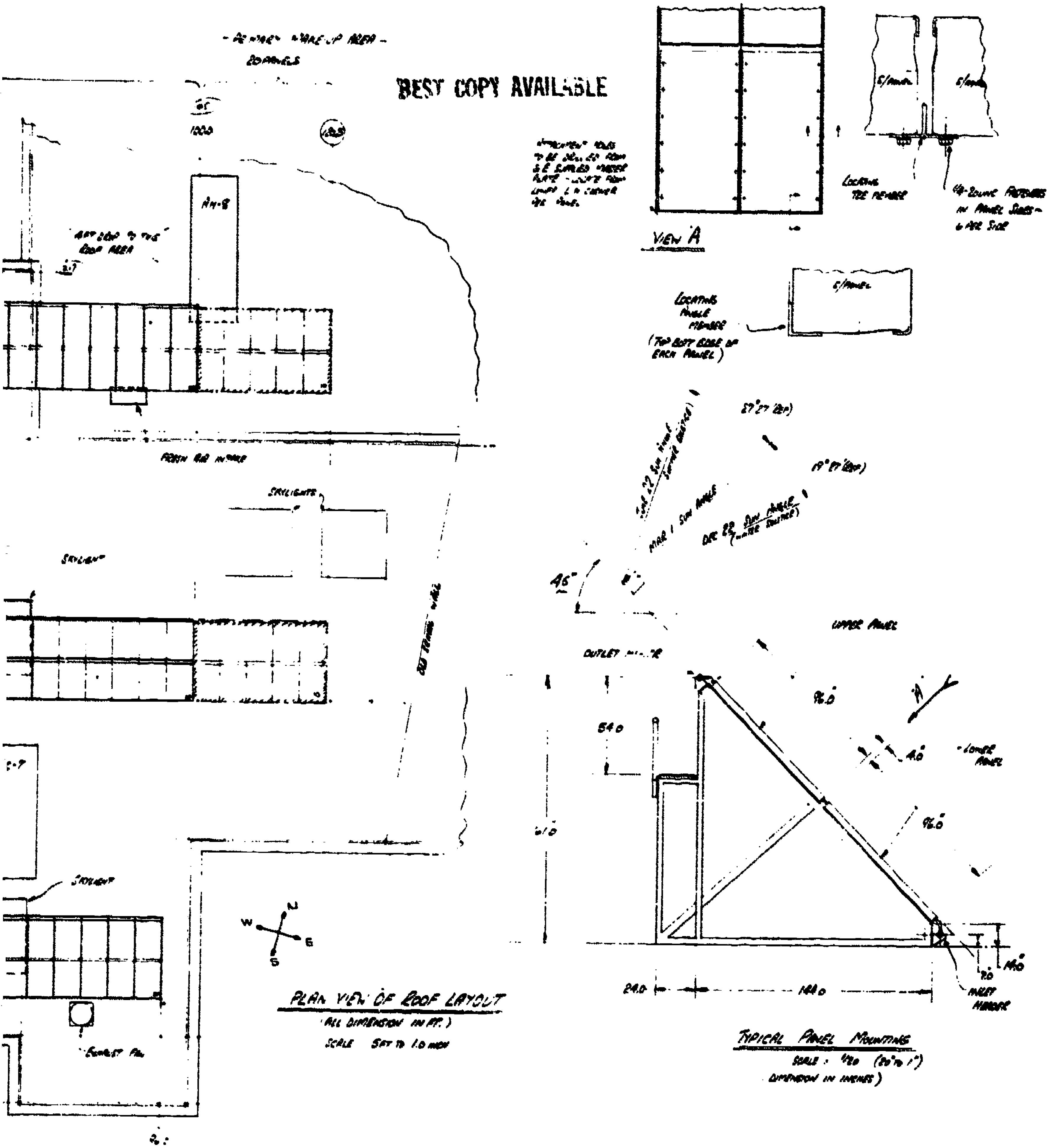

Figure 4-10. Layout of General Arrangem[ent] Boston School Solar Heating Installation

This figure shows a system comprised of three rows of collectors with each row having two independent banks of collectors. The basic array size was 124 collectors arranged in six independent banks. An option of an additional ten collectors existed on the east end of the middle and north rows and another option for ten was possible on the west end of the north row. The west end of the middle row of collectors was abbreviated due to a concern that it would be shadowed by the stairway header structure. The school faced magnetic south which, with the local magnetic declination, meant that the array being positioned parallel to the building line, actually faced 15 degrees east of south. This represents a small sacrifice in total energy gathering capability since the system's effectiveness will fall off earlier in the afternoon when ambient temperatures and, consequently, system efficiencies, are typically higher. However, this easterly facing results in a faster system warmup transient which is of more significance with a school's normal 7:00 AM to 4:00 PM usage period.

Array tilt angles of 45 to 55 degrees were evaluated and 45 degrees was selected which results in theoretical performance peaks slightly prior to March 21 and subsequent to September 21. This angle was felt to be the best compromise of the following factors:

1. Year round performance testing (see Figure 4-11 for sun angle effects)
2. Heating (steeper angles are better but sky conditions in late December/early January nullify the benefits of much steeper angles)
3. Ease of construction layout by the steel fabricator
4. Visual match with skylights

The array performance thus peaks in early fall and early spring but is not far off its optimum in the late January and February peak heating season as shown in Figure 4-11.

In this time frame it became apparent that the skylights could not be the principal support for the collectors. The initial estimates of the desired thermal energy storage tank size was 6000 gallons based on earlier studies which indicated that 10 to 15 pounds of water/square foot of collector was near optimum for the northeastern states. This represented a concentrated load of 50 to 60,000 pounds and it also appeared that there was no location which was both convenient and adequate to carry this load. As a consequence, the system was configured initially without a thermal energy storage tank. This placed emphasis on the easterly facing and

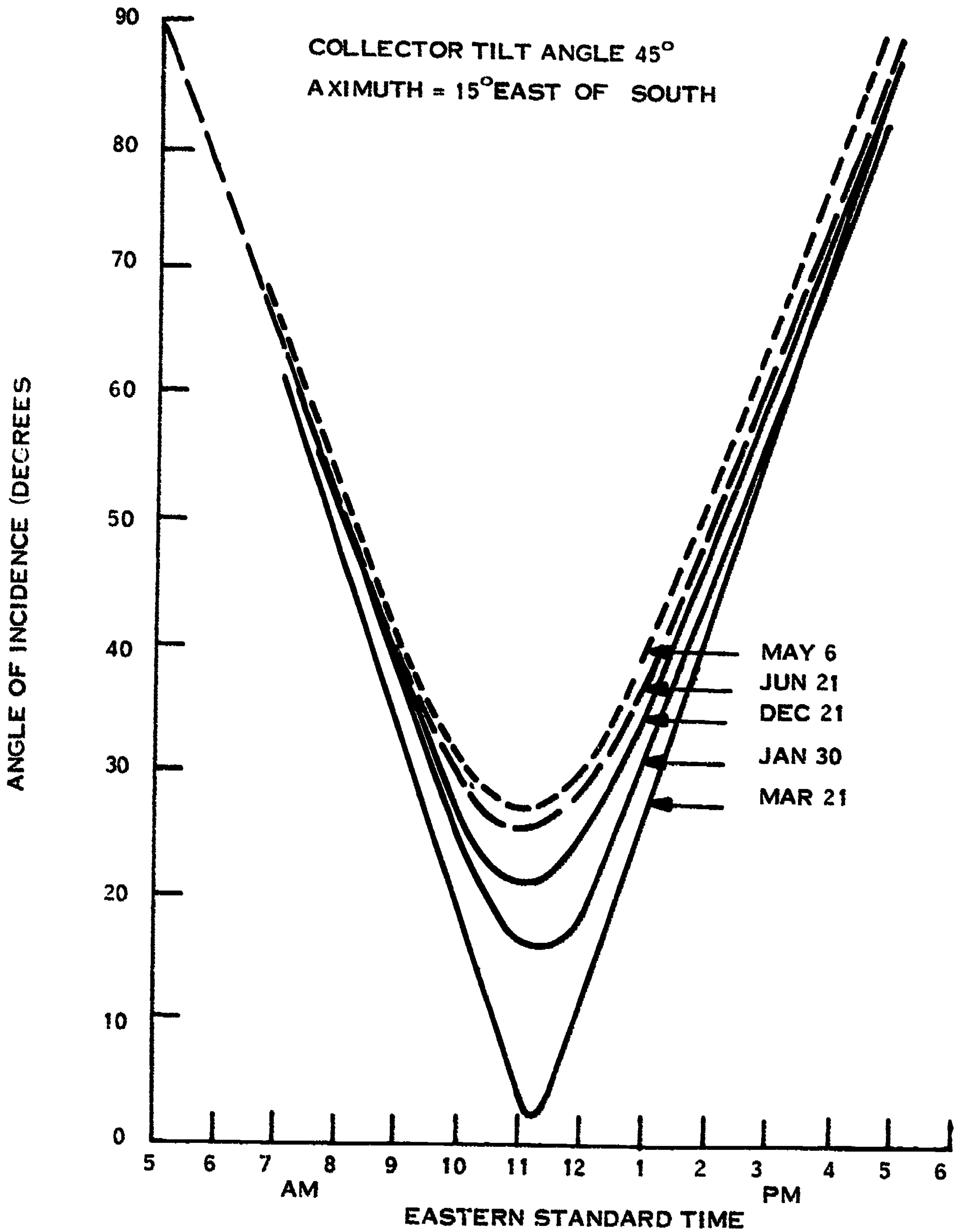

Figure 4-11. Direct Sunlight Incidence Angle Variation for the Grover Cleveland School Solar Collectors

obtaining minimum system thermal inertia so that the system would achieve useful temperatures as early as possible each day to maximize the solar contribution to the high heating load period (mornings) and, thus, the total contribution. Staff personnel of Ballinger Company, the architect engineering subcontractors, had provided some consultation throughout this phase. They then utilized the results of the system layout as inputs for their structural design efforts.

4.2.2 PIPING DESIGN

The major objectives of the piping design were as follows:

1. Provide capability to add or isolate a significant group of collectors to/from the system with a minimum perturbation

2. Provide capability to isolate one or two collectors from the system with a minimum perturbation

3. Minimize the need for flow balancing but provide the capability should it be required

4. Minimize fluid inventory and piping sizes to minimize thermal inertia of the system but maintain reasonable pumping power requirements

To avoid confusion, the following definitions will apply to piping:

1. Bank. A group of collectors all supplied from one inlet header, typically 16 percent of the system and 24 collectors.

2. Header. A pipe to which a group of collectors (bank) is plumbed hydraulically in parallel. Its function is to distribute fluid equally to the collectors.

3. Feeder. A pipe which carries fluid from point to point and is not a header. It may connect to other feeders, mechanical equipment, or a header pipe.

The information generated in this task provided input to Ballinger Company for their final sizing and generation of the piping drawings. This task consisted of choosing a collector interconnection approach and then a layout and sizing of the piping network to supply fluid to the collectors.

4.2.2.1 Collector Interconnection

The anticipated performance point for the collector panels was a pressure drop of 0.2 psi at a total flow of 0.8 gpm per collector with a nominal fluid temperature rise of 8° F. This pressure drop is quite low which is an advantage from the standpoint of required pumping power but it places a requirement for very low pressure drop in the header to insure uniform flow distribution between collectors within a bank. (If the header pressure drop is significant with respect to the collector pressure drop then the majority of the flow will go through the collectors on each end of the bank; the bank's center collectors will then have a very low or, even possibly, no flow through them.) This can be overcome by placing a parasitic pressure drop, i.e., a balancing valve, in series with the collector; however, this negates the low pumping power advantage.

The collectors actually consist of two hydraulically independent absorber plates and as mentioned previously, system geometry considerations resulted in the configuration of two collectors in tandem. As a consequence, there are several possible ways to interconnect the collectors to increase pressure drop between inlet and outlet headers. Each concept has an effect on pressure drop, system reliability, system flexibility, and hardware/labor requirements (cost and schedule). It is possible to plumb these panels into series parallel networks, utilize solenoid valves, and generate very high system reliabilities in true aerospace fashion. However, this approach did not seem warranted due to the high degree of integrity expected from the collector and also, the fact that the cost would have been prohibitive.

Many concepts were postulated but only four were given serious consideration. They are shown in Figure 4-12 with the first two concepts utilizing high/low headers and the last two providing a crossover so that all the piping can be accessible. The high/low header approach has a disadvantage in that the installation/removal of collectors is complicated somewhat in that they must be fit between headers via flexible hose or flat flanged unions. However, it does have the distinct advantage that the static pressure differential can be utilized to help insure uniform flow distribution within the bank. The number of valves required per collector was a major concern both because of total cost and the problems of obtaining a large quantity on schedule. The quantity of header penetrations was of concern due to both the labor required and the resultant reliability. Concepts 3 and 4 place four panel pressure drops and temperature rises in series. This is still minor compared to the static pressure differential available with Concepts 1 or 2 but the large temperature differential would make the system thermal instrumentation more accurate. However, with Concept 3 this would result in a large temperature differential across the bottom collector's absorber plate which produces heat flow in the lateral direction and, if nothing else, complicates the collector analysis.

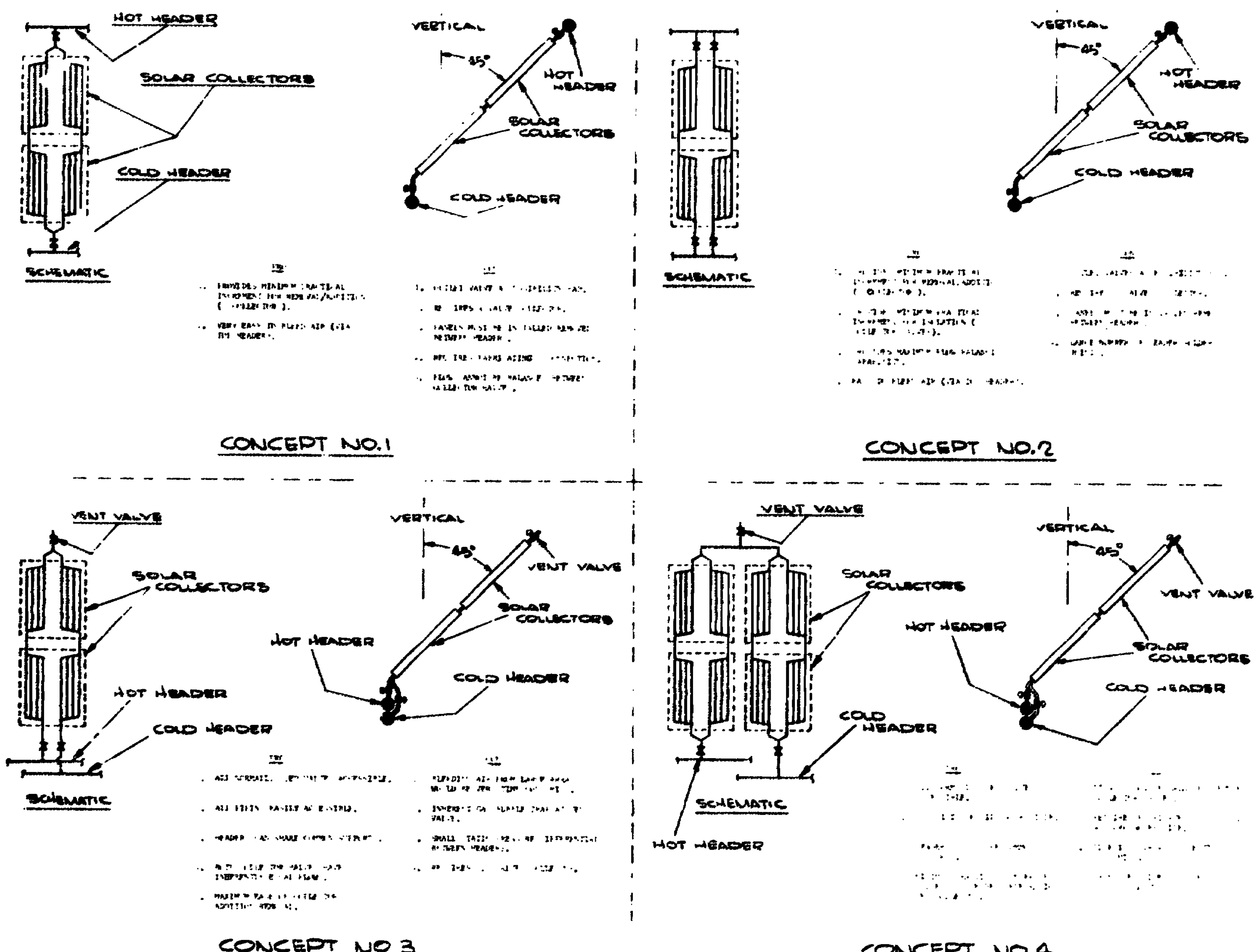

Figure 4-12. Collector Concepts Considered

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After evaluating the various considerations, a variation of Concept 2 was chosen principally because it provided the greatest freedom from uncertainties, i.e., flow balancing, air entrapment, etc. However, prior to fixing the configuration, a sample header penetration joint was made by the plumbing subcontractor and evaluated by General Electric. The variation eliminated half of the valves by substituting one valve at an accessible location on the hot header for all the outlet valves in a bank. Since flexible rubber hoses were chosen as the means of collector to header connection, it was deemed that the header valve could be shut, the hot header to collector connection broken and plugged, and the header valve reopened should an individual collector removal sequence ever become necessary.

4.2.2.2 Piping Network

The decision to utilize six banks instead of three (which is at least visually suggested by the existence of three rows) was prompted by the desire for a large degree of system flexibility, ease of flow balancing and simplicity of construction.

A philosophy decision was made to keep the system flows as inherently balanced as possible which translated to a "Z" flow pattern through each bank, i.e., lower left in and upper right out. While exact bank configurations had not been determined at the time, two general piping schematics were prepared and are shown as Figure 4-13 and 4-14. Both configurations have virtually the same number of valves and the same degree of flexibility. However, the configuration shown in Figure 4-14 was chosen because, for a given pressure drop, it:

- Minimizes the liquid inventory by 20%
- Minimizes the surface area and length of hot feed/header pipe by 10%
- Minimizes the required lengths of large diameter pipes by 40%

The transient system response is addressed by the first and last consideration and the system efficiency by the second and last consideration. The cost of fittings, valves and hydraulic instrumentation is addressed by the last consideration.

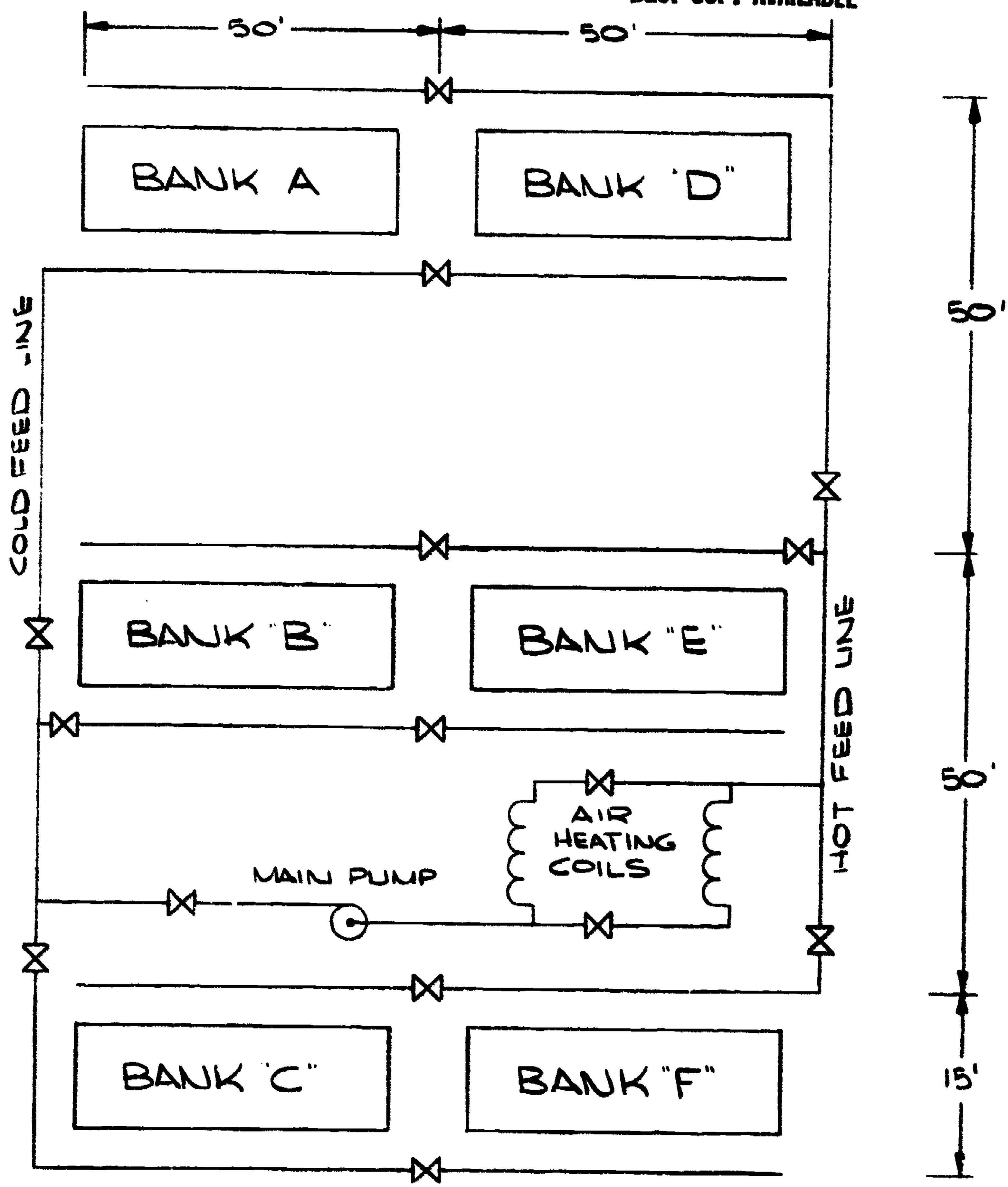

Figure 4-13. Side Feed Piping Network

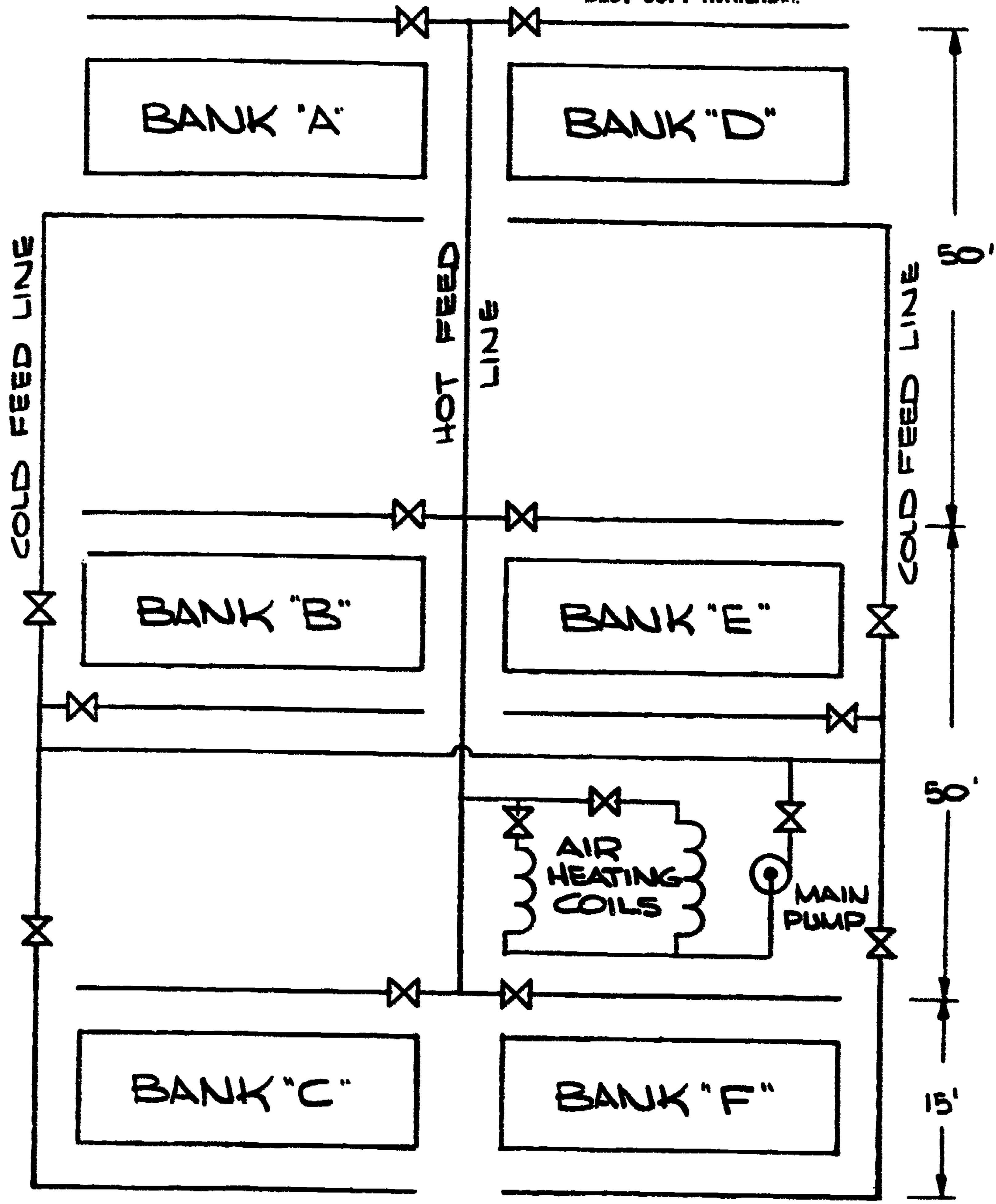

Figure 4-14. Side Feed, Center Return Piping Network

Preliminary sizing calculations were made based on the configuration of Figure 4-14, an assumed solution which was 45 percent ethylene glycol and 55 percent water (freezing point, -22° F), and a flow rate of 0.8 gpm per collector. The results were as follows:

- Headers = 1.5 in., O.D.
- Feeders carrying flow for one bank = 1.0 in. O.D.
- Feeders carrying flow for two banks = 1.50 in. O.D.
- Feeders carrying flow for three banks = 1.75 in. O.D.
- Feeders carrying flow for four banks = 2.0 in. O.D.
- Feeders carrying flow for six banks = 2.5 in. O.D.

The predicted loop pressure drop was 23.4 psi at 60 gpm with a main pump requirement of 1.5 HP. These calculations ignored fittings due to the lack of exact bank configurations, heating coil pressure drops, etc. To allow for this the preliminary estimate sizing was set at a loop pressure drop of 46 psi with the pump requirement being 3 HP at 60 gpm. Actual values were 42 psi at 64 gpm (see Table 6-2, Mode 3) which agrees well; however inspection of performance curves for available pumps lead to selection of a 5 HP pump.

Both Armaflex and Armaloc insulation were considered and the higher performance Armaloc was selected because it was both less costly and more available in sizes applicable to our system. The nominal insulation thickness was 1 inch and the heat loss was almost negligible on the system, i.e., 9.1 BTU/hr ^{o}F per 100 feet of 2 inch O.D. pipe.

A transient response prediction was calculated for this system in terms of time after sunrise with the assumptions of a peak collected energy density of 100 BTU/hr ft^2 (see Table 6-4 for comparison to actuals), no heat loss from the system, and a flowing liquid inventory of 150 gallons. The results follow:

Time after Sunrise ~ Hr	Fluid Temperature Rise ~ F
0	0
.5	3.3
1.0	13.0
1.5	29.1
2.0	51.5
2.5	79.0
3.0	112.2

As this work was being completed the control concepts were being finalized and a location was found near the east end of Bank E capable of supporting a small thermal energy storage tank. A location underneath Bank E was selected for the main pump area and a new feature was added to the system. The new feature is the three bypass heat exchangers discussed in Subsection 4.2.3.2 following. They are basically liquid to air auxiliary heat exchangers which provide the capability to dump excess heat which cannot be utilized (a typical summer situation) and to accelerate the morning warmup transient. At this point reflection on overall system reliability also led to the conclusion that pressure should be minimized on the collector's rubber hose connections and, consequently, the main pump was relocated to place the suction side immediately downstream of the collector outlet. Main pump NPSH requirements were satisfied by pressurizing a make up water tank. The unconventional placement of the pump on the "Hot" side of the loop is not as significant as it would appear, since the loop temperature differential decreases substantially as the temperature level increases (due to both collector efficiency and system mode changes).

The piping network schematics were revised using these inputs and the final versions of the network and pump area are shown in Figures 4-15 and 4-16, respectively.

4.2.3 MAJOR SYSTEM COMPONENTS

There were three major components or areas of the heating system which required an individual design activity. These were the Nesbitt Heating Unit Modification, the bypass heat exchanger, and the thermal energy storage tank.

4.2.3.1 Nesbitt Heating Unit Modification

The Nesbitt heating unit is a relatively compact package which provides all functions normally associated with a year round, hot air comfort system. The particular units to be modified were designated AC-6 and AC-7 in the building plan and are referred to as rooftop, reheat multizone, model RMA units by the manufacturer. Each of the two units has a capacity of 410,000 BTU/hr and 30 tons of heating and cooling, respectively. According to the school plans AC-6 and AC-7 serve a virtually identical floor area and have an identical heating load. A high ceiling first floor class area of 9074 square feet plus the two story high 2211 square foot lobby is served by AC-6 while a more conventional classroom area of 9074 square feet on the upper floor and some leakage to the lobby upper volume are provided

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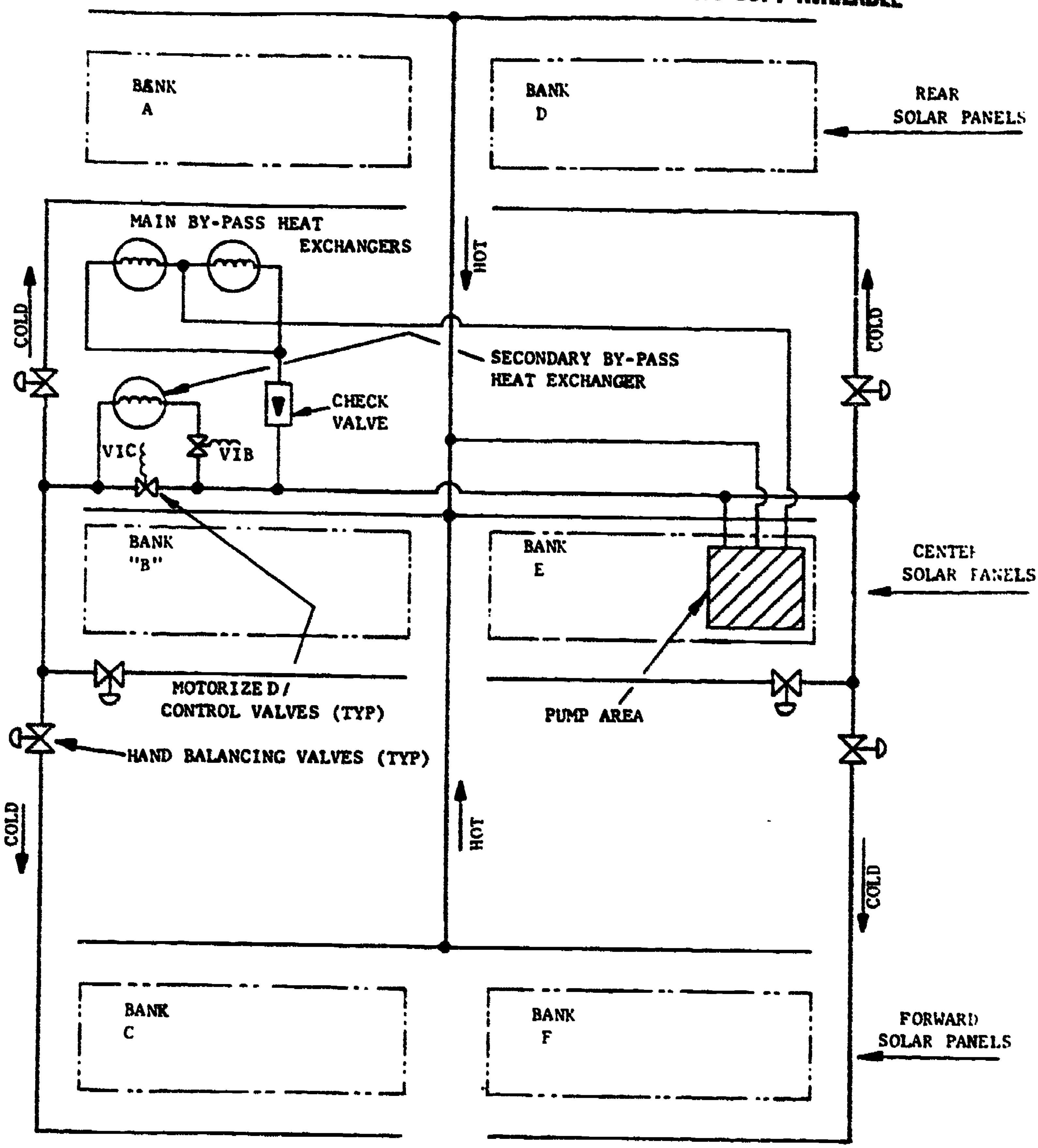

Figure 4-15. Piping Schematic - Minimum Feed Volume, Minimum Header Volume and Minimum Hot Pipe Surface

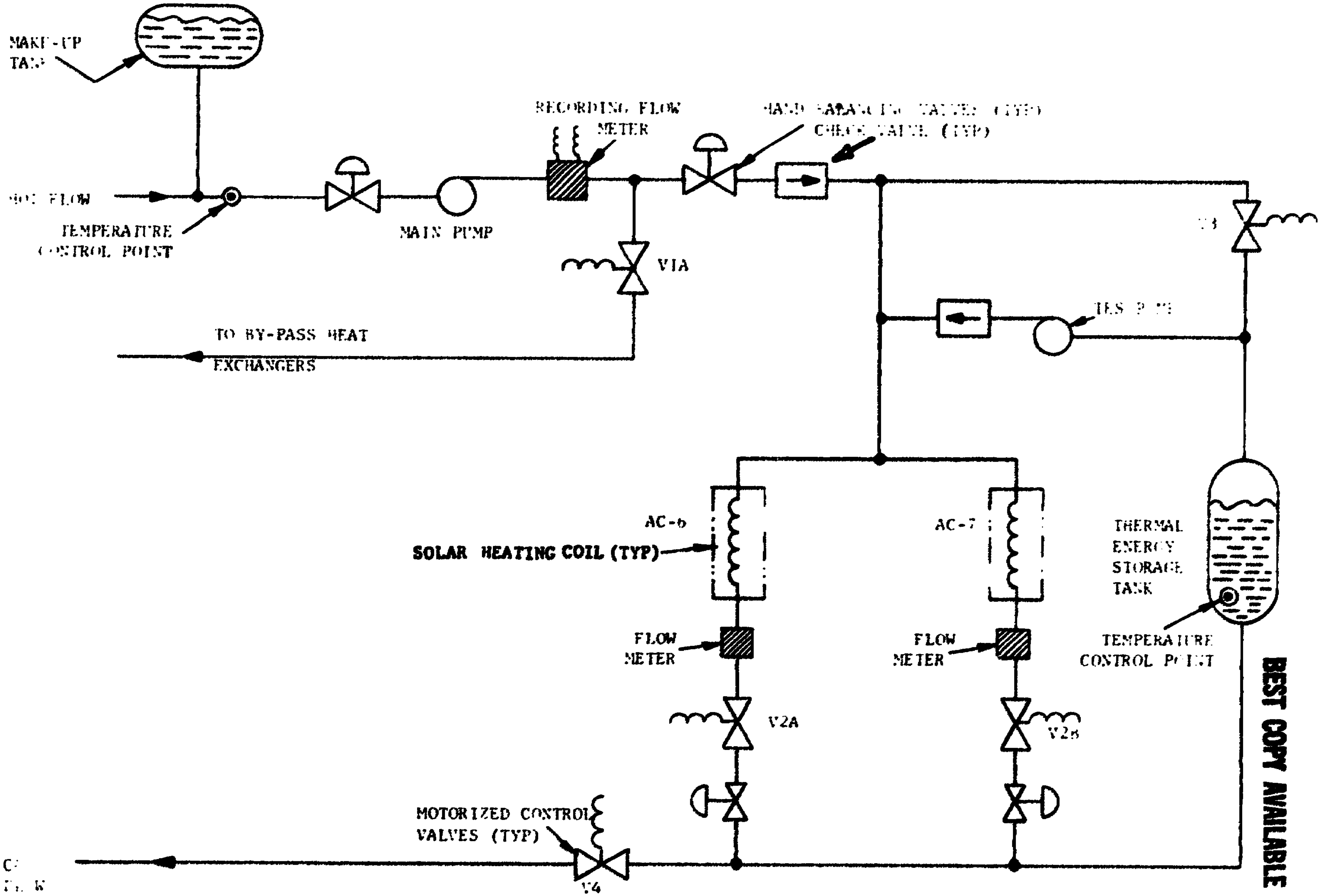

Figure 4-16. Plumbing Schematic - Pump Area

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by AC-7. The general approach to the modification was to find a location in, or around, the unit which would be suitable for a hot water to air heat exchanger ("coil"). The location would not only have to be geometrically suitable but functionally useful and amenable to the existing control system or a modest modification thereof.

4.2.3.1.1 Modification Concept

An exterior view of one of the units was shown in Figure 4- 9 and Figure 4-17 provides a side view with the locations of various functions identified. It is possible with care and qualifications to place heating coils in any or all of the locations shown in Figure 4-18; however, many of the locations are not desirable. The function of the unit is to draw return air from the school (via a fan), discharge a fraction of it and replace it with outside air. The mixed air then travels through a filter section, the air conditioning refrigeration coil, and the main blower. Downstream of the main blower, the air enters a plenum and is split horizontally into two decks; the heating elements being located in the lower or "hot deck" and the upper "cold deck" being essentially a bypass duct. Both decks terminate in two small plenum volumes immediately upstream of the dampers in the exit plane of the unit. The unit internal controls maintain hot and cold deck exit air temperatures while the room thermostats control the exit damper positions - mixing a proportion of hot and cold air to satisfy the rooms' demands. The exit planes of each of these heating units can be segregated into different individually controlled heating zones and in this case AC-6 has 10 and AC-7, 6 zones.

Each of these locations shown in Figure 4-18 were looked at as Concepts 1 through 5 shown in Figures 4-19 through 4-23, respectively. A major functional problem was common to Concepts 1, 2 and 4 in that the effect of adding heat upstream of the hot/cold deck separation would be to heat the mixed air and, thus, the cold deck temperature. While this would be fine for the heating only situation it would either compromise unit performance during those periods when some air conditioning was needed or it would necessitate the solar heating coil cycle to a condition of no heat input whenever either economizer or refrigeration cycle air conditioning was called for. This reason along with other disadvantages led to the elimination of concepts 1, 2 and 4. Concept 3 was the simplest modification concept of all and

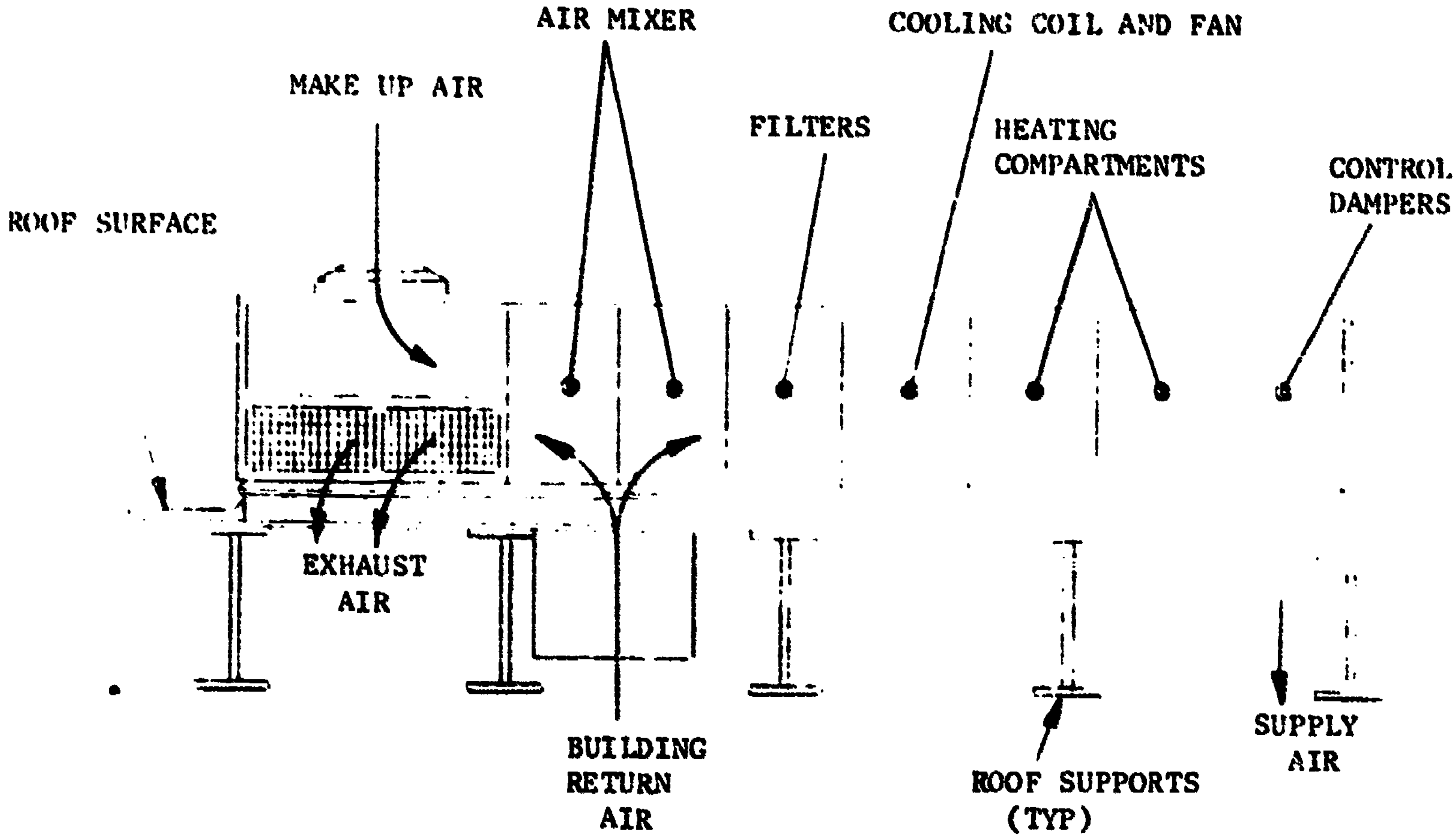


Figure 4-17. Side Elevation of Nesbitt Roof Heating/Cooling Unit

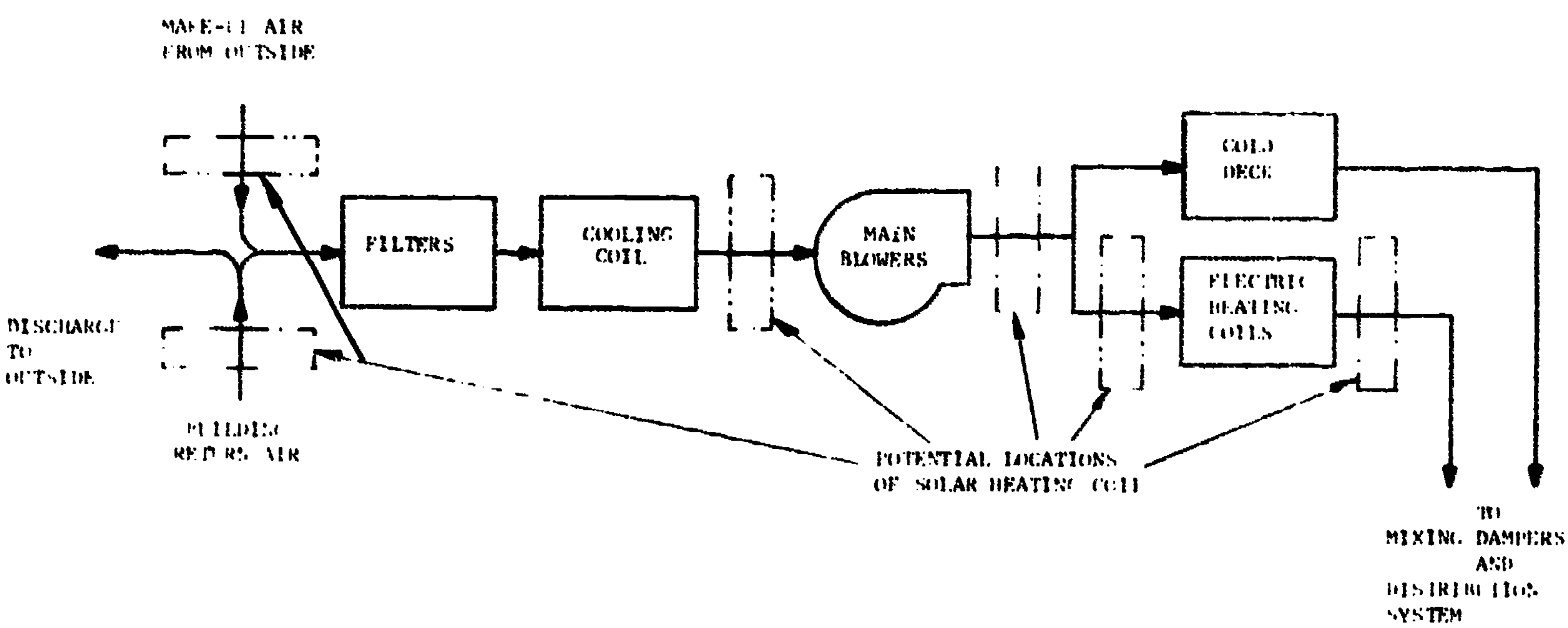
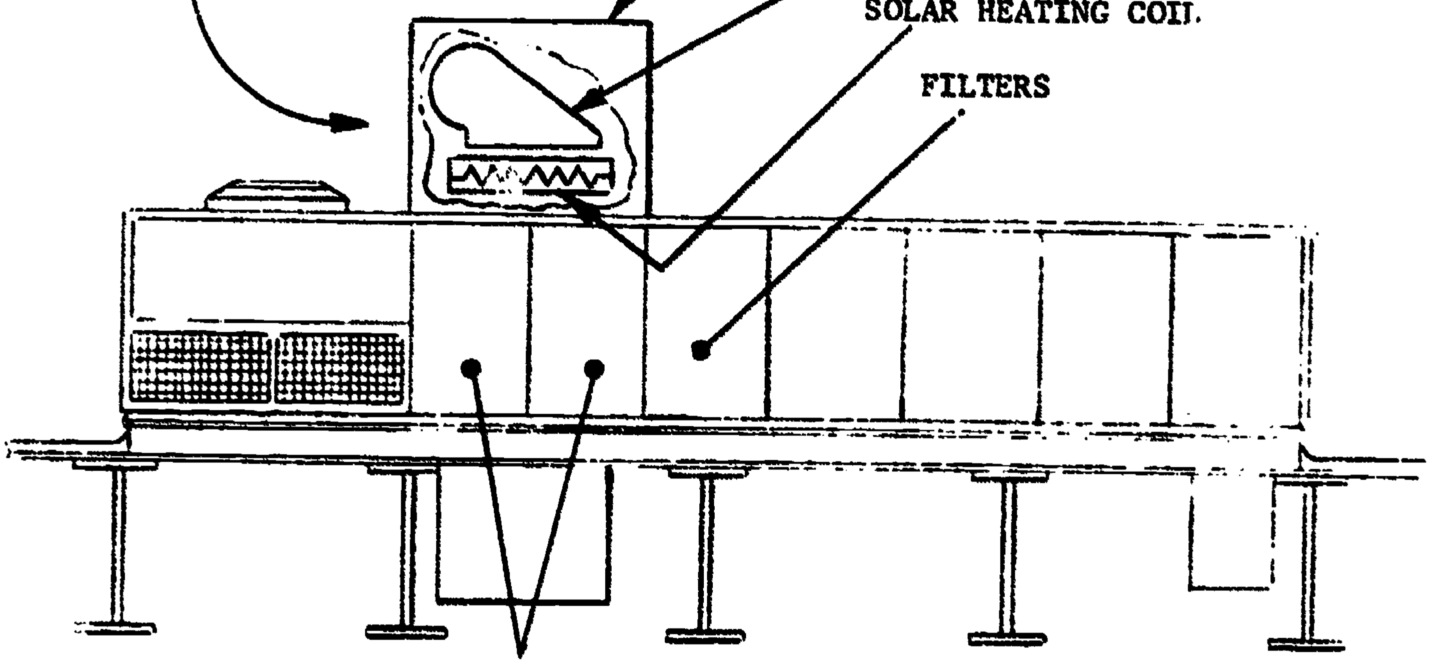


Figure 4-18. Schematic Rooftop Heating and Cooling Unit at Grover Cleveland School



SIDE ELEVATION OF NESBITT ROOF HEATING/COOLING UNIT

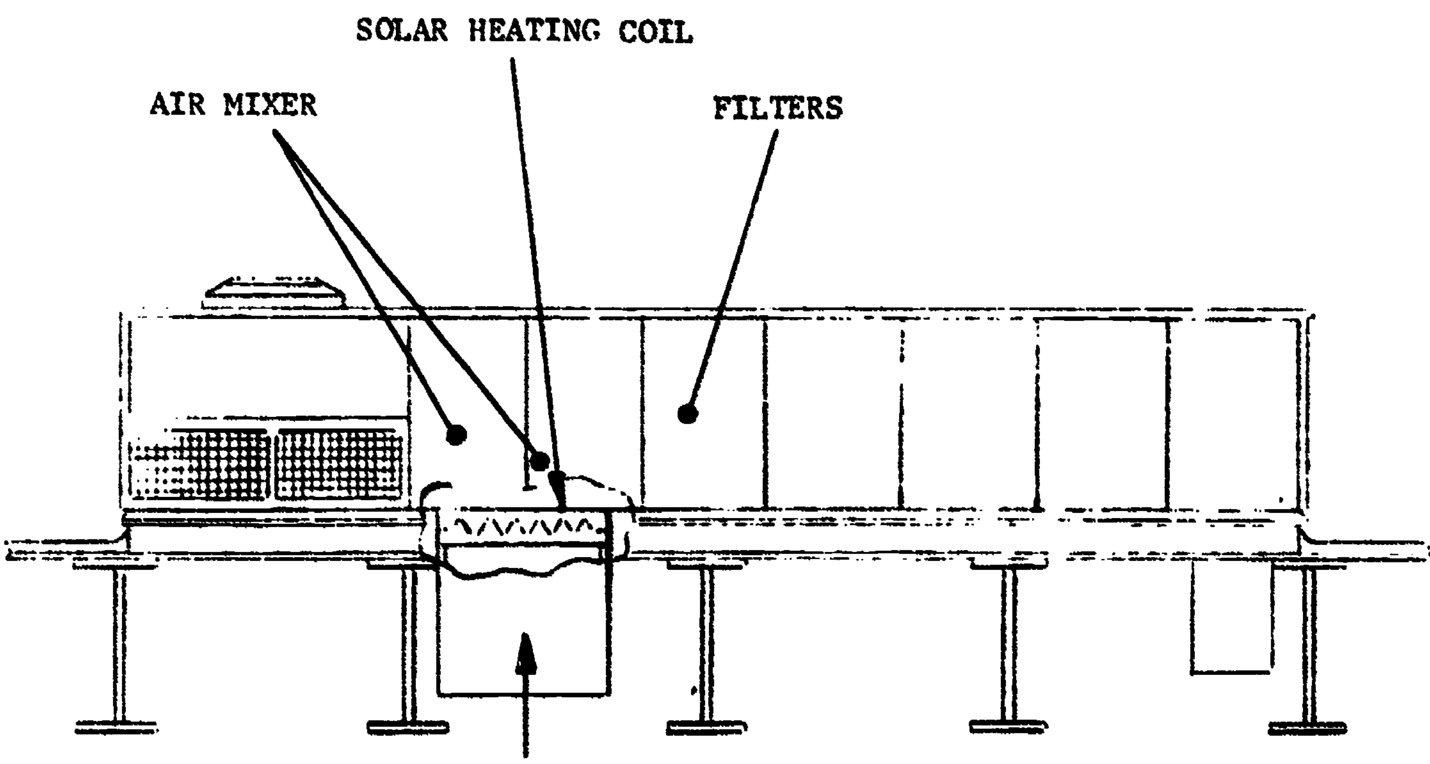
ADVANTAGES

1. USEFUL AT MINIMUM SOLAR COLLECTOR TEMPERATURES

DISADVANTAGES

1. HEATS ONLY AIR TAKEN FROM OUTSIDE
2. WOULD ELIMINATE EFFECTIVENESS OF "ECONOMIZER CYCLE" AIR CONDITIONING
3. COMPLICATED CONTROL SYSTEM
4. REQUIRES FABRICATION OF WEATHERPROOF SHROUD FOR FAN AND SOLAR HEATING COIL

Figure 4-19. Modification Concept No. 1 - Inlet Air Heating



SIDE ELEVATION OF NESBITT ROOF HEATING/COOLING UNIT

ADVANTAGES

1. AN UNENCUMBERED AREA, EASY PENETRATIONS, ETC.

DISADVANTAGES

1. REQUIRES ACCESS TO BOTTOM OF UNIT AT ROOF LINE
2. SOME OF HEATED AIR WOULD BE DISCHARGED VIA EXHAUST DAMPERS
3. "ECONOMIZER CYCLE" AIR CONDITIONING JEOPARDIZED BY HIGH MIXED AIR TEMPERATURES
4. COMPLICATED CONTROL SYSTEM

Figure 4-20. Modification Concept No. 2 - Return Air Heating

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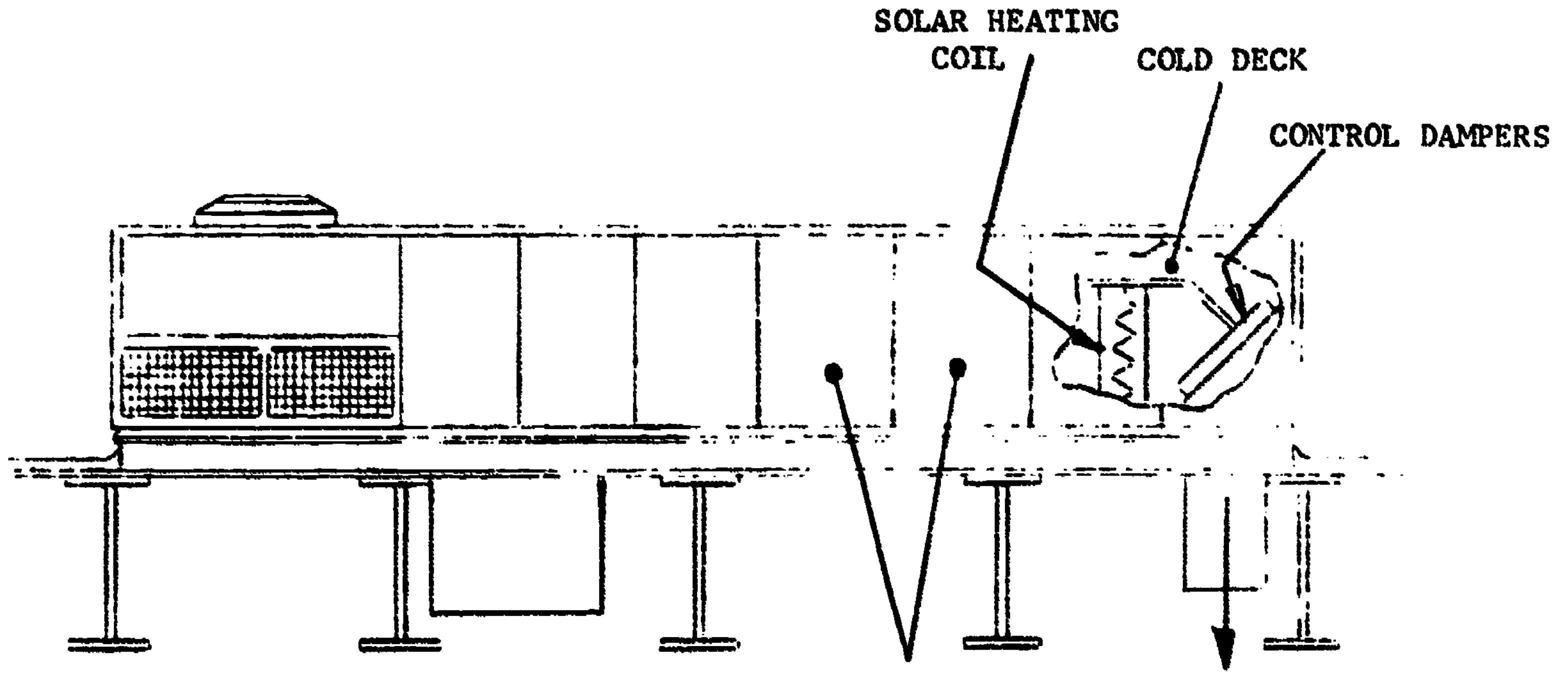

SIDE ELEVATION OF NESBITT ROOF HEATING/COOLING UNIT

ADVANTAGES

1. SIMPLEST MODIFICATION OF ALL CONCEPTS

DISADVANTAGES

1. REQUIRES SOLAR COIL TO OPERATE AT MAXIMUM TEMPERATURE TO BE EFFECTIVE

2. SOME INTERACTION WITH NESBITT HEATER CONTROL LOGIC

Figure 4-21. Modification Concept No. 3 - Exit Hot Air Heating

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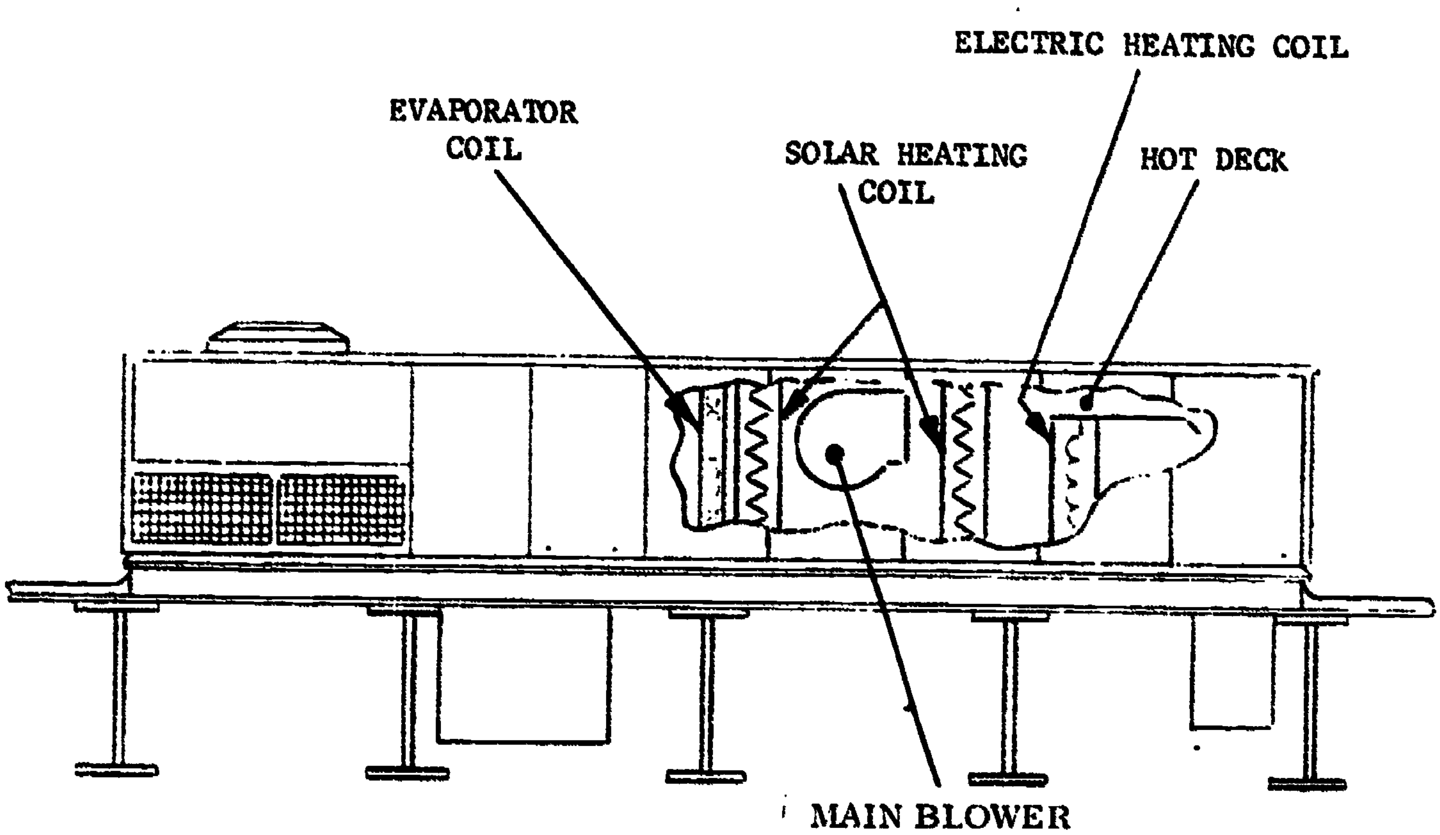
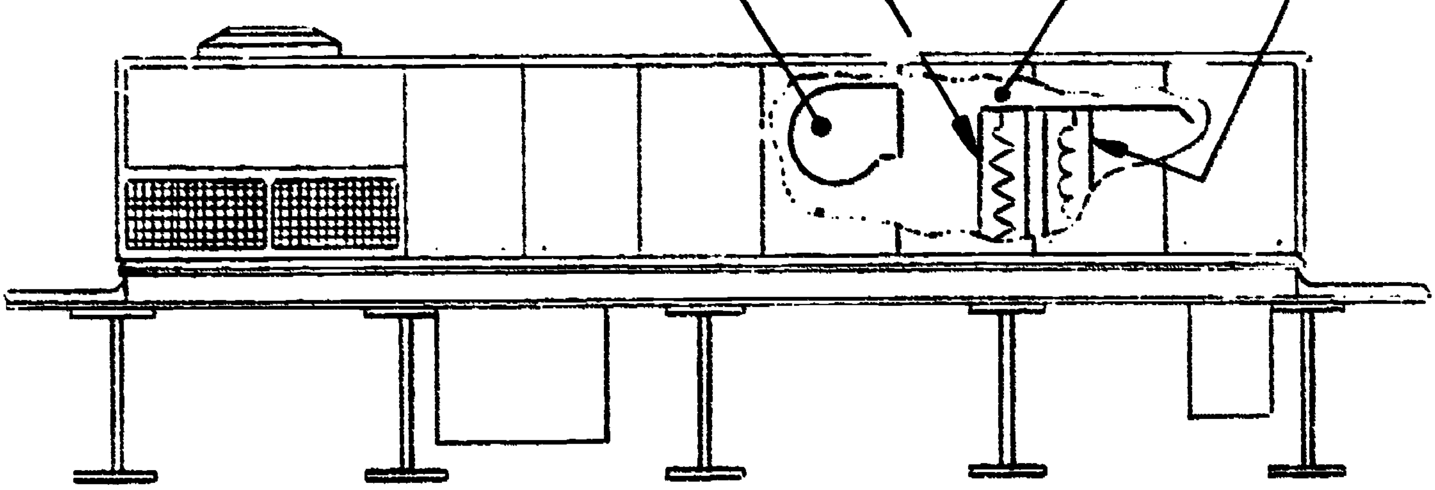


SIDE ELEVATION OF NESBITT ROOF HEATING/COOLING UNIT

ADVANTAGES	DISADVANTAGES
1. CAN OBTAIN LARGEST HEATING CAPACITY WITH THESE LOCATIONS.	1. EFFECTIVENESS OF ALL AIR CONDITIONING JEOPARDIZED.
	2. LIMITED SPACE/CONGESTED AREA OF UNIT.
	3. CONTROL SYSTEM INVOLVED.

Figure 4-22. Modification Concept No. 4 - Total Mixed Air Heating



SIDE ELEVATION OF NESBITT ROOF HEATING/COOLING UNIT

ADVANTAGES

1. NO MODIFICATION OF CONTROL SYSTEM.
2. UNIT PENETRATIONS IN AN UNCONGESTED AREA.
3. SIMPLE MODIFICATION CONCEPT.

DISADVANTAGES

1. GEOMETRY AVAILABLE RESTRICTS TO 2 ROW, 200,000 BTU/HR COIL.
2. EXISTING ELECTRIC HEATING COIL MUST BE INVERTED TO PROVIDE ROOM.

Figure 4-23. Modification Concept No. 5 - Hot Deck Preheating would not significantly affect the Nesbitt control system although some proportioning of the heating would be required. However, it had the distinct disadvantage that the solar heating coil location is in the hottest region of the unit and thus the fluid loop temperature's minimum useful value is larger than that of Concept 5. Concept 5 had an additional advantage in that it does not require modification of the existing control systems.

Concept 5 was then selected and, based on discussions with Nesbitt field and factory personnel, a location in the unit's hot deck between the existing "reheat" and electric heating coils was selected. The "reheat" coil is plumbed into the air conditioning cycle's refrigerant loop and utilizes warm condensate to heat air whenever the refrigeration cycle is activated. This plumbing consideration, together with the need to provide an air plenum volume at the inlet to the hot/cold decks, required that the "reheat" coil not be relocated. The electric heating coil is smaller than the volume allocated to the "heating section" of the hot deck and also eccentric with respect to its mounting interfaces. As a result, it was deemed that the electric coil could be inverted, thus moving the coil itself downstream and providing a 7 in. X 28 in. X 70 in. internal volume available for the "solar" coil. This location had several advantages from a system standpoint, specifically:

1. The existing controls without modification would operate the Nesbitt unit since the unit controls on hot deck exit air temperature.

2. The control system for the solar system was simplified. The solar coil functions as an air pre-heater for the electric coil and thus can run at full flow normally and be shut off only when the RMA hot deck exit temperature becomes excessive or the unit goes on refrigeration cycle air conditioning.

3. It was a relatively straightforward physical modification with relocation of some mercury wetted relays being the only additional complication.

The Nesbitt unit considerations thus fixed the size and pressure-drop requirements of the "solar" coil. This latter requirement comes from the need to maintain hot/cold deck pressure drop characteristics in a range which can be accommodated by the existing zone control dampers at the unit's exit plane.

The "coil" is basically a finned tube, water to air heat exchanger whose effectiveness is a function of, among other factors, the number of fins per inch, the number of rows of tubes, and the tube spacing within the row. Heat transfer effectiveness generally conflicts with pressure drop considerations and, thus, the selection is a tradeoff of performance characteristics with restrictions on volume and availability.

Identification of a coil vendor who could meet the 2 to 4 week available lead time was a major problem since coils are a "made to order" item. Trane Co. was found to have an "emergency" fabrication cycle which can produce their standard dimension coils in 3 to 5 days for a premium price. Various sizes of coils were available and a two row coil having outside dimensions of 6-1/2 in. X 26-1/4 in. X 67 in. was the largest coil that would fit into the volume available. This coil had a finned face area of 24 in. X 60 in. and was available with fin spacings of nominally 6, 9 and 12 fins per in. and tube spacing within rows of 1-1/2 in. and 3 in. No precise criteria was available as to what additional pressure drop could be accommodated by the Nesbitt unit. However, the unit is designed for various type "heat sources" including 2, 3 and 4 row hot water coils with 9 and 12 fins per in. For the unit to operate correctly without damper modifications, the proposed "duplex heat source" (solar plus electric coils) should have a combined pressure drop equal or less than one of the standard Nesbitt heat sources, i.e., a 4 row water coil. Since the electric coil has almost negligible pressure drop, < .05 in. H_2O, the Nesbitt factory concurred that any 2 row coil with 9 to 12 fins/in. or less would be acceptable. As a result of these considerations and some preliminary performance figures provided by Trane on various geometries, a spacing of 1.5 in. per tube with 9 fins per in. was selected for the 24 in. by 60 in., two row coil. This coil had the highest heat transfer effectiveness available without violating any constraints. The coils were ordered and delivered the seventh day after the order was placed.

4.2.3.1.2 Modified Unit Performance Predictions

This section presents specific data intended for system performance evaluation. The calculations are based on a series of coil selection computer runs done by Trane. An excerption of the results is given in Table 4-1.

Figure 4-24 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 60° F entering air temperature which appears reasonable since a majority fraction of the

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Table 4-1. Performance Figures for a Trane Type W, Series 16, Two Row, Water/30% Glycol Coil With 60° F Entering Air

Air Flow Rate ~ SCFM	Liquid Inlet ~ ° F	Heat XFR ~ MBH	Air ΔP ~ In. of H_2O	Air ΔT ~ ° F	Liquid Flow ~ gpm	Liquid Δp ~ Ft. of H_2O	Liquid ΔT ~ ° T
9700	120	170	.85	16.3	14.6	.6	25.1
		180		17.2	16.9	.8	22.9
		200		19.1	23.1	1.3	18.6
		230		22.0	39.9	3.3	12.4
		260		24.8	84.8	12.8	6.6
8500	120	200	.67	21.8	27.8	1.8	15.5
		210		22.9	34.2	2.5	13.2
		240		26.2	76.9	10.7	6.7
	100	130		14.2	26.7	1.7	10.5
		140		15.3	36.3	2.9	8.3
		150		16.3	52.0	5.5	6.2
	80	62		6.8	24.2	1.5	5.6
		64		7.0	27.0	1.8	5.2
		66		7.2	30.3	2.2	4.7
7500	120	191	.54	23.5	28.0	1.8	14.6
		200		24.7	35.4	2.7	12.1
	100	120		14.8	24.0	1.4	10.8
		130		16.1	33.3	2.5	8.4
		140		17.3	49.3	5.0	6.1
	80	60		7.4	25.7	1.6	5.1
		63		7.8	31.2	2.3	4.4
		67		8.3	40.8	3.8	3.6

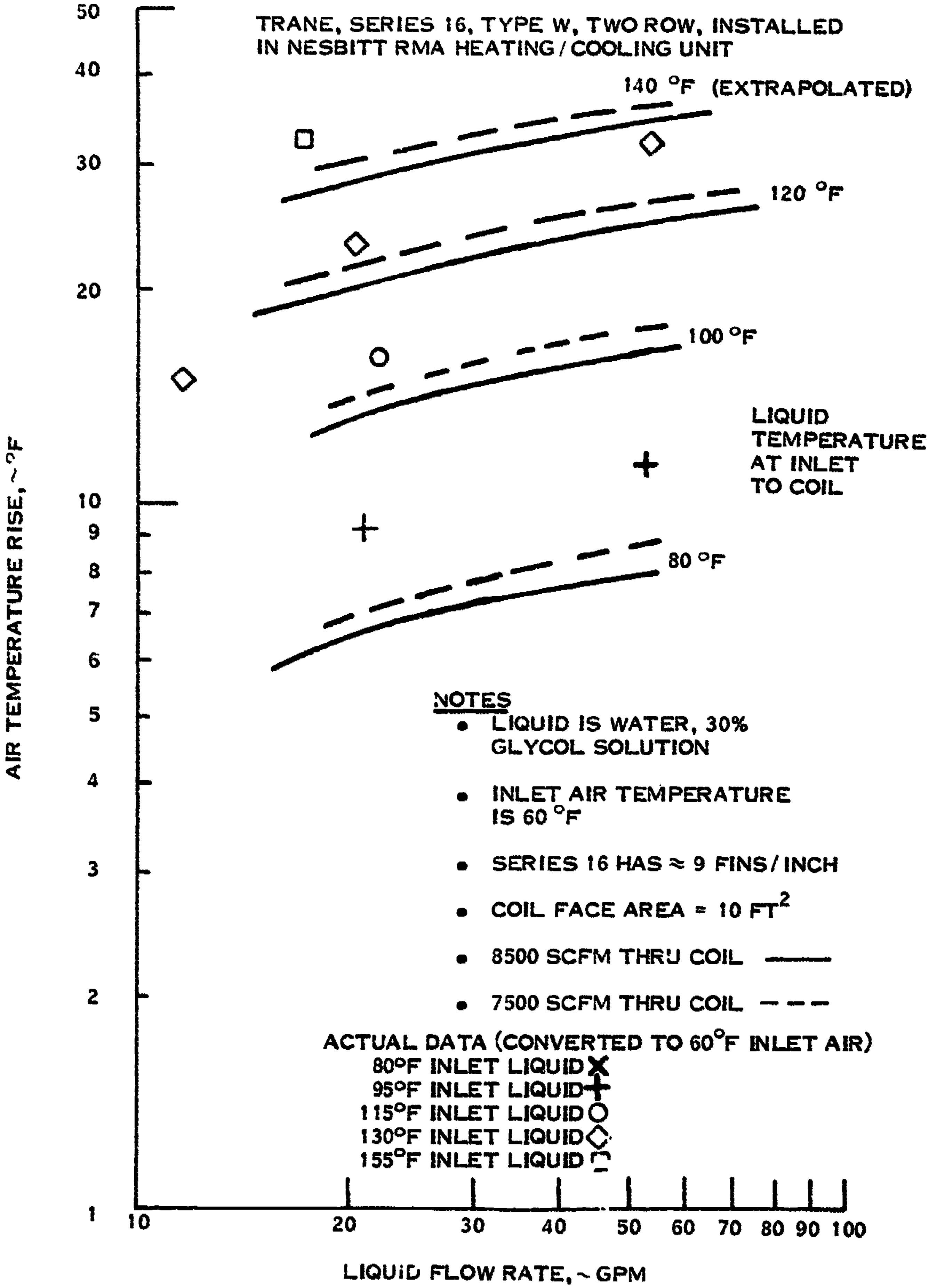

Figure 4-24. Predicted Heating Performance for Water/Glycol Coil

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 60° F, 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 80, 60, 40 and 20° F moving from top down on the figure. The 140° F 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 1000 SCFM variation in air flow rate. It is expected that in "normal" operation an air temperature rise of 20 to 30°F across the solar coil will be achieved. In the majority of the March-May time frame this should be all that the building will require since normally the hot deck control point varies from 70 to 130°F and the 90 to 130°F portion of the range is only experienced under high heating demand situations. Some actually experienced operating points are also shown on Figure 4-24 for comparison. The generally "high" values of air temperature rise are due to the likelihood of less than 7500 SCFM air flow through the hot deck.

Figures 4-25 and 4-26 provide coil heat transfer characteristics based respectively on water and air side data. It is expected that the water side data is easier to obtain and thus Figure 4-25 is probably of more use. The heat transferred (MBH value) should be independent of which figure is utilized and, thus, either figure can be utilized "backwards" utilizing the MBH value as the common point, i.e., to obtain hot deck air flow rate.

Figure 4-27 presents liquid and air side pressure drop predictions. It is seen that water side pressure drops will run in the 1 psig range and liquid temperature variations will have a negligible effect. The air side pressure drops are above Nesbitt's nominal value of 0.35 in. H_2O for all flow rates above about 6000 SCFM which means that approximately 40 percent of the unit's total 9700 SCFM normally goes through the cold 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 30 gpm each, with a 17° F drop at which point they will deliver approximately 235,000 BTU/hr each assuming 60° F inlet air and 120° F inlet water. Increases in inlet water temperature will significantly increase the heat transfer capability.

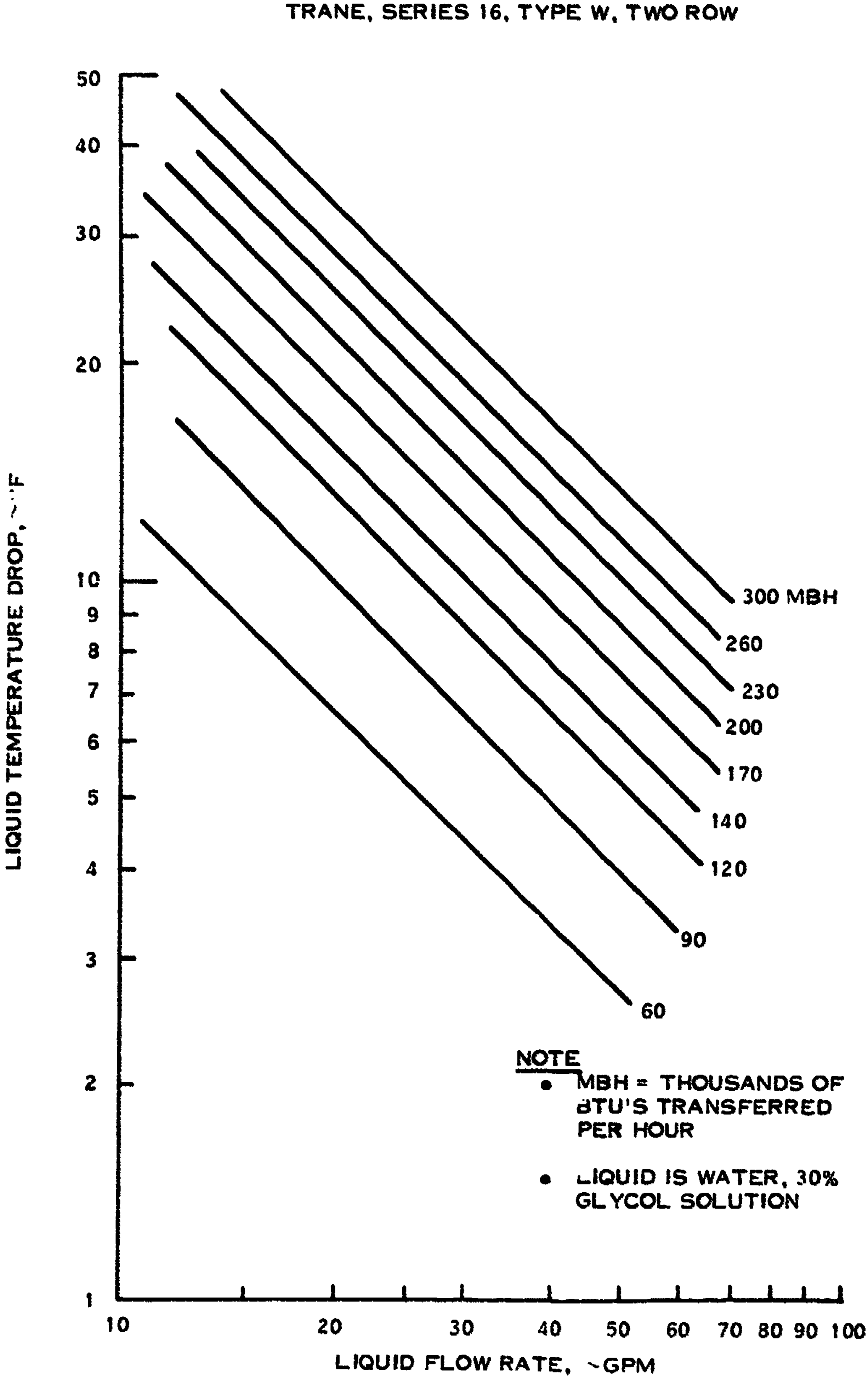

Figure 4-25. Predicted Heat Transfer Characteristics Based on Water Side Data for Water/Glycol Coil

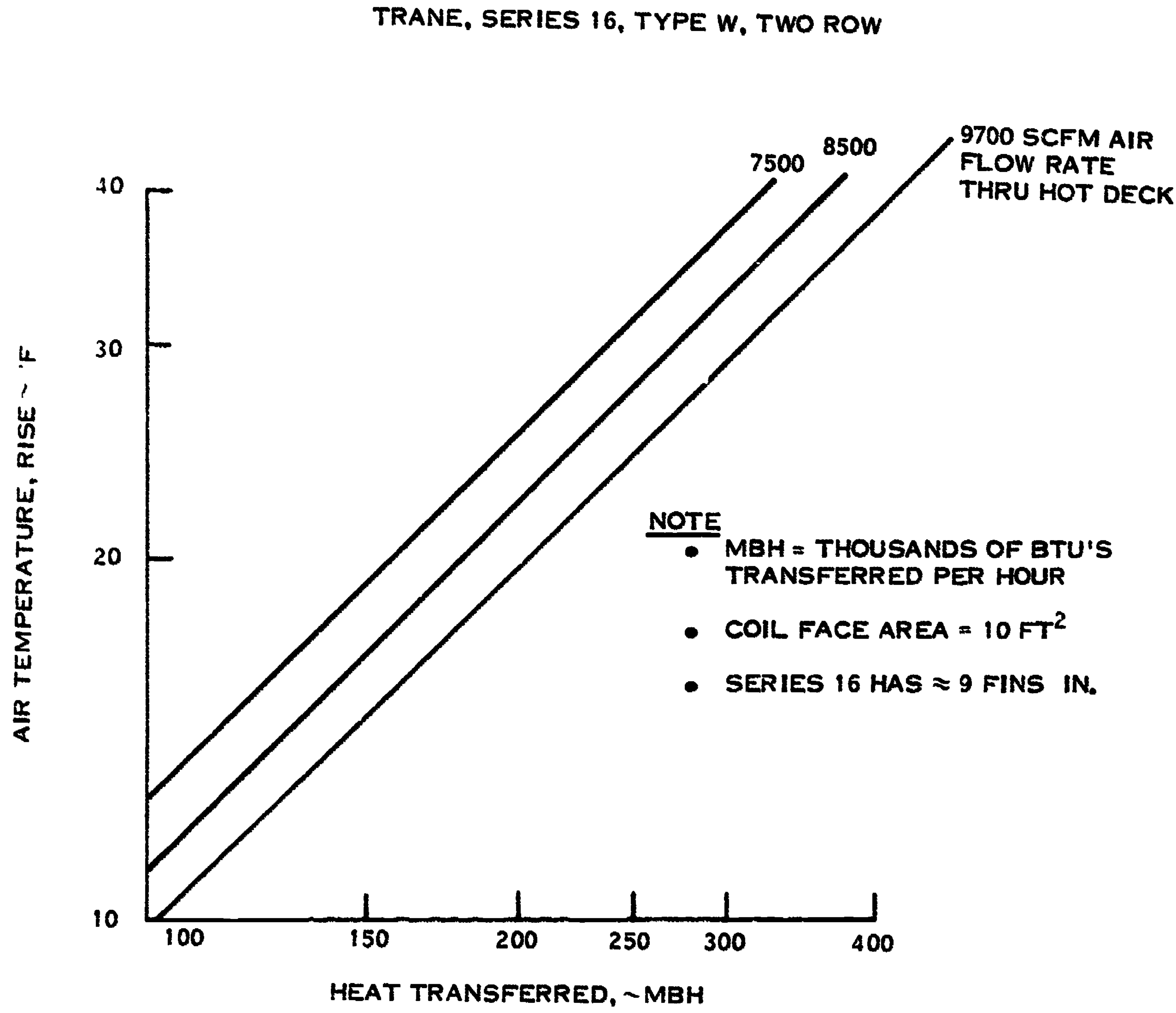

Figure 4-26. Predicted Heat Transfer Characteristics Based on Air Side Data for Water/Glycol Coil

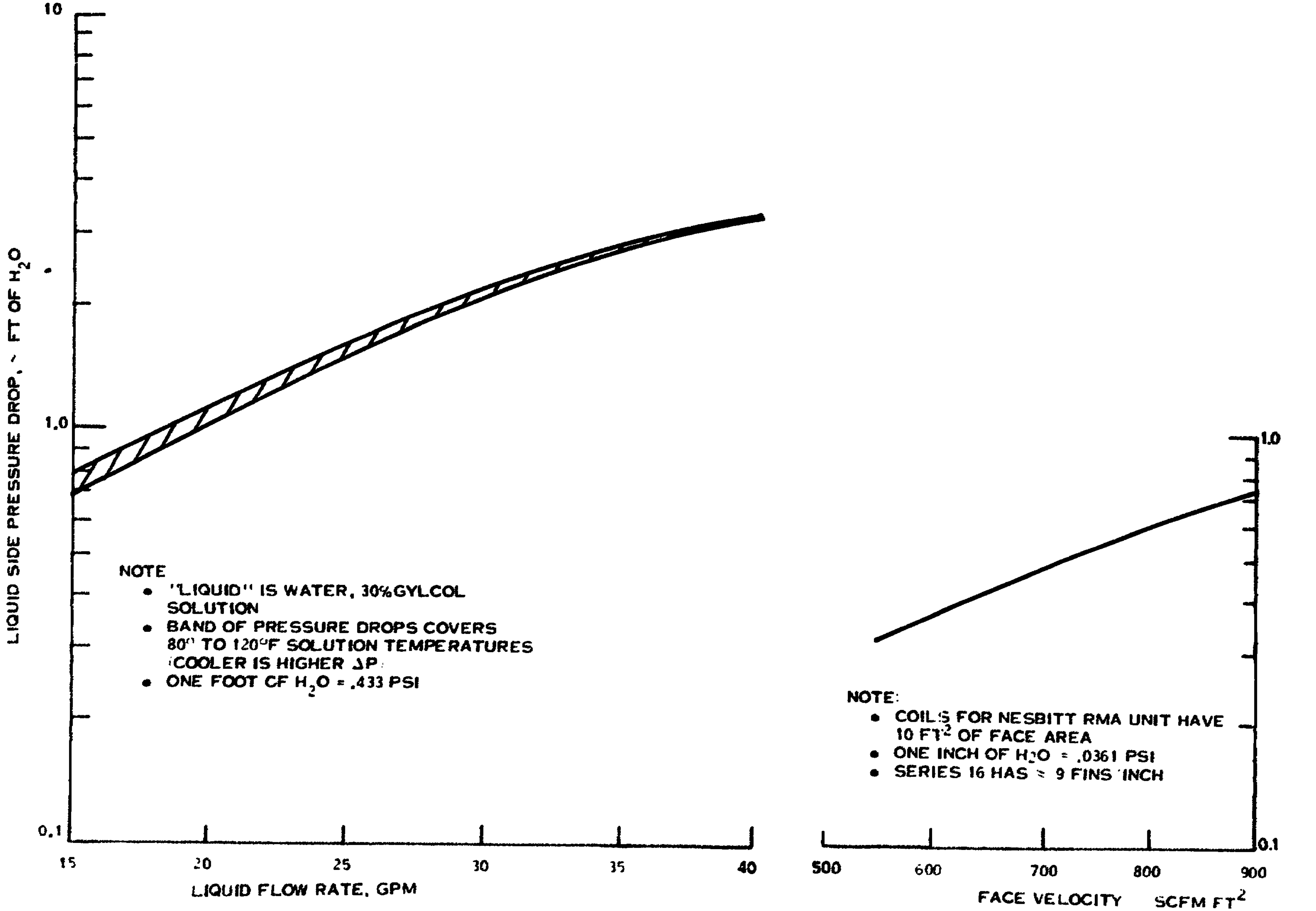

Figure 1-27. Predicted Pressure Drop Characteristics for Water/Glycol Coil

4.2.3.2 Bypass Heat Exchanger

4.2.3.2.1 Bypass Heat Exchanger Function

The bypass heat exchanger provides both heat recovery and heat dump functions. It originated due to anticipated need for a means of dumping heat should an "overtemperature" condition of any kind occur. The concept of a heat dump also made it possible to operate the system without a thermal energy storage tank (since it provides another means of circulating fluid without passing through the heating units) and would be useful during a contemplated summer experimentation period.

Various types and locations for such an auxiliary 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 and which is visible in Figure 4-7 led to a dual function unit. The roof mounted ventilators represent a significant heat removal from the school — this is not unusual since schools by design intent have large rates of air exchange. A qualitative indication can be seen as the melted snow around three of the ventilators shown in Figure 4-7. A closer view is shown in Figures 4-28 and 4-29. The morning the pictures were taken it was between 6 and 10° F with almost no wind and the exhausting warm school air had both melted the previous day's snow and, in spots, dried the roof. Figure 4-28 shows a view looking east along what will become the rear or north row of collectors, and Figure 4-29 shows a view also looking east along what will become the center row of collectors. These three ventilators shut off only at night and provide a steady flow of 70 to 75° F air. The near and far ventilators in Figure 4-28 operate at 1050 and 2750 cfm, respectively, and the unit shown in Figure 4-29 operates at 1575 cfm.

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. A discussion of how the control system functions to accomplish this is given in Section 4.2.4.

Figure 4-28. Roof Ventilators, Rear Row

Figure 4-29. Roof Ventilators, Center Row

The use of bypass coils were then attractive to the system in that:

1. They made the system more flexible, i.e., operable without a thermal energy storage tank if need be
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 provide a means to preheat the air and accelerate the fluid's morning warm up transient
4. They provide additional system safety and allay some implied fears of over heating the school

4.2.3.2.2 Bypass Coil Design

The key problem in adapting heat exchangers to the ventilators is to obtain reasonable heat transfer effectiveness with virtually no air side pressure drop. The significance of the pressure drop is that the ventilators are not designed to work against a backpressure and a modest additional resistance would drastically reduce their flow rate characteristics. The three particular ventilators utilize radial flow turbine type blowers and discussions held with manufacturers led to the conclusion that additional resistance resulting in up to 0.05 in. of water pressure drop would not significantly affect the flow characteristics. A decision was made to design a common coil which would surround each unit and let the center hole of the conical cover be tailored to fit the three different size ventilators. This was done to simplify and speed the manufacturing process. The result was a geometry which fit the 2750 cfm unit and utilized adapters and extensions to mate the conical cover to the small units.

The coils utilized 0.5 in. O.D. aluminum spine fin tubing which was readily available from stock. This type tubing is normally utilized in household air conditioners and has extremely low air side pressure drop characteristics in relation to the heat transfer coefficients which can be developed. The resulting geometry is shown in Figure 4-30. The predicted performance characteristics on the three ventilators is given in Table 4-2 and all three units show acceptable pressure drop values.

As shown in the loop schematic, Figure 4-15, the total loop flow would be circulated through the coils on the 2750 and 1050 cfm units in parallel and half of the loop flow would reach the

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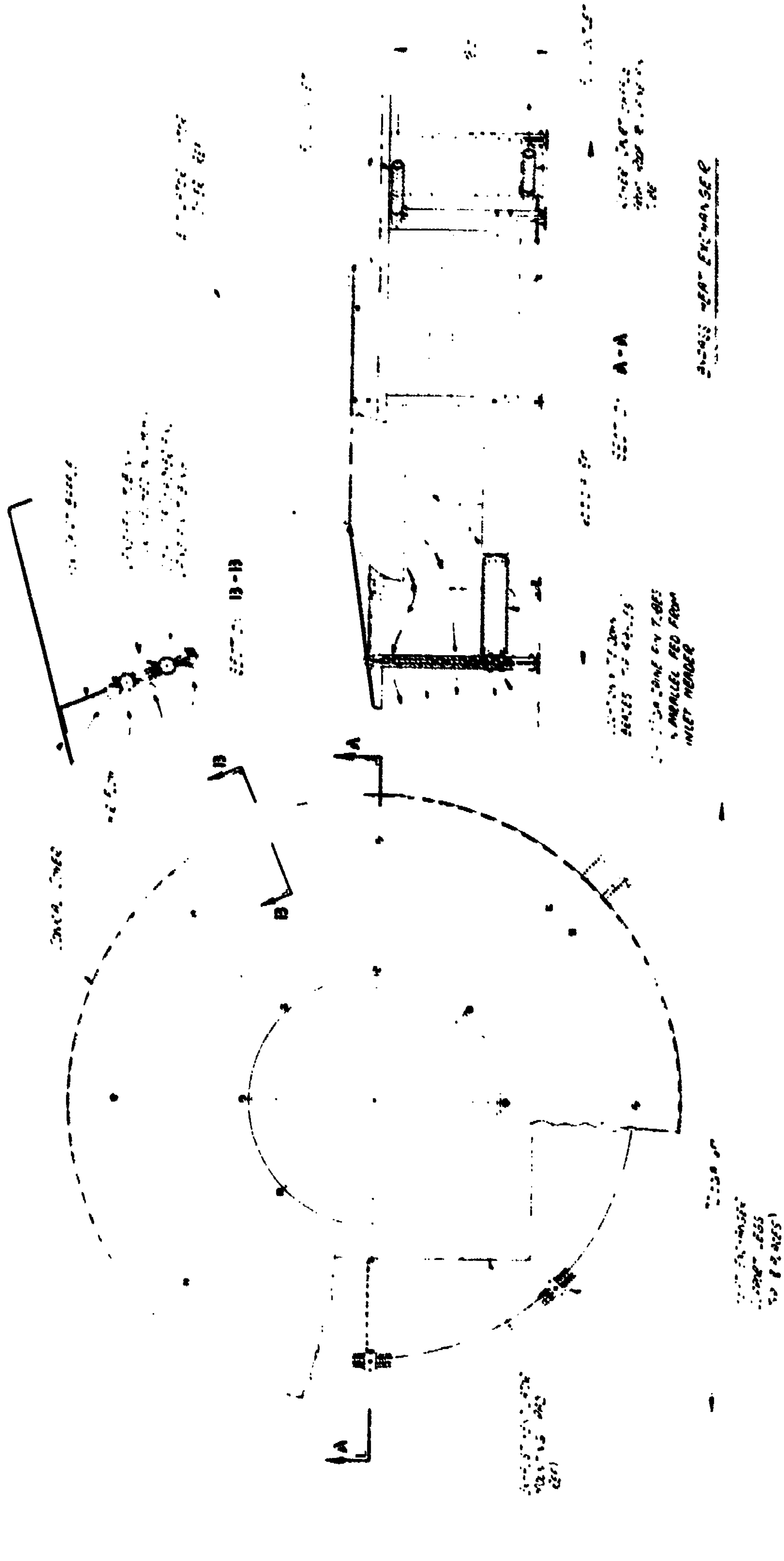

Figure 4-30. Bypass Heat Exchanger Diagram

Table 4-2. Bypass Coil Performance Characteristics

Air Flow ~ CFM	Air ΔP ~ in. of H_2O	Water ΔP @ 30 gpm ~ psi	Total UA ~ Btu/hr°F
2750	.0225	3.3	4250
1575	.0062	3.3	2700
1050	.0044	3.3	2010

1575 cfm unit. As a consequence, 30 gpm per coil corresponds to the 60 gpm loop design point. The grand total UA (overall heat transfer coefficient) is 8960 BTU/hr °F which is to say that these coils should have the capability to reject about 900,000 BTU/hr when the loop fluid is 175 to 185°F and should input about 450,000 BTU/hr into the loop when the fluid is 15 to 25°F. Since the loop output was not expected to exceed 1,000,000 BTU/hr, this was felt to be adequate. In actuallity the loop did exceed 1,000,000 BTU/hr and something less than the predicted UA was achieved; however the loop can be held below 225°F.

4.2.3.3 Thermal Energy Storage (TES) Tank

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 50 to 60,000 pounds. In addition, the Boston Public Facilities Department had 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, even 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 20,000 pound load and a search was begun to find a usable tank in the 2000 gallon 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 2000 gallon 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 was chosen for the TES tank.

The design of the tank had to consider that its rated working pressure was 7 psig 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 4-31. The stagnant layer of liquid surrounding the coil will thermally stratify but the consequences of this are somewhat negated by routing the main loop fluid in through the top and out the bottom of the tank. As mentioned in the control system discussion of Section 4.2.4, 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.

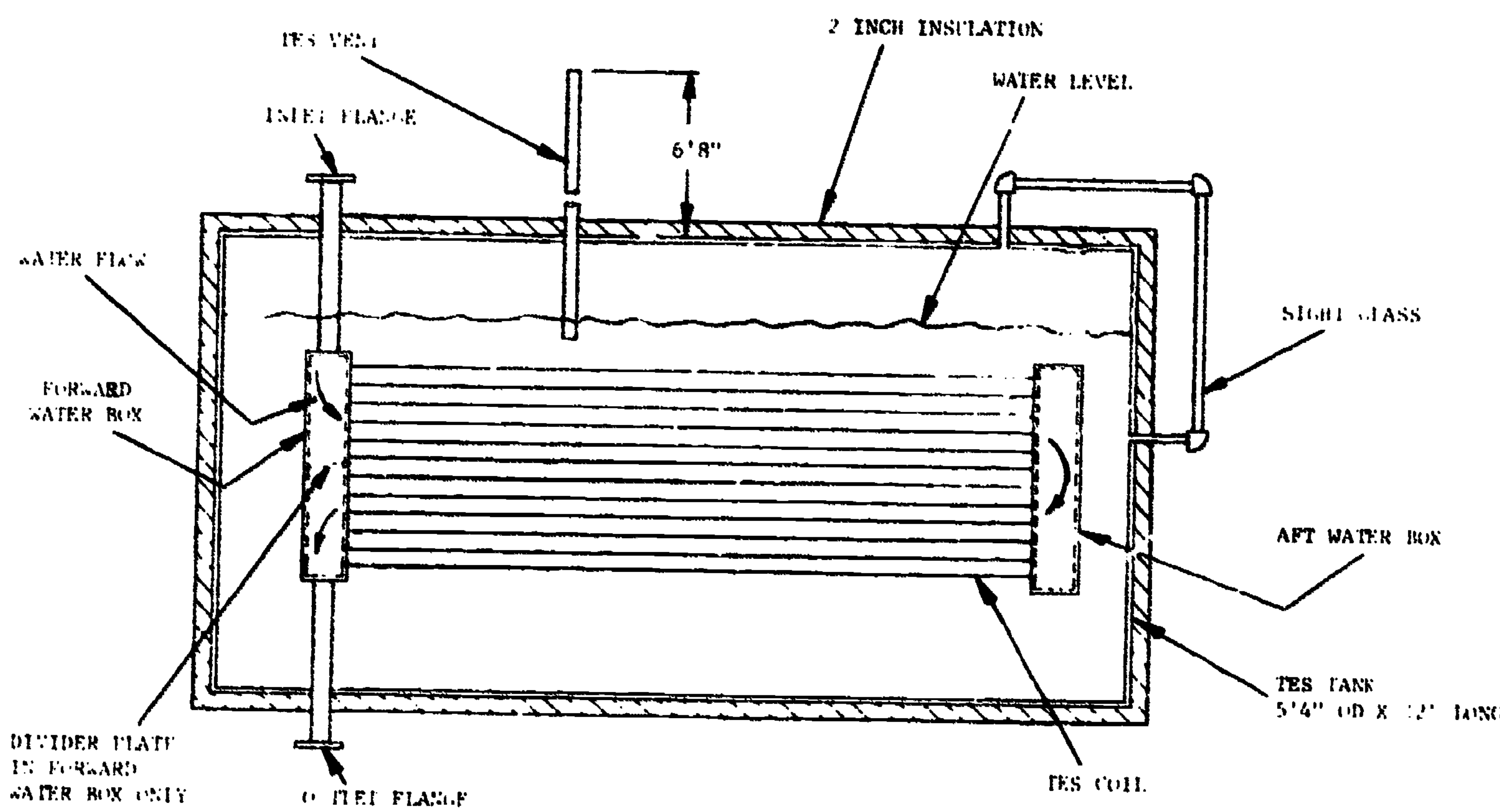

Figure 4-31. Cross Section Pictorial of Thermal Energy Storage Tank

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 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.

The approach temperature is a function of heat transfer area and rate and 300,000 BTU/hr was selected as a rate which was likely representative of both the storage and withdrawal modes. Calculations were made which indicated that approximately 200 square feet of area would be required to obtain approach temperatures in the range which was deemed to be acceptable (5 to 7^{o}F). This was accomplished using the tube bundle and water box approach shown in Figure 4-31.

A secondary 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 4-31 was to utilize a trapped air bubble with a vent pipe. As the TES fluid warms, the lower end of the vent pipe is first covered; further expansion compresses the 10 in. 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 12 ft and therefore the maximum pressure possible in the TES tank is between 5.0 and 5.5 psig depending on TES fluid density. A 30 gallon catch tank was placed on top of the TES tank and in series with the vent pipe because it was on site and to minimize the spillage during the initial TES warm up cycles.

The basic tank had a capacity of 2000 gallons; the volume occupied by the air bubble and the TES coil is 302 gallons and the TES coil and tank are steel and weight almost 3000 lbs and 1200 lbs respectively. If the tank itself is discounted the thermal storage capacity is 15,000 BTU/° F.

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The maximum heat loss rate was conservatively calculated at 35 BTU/hr for every degree Farenheit of temperature difference between the TES fluid and ambient. This translates into a loss of about 1° F 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 20°F (see paragraph 6.1.4). The configuration as built is shown in Figure 4-32.

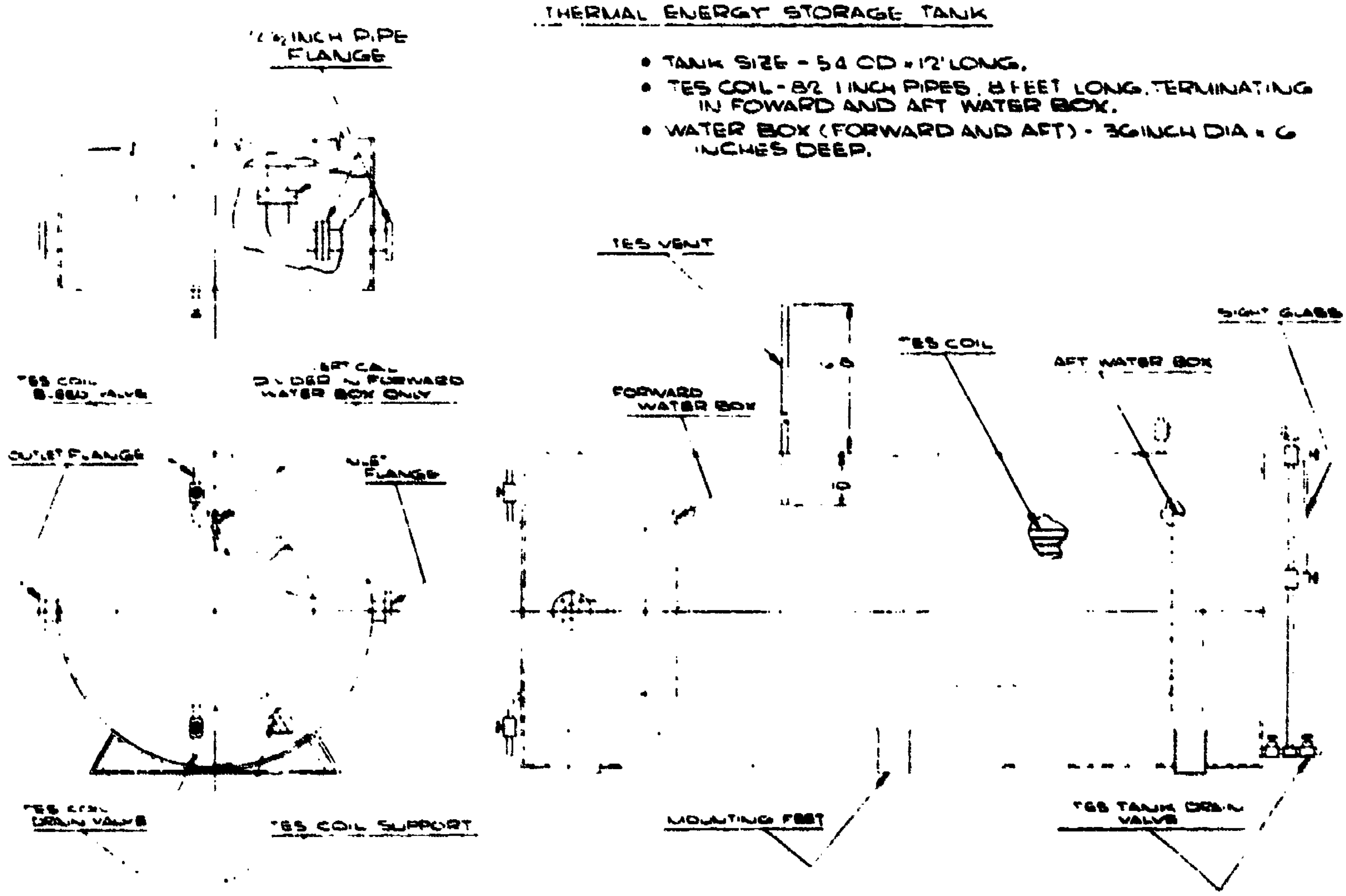

Figure 4-32. Thermal Energy Storage Tank

4.2.4 SYSTEM CONTROLS AND INSTRUMENTATION

4.2.4.1 System Controls

The system control concepts and philosophies were developed essentially in parallel with the piping network discussed in Section 4.2.2. The major design goals were to:

1. Keep the controls as simple as possible
2. Group the control elements in one area
3. Utilize as few active elements as possible
4. Provide functions of delivering, storing and dumping heat from the main loop; heating from the TES; and a lockout function to prohibit pumping heat into the heating units whenever they cannot utilize it, i.e., when they are in a refrigeration air conditioning mode
5. Make the controls fully automatic but with a capability for on site readjustment and a manual override
6. Package the controls as an entity and as "goof proof" as possible

These goals were largely met by the control valve/piping functional network selected and shown in Figure 4-33. This network required five valves; however, use of the third bypass heat exchanger required two additional valves (designated 1B and 1C).

The emphasis on simplicity and a minimum of active elements resulted in a system which carries out all the required functions with five basic operating modes. These modes are described in Table 4-3. There are additional operating modes 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. All of the valves are motorized but operate only in a two position fashion (open/close).

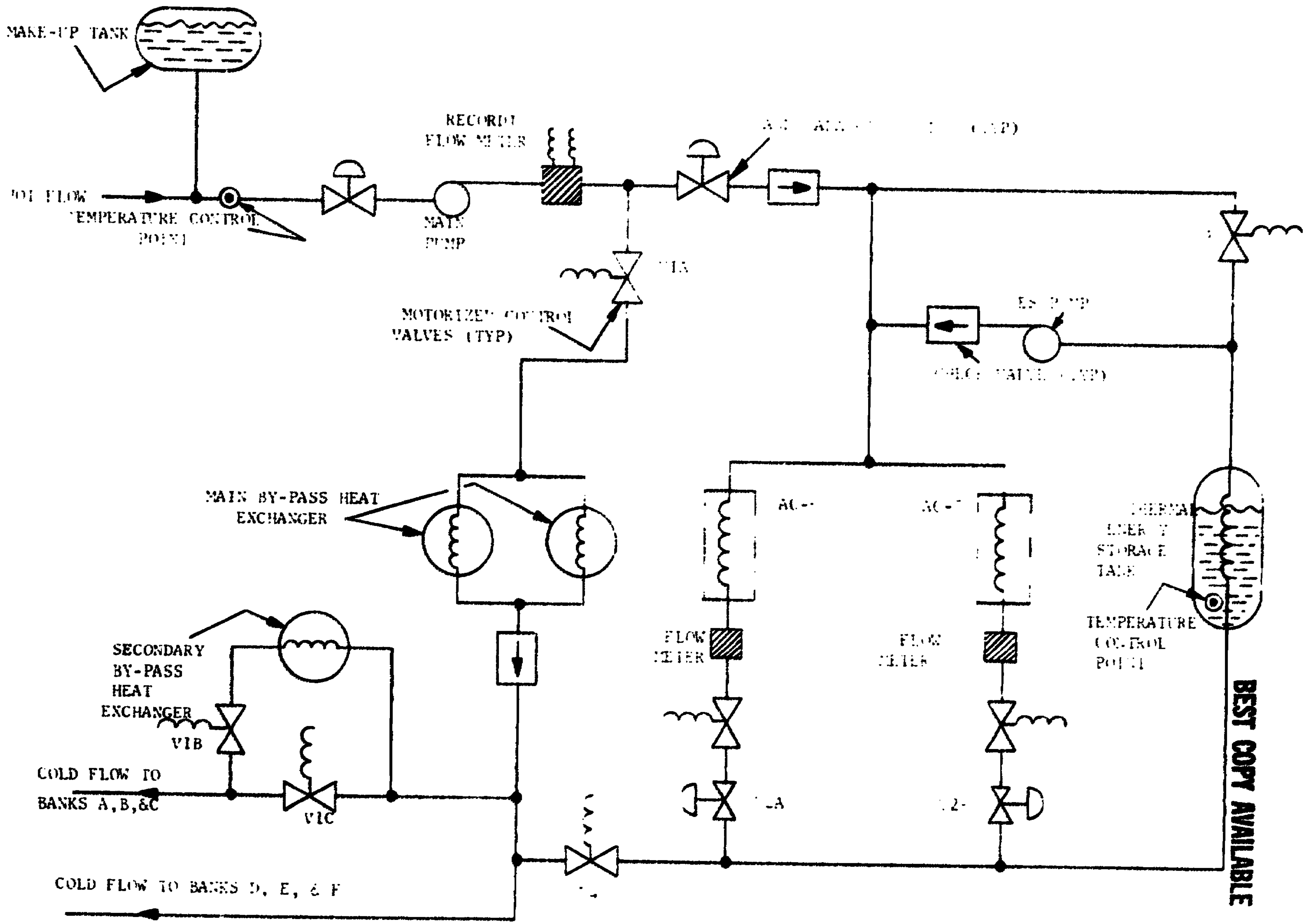

Figure 4-33. Functional Schematic

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Table 4-3. Solar Heating System Basic Operating Modes

Current Condition Existing	Control Position									Physical Description of Condition
			Valve Number							
	Main Pump	TES Pump	1A	1B	1C	2A	2B	3	4	
1. Expansion tank* below 80°F and thermal energy storage tank below 130° F	On	Off	Open	Open	Close	Close	Close	Close	Open	System too cold to provide heat
2. Expansion tank below 80° F but thermal energy storage tank above 130° F	On	On	Open	Open	Close	Open	Open	Close	Close	Collector loop too cold to provide heat but stored heat adequate
3. Expansion tank between 80° F and 145° F	On	Off	Close	Close	Open	Open	Open	Close	Open	Useable to more than adequate heat supplied from collectors
4. Expansion tank above 145° F	On	Off	Close	Close	Open	Open	Open	Open	Open	Significant extra heat being supplied by collectors
5. Expansion tank above 225° F	On	Off	Open	Open	Close	Close	Close	Open	Open	Excessive heat being supplied by collectors

*The expansion tank is a slight misnomer since the control temperature is taken just upstream of the main pump and represents collector outlet temperature.

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 80° F) 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 (described in Section 4.2.3.2) are in a steady stream of 70 to 75° F 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 AC6 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 (225° F) 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 (165° F). Either relay closure within a heating unit results in a closure of the appropriate valve 2.

The temperature set points which determine the operating mode transitions, were chosen empirically during the first two weeks of operation (with the exception of 80° F and 225° F) which were fixed by system considerations). These determinations are discussed in Section 6.1.4.

4.2.4.2 Control Console

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 shortly before 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 110 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 then is shown in Figure 4-34 and 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.

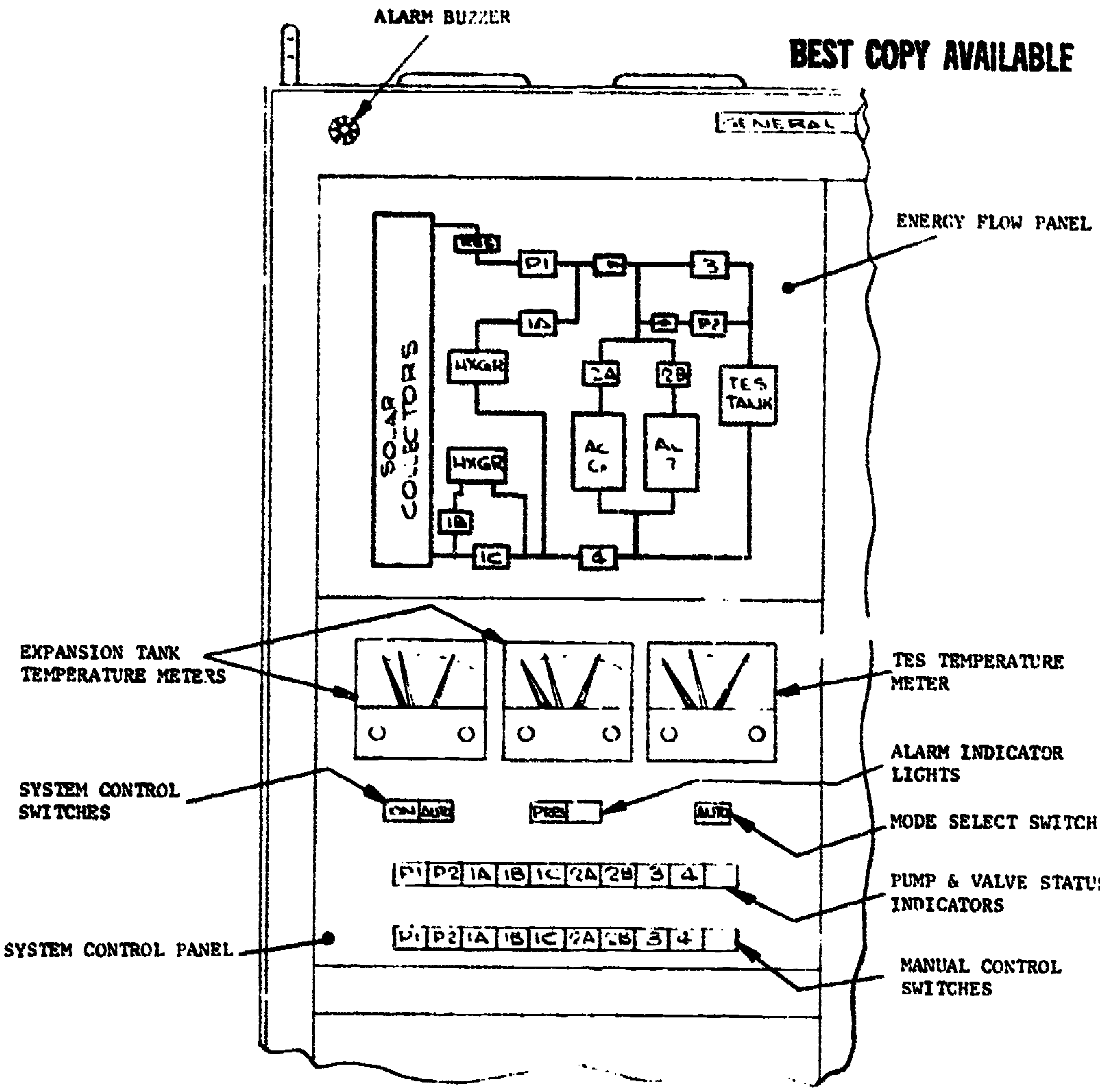

Figure 4-34. Control Portion of Console

4.2.4.3 Instrumentation

The instrumentation is used to obtain data and calculate efficiency. Since the system was to be operated primarily in an unattended mode, the selection criteria were to utilize components which would minimize the need for interpretation; i.e., digital printout, have long term stability, and be reasonably easy for the custodians to monitor and the engineers to analyze. The instrumentation system is completely independent of the control system. The instrumentation consists of thermometers, thermocouples, flow meters, a solar flux sensor, weather instruments, and a data acquisition subsystem. A diagram of the system showing the locations of the various sensing elements is shown in Figure 4-35.

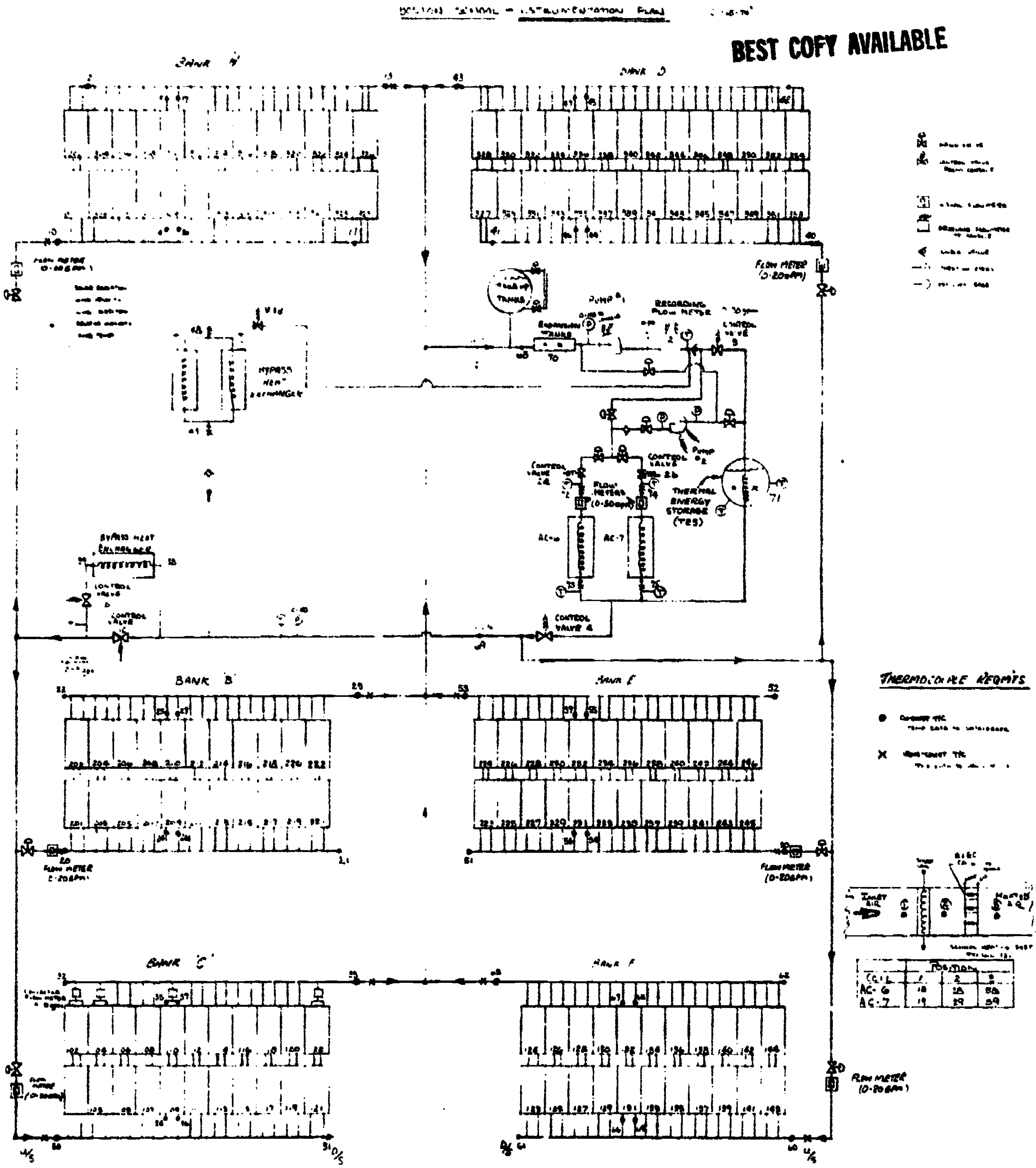

Figure 4-35. Boston School Instrumentation Plan

The data acquisition subsystem is housed in the console bay not occupied by the control system and is shown pictorially in Figure 4-36. 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 Datalogger which scans 100 channels every 30 minutes. The instantaneous data displays provide visual indications of the current operating condition of the system. The recorded data is annotated by the school custodian normally three times per day (time and date for later usage) and the collected data is returned to Valley Forge, Pa. normally once per week. 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 2.0 inches wide, pressure sensitive paper driven at 1.0 inch 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. Valv 1A Open/Close
   f. Valve . 3 Open/Close
   g. Valve 1C Open/Close
   h. Spare Channel
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.

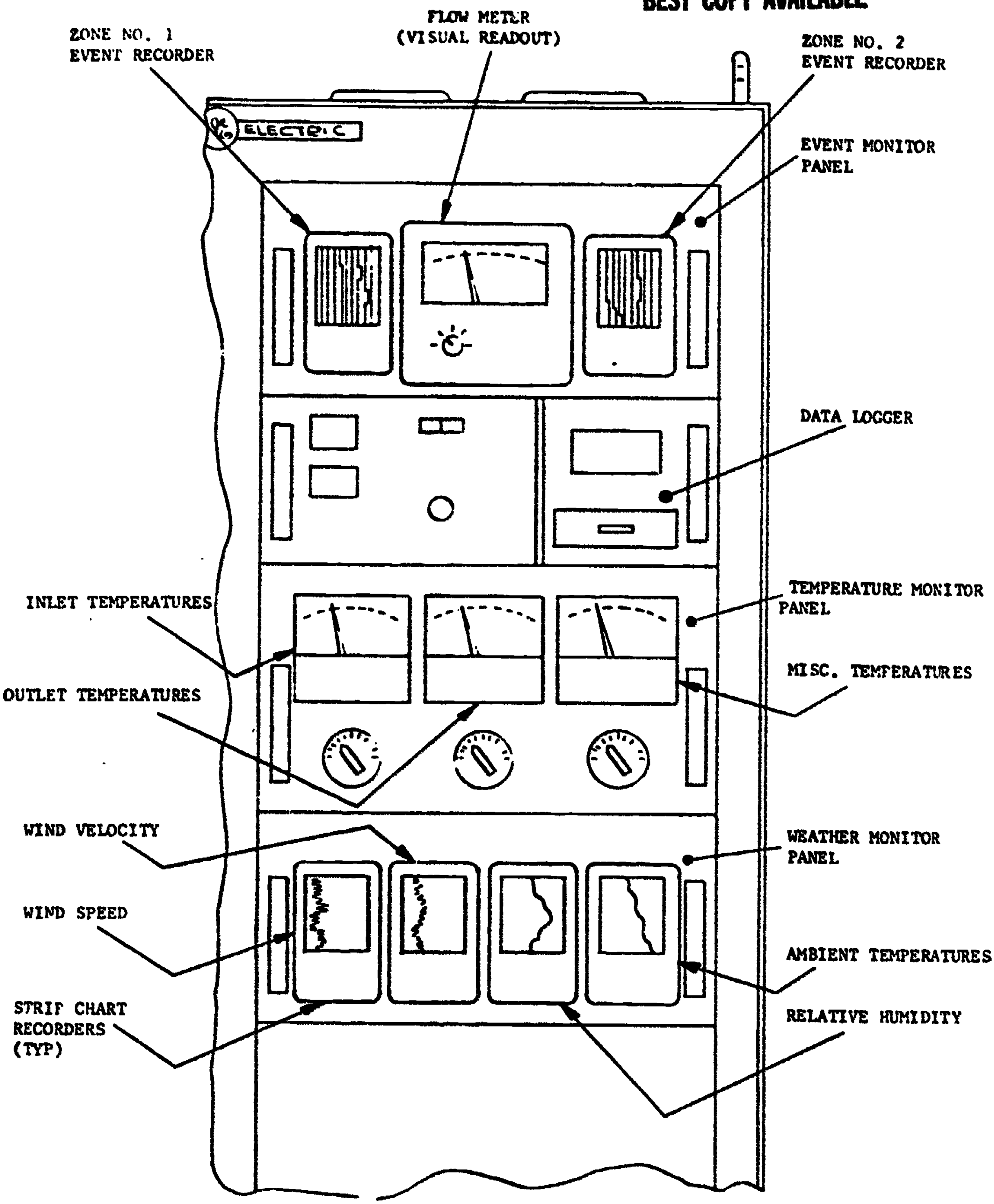

Figure 4-36. Data Acquisition Portion of Console

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. Useage of thermocouples with the datalogger as opposed to other temperature measuring devices, eliminated compensation for lead lengths, calibration as installed, and susceptability to power supply fluctuations. In addition, premium thermocouple wire with a guaranteed accuracy of $\pm .75^{\circ}F$ was utilized and was routed along the steel support structure and through dedicated conduits. This provided such an effective electromagnetic shield that no "noise" was discernable even on the longest leads when a neighboring elevated train passed. The 100 channels of data are recorded sequentially on printed paper every 30 minutes which is a marginal frequency for insolation but adequate for the other data. There is approximately a two day supply of paper in the datalogger and, as a consequence, the school custodian periodically both annotates and reloads the datalogger paper. The first two millivolt channels are utilized for solar flux and loop flow rate and Channels 3 through 9 are unallocated presently. Channels 10 through 75 are various system temperatures and Channels 76 through 99 are detail temperatures obtained from within four instrumented collector panels. A detailed list is provided in Table 4-4.

The instantaneous data displays are not recorded and are intended primarily for 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.

The specific locations of the 30 iron/constantan thermocouples is also shown in Figure 4-35. As can be seen from the figure, the iron/constantan thermocouples are redundant to the copper/constantan thermocouples. The original objective was to provide redundancy as well as a check on the more significant system instrumentation. However, the redundant instrumentation line feature had to be sacrificed due to unavailability of copper/constantan panel "thermometers" within the required schedule.

Table 4-4. Data Logger Channel Assignments

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Channel	Data Point Location	
0	Internal Calibration	
1	Pyranometer (Epply 8-48)	
2	System Flow Meter	
3	Unallocated spares	
4		
5		
6		
7		
8		
9		
10	Bank "A"	Inlet Manifold Up-Stream
11		Inlet Manifold Down-Stream
12		Outlet Manifold Up-Stream
13		Outlet Manifold Down-Stream
14		Collector 309 Up-Stream
15		Collector 310 Up-Stream
16		Collector 309 Down-Stream
17	Bank "A"	Collector 310 Down-Stream
18	AC-6 Inlet Air	
19	AC-7 Inlet Air	
20	Bank "B"	Inlet Manifold Up-Stream
21		Inlet Manifold Down-Stream
22		Outlet Manifold Up-Stream
23		Outlet Manifold Down-Stream
24		Collector 209 Up-Stream
25		Collector 210 Up-Stream
26		Collector 209 Down-Stream
27	Bank "B"	Collector 210 Down-Stream
28	AC-6 Solar Coil Air Exit	
29	AC-7 Solar Coil Air Exit	
30	Bank "C"	Inlet Manifold Up-Stream
31		Inlet Manifold Down-Stream
32		Outlet Manifold Up-Stream
33		Outlet Manifold Down-Stream
34		Collector 109 Up-Stream
35		Collector 110 Up-Stream
36		Collector 109 Down-Stream
37	Bank "C"	Collector 110 Down-Stream
38	Main Heat Exchanger Inlet	
39	Main Heat Exchanger Outlet	
40	Bank "D"	Inlet Manifold Up-Stream
41		Inlet Manifold Down-Stream
42		Outlet Manifold Up-Stream

Table 4-4. Data Logger Channel Assignments (Continued)

Channel	Data Point Location
43	Bank "D" Outlet Manifold Down-Stream
44	Collector 333 Up-Stream
45	Collector 334 Up-Stream
46	Collector 333 Down-Stream
47	Bank "D" Collector 334 Down-Stream
48	Secondary Heat Exchanger Inlet
49	Secondary Heat Exchanger Outlet
50	Bank "E" Inlet Manifold Up-Stream
51	Inlet Manifold Down-Stream
52	Outlet Manifold Up-Stream
53	Outlet Manifold Down-Stream
54	Collector 233 Up-Stream
55	Collector 234 Up-Stream
56	Collector 233 Down-Stream
57	Bank "E" Collector 234 Down-Stream
58	AC-6 Hot Deck
59	AC-7 Hot Deck
60	Bank "F" Inlet Manifold Up-Stream
61	Inlet Manifold Down-Stream
62	Outlet Manifold Up-Stream
63	Outlet Manifold Down-Stream
64	Collector 133 Up-Stream
65	Collector 134 Up-Stream
66	Collector 133 Down-Stream
67	Bank "F" Collector 134 Down-Stream
68	Solar System Supply
69	Solar System Return
70	Expansion Tank
71	Thermal Energy Storage Tank
72	AC-6 Input
73	AC-6 Output
74	AC-7 Input
75	AC-7 Output
76	Collector 101 Inner Window
77	Outer Window
78	Inlet of Absorber Plate
79	Middle of Absorber Plate
80	Outlet of Absorber Plate
81	Collector 101 Pan Rear Surface

Table 4-4. Data Logger Channel Assignments (Continued)

Channel	Data Point Location
82	Collector 102 Inner Window
83	Outer Window
84	Inlet of Absorber Plate
85	Middle of Absorber Plate
86	Outlet of Absorber Plate
87	102 Pan Rear Surface
88	103 Inner Window
89	Outer Window
90	Inlet of Absorber Plate
91	Middle of Absorber Plate
92	Outlet of Absorber Plate
93	103 Pan Rear Surface
94	104 Inner Window
95	Outer Window
96	Inlet of Absorber Plate
97	Middle of Absorber Plate
98	Outlet of Absorber Plate
99	Collector 104 Pan Rear Surface

4.2.5 ARCHITECT ENGINEERING TASKS

A Philadelphia based Architectural Engineering Firm, Ballinger, was subcontracted to provide consultation as required, generate the structural design and the various drawings required for construction, and assist in the selection of a general contractor. Construction drawings of the Cleveland School were provided to Ballinger and they participated in the familiarization/school selection tours.

4.2.5.1 Structural Design

The structural support system was required to locate, and retain in their proper relationships, the collection and distribution subsystems. Further, it was required to transmit, to the buildings primary structural system, all vertical and horizontal loads imposed by the collection and distribution systems.

The principal design constraints were as follows:

1. The roof's horizontal framing system did not have sufficient reserve capacity to support the additional vertical loads of the collection and distribution systems.

2. The skylights initially appeared to offer closely spaced support points, and therefore an economical support system. However, detailed analysis revealed that the skylights were roof-supported, could not accept additional stresses, and must in fact be isolated from additional stresses; in other words, they hindered rather than helped the design.

3. Corollary to Constraint 2, the building's columns were revealed to be on 50 foot centers, east to west, rather than the 25 foot spacing suggested by the skylights, and on a random spacing along the north to south lines.

4. The entire building framing system was composed of relatively light members, including trussed girders and tube columns. This is efficient in terms of meeting basic performance requirements with minimal material, but does not lend itself to modification for superimposed stresses.

5. Collector panels were available only in a size of 4 feet x 8 feet; the required collector area and the available roof area dictated 16 foot high collector banks. The collector panels required support only on the 8 foot dimension and could span the 4 foot dimension without external support.

6. The time available for construction dictated the use of "off-the-shelf" framing members, and immediately available techniques and skills.

7. The structure was required to be removable, to the greatest extent possible; and preferably in its entirety.

Design and construction proceeded simultaneously. A visual analysis of the building structure was made by Ballinger structural engineers. Since the school contract construction drawings were of the "performance" type, specific roof members were not delineated or described therein. Fabricator's shop drawings were not sufficiently detailed to permit quantitative analysis of all roof framing members and connections. Interface details were therefore designed on the basis of conservative engineering judgment, and reflect the experience of both Ballinger and Boston Public Facilities Department engineers.

Quantitative analysis of the building columns and footings was possible, and indicated a modest reserve capacity, sufficient to accept the additional loads imposed by the proposed Solar Heating System. The design concept thus developed as a longspan structure, bridging between columns, and carrying subframes to which the collection and distribution components could be attached.

The constraints imposed by the project schedule precluded more sophisticated truss support techniques which would have been evaluated had time permitted.

- Steel trusses required design and fabrication time which was not available.
- Structural aluminum members, and their fabrication techniques, were not readily available.

Accordingly, the system was based on readily available hot-rolled structural steel shapes, and techniques familiar to local fabricators and erectors.

The resulting design utilized rolled steel wide flange girders to span the 50 foot distance between column lines and located to suit the collector panels. The girders were in turn supported by wide flange members on the north-south column lines, extending to the maximum number of available building columns, for maximum distribution of new loads. Steel tube posts were welded to tops of the building columns, and detailed to receive the new horizontal framing members. At the posts, the existing roof was removed, rebuilt, and flashed into the posts for permanent weather-tightness. With the concurrence of the Boston Public Facilities Department, the posts will remain in place.

The structure was then stiffened in the horizontal plane with diagonal bracing members. This minimized wracking strains on the collector panels and piping, and improved distribution and predictability of horizontal loads imposed on the building structure.

The collector panels and adjacent piping were supported by trussed "A" frames at nominal 8 foot intervals, and inclined beams at the intermediate 4 foot lines. This superstructure was X-braced for lateral stability. The collector panels were assumed to be self-supporting, but to contribute nothing to the rigidity of the total assembly.

With the exception of the weldment of the posts to the building columns, all field connections were made with high strength bolts.

Member sizes and connection details were kept constant over wide ranges, to simplify fabrication. The improved speed and reliability of fabrication were considered to justify the additional material used.

4.2.5.2 Construction Drawings

Ballinger prepared construction drawings designated as P-7400-101, 201, 202, 203, 204, 301, and 401 which are shown in Figures 4-37 through 4-43 respectively.

These drawings were provided to both Boston School and facilities personnel as well as the constructing contractors. There was a significant liaison activity and detail modifications were made as required by field conditions, material availability, etc.

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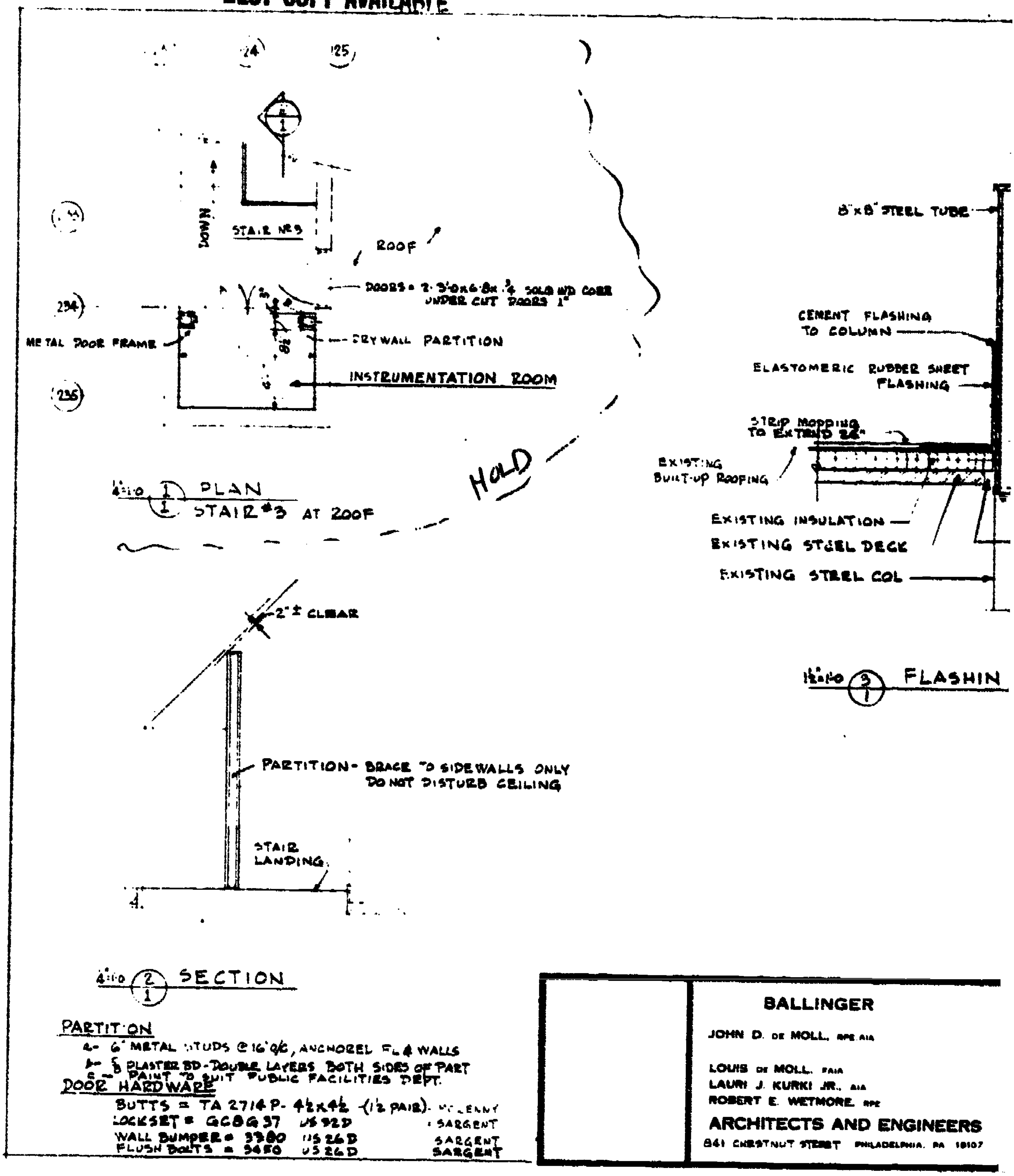


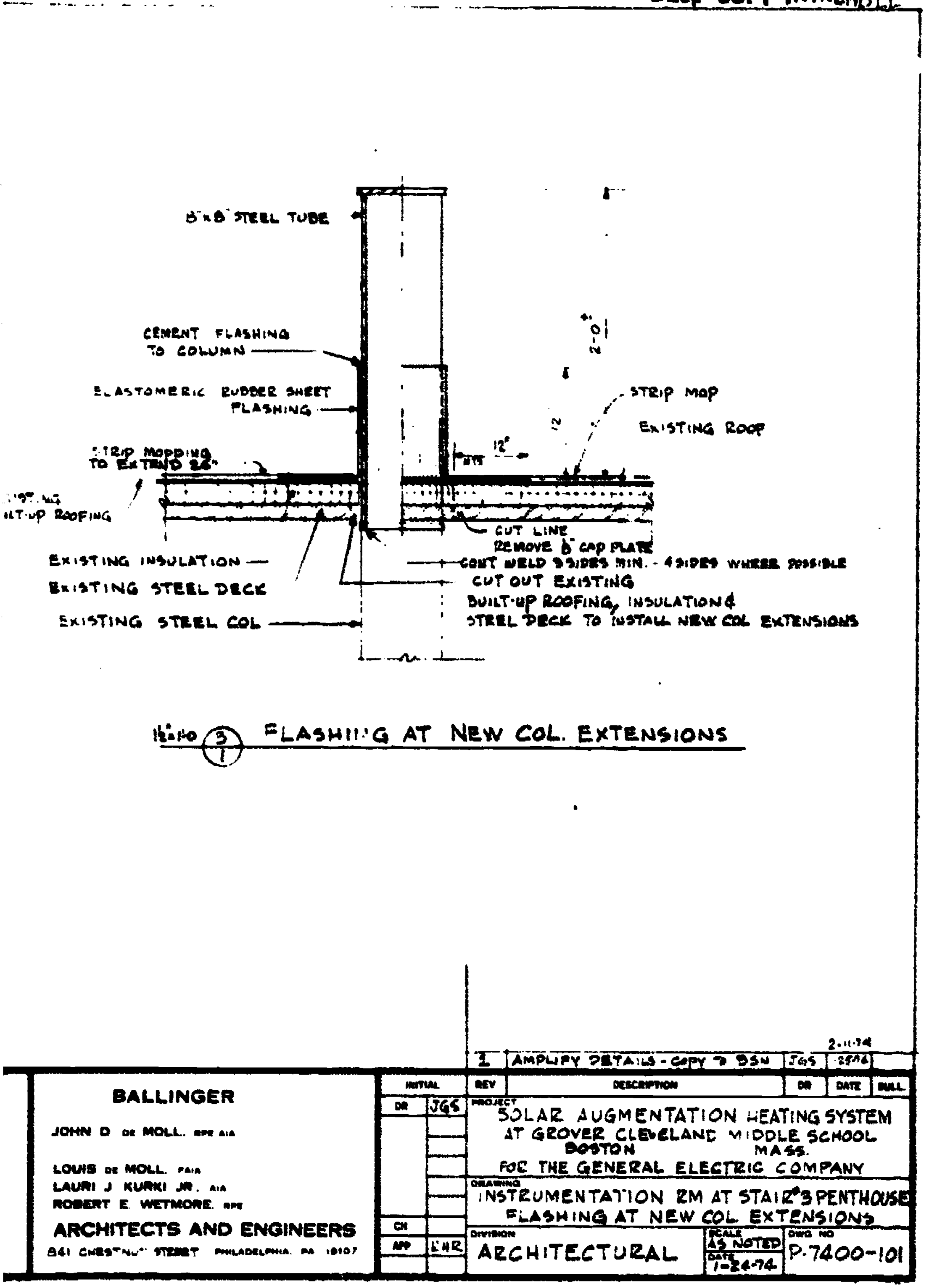
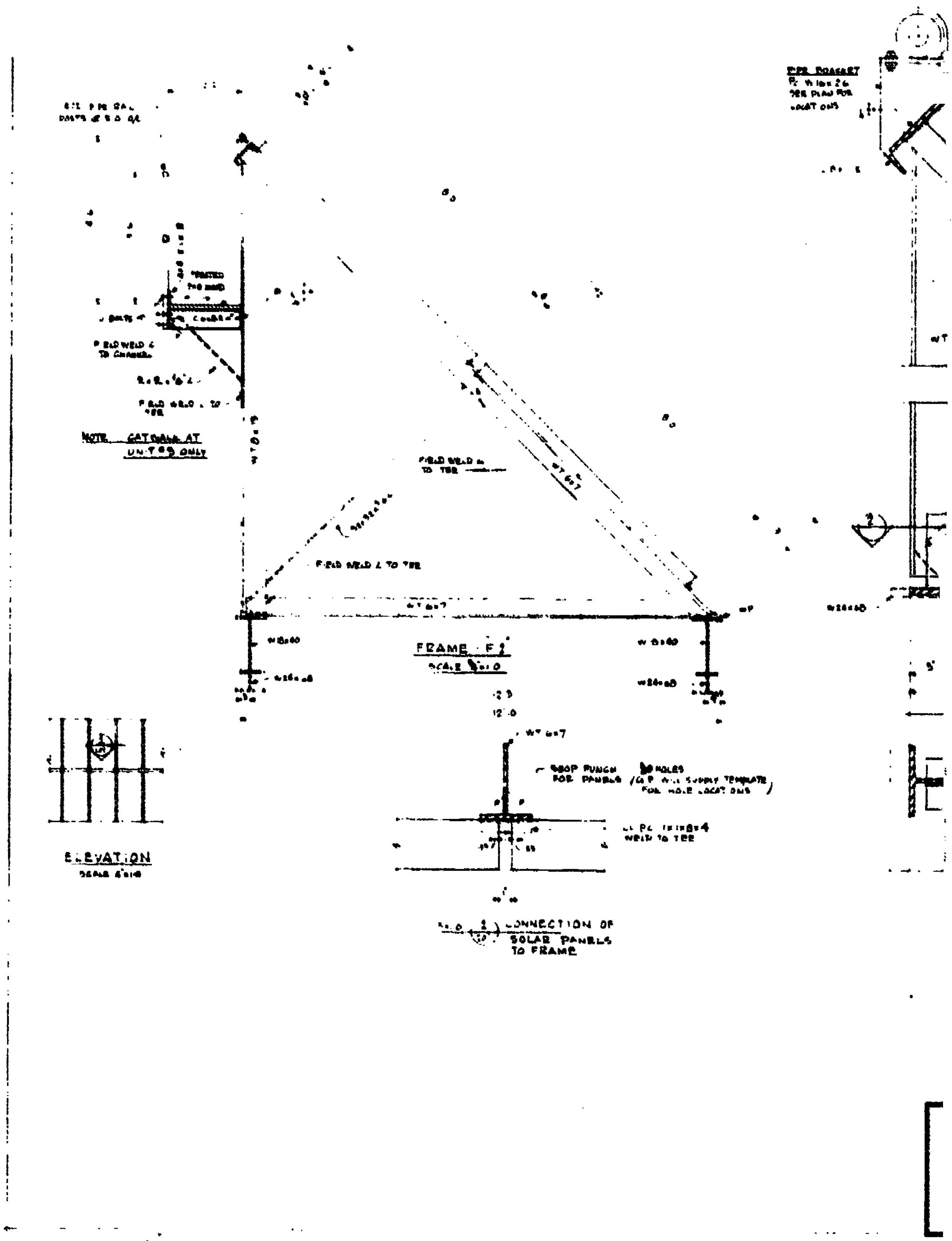


Figure 4-37. Instrumentation RM at Stairwell #3 Penthouse. Flashing at New Column Extensions Ballinger Dwg P-7400-101


FIELD WELD L TO TEE
ELEVATION
CONNECTION OF
SOLAR PANELS
TO FRAME

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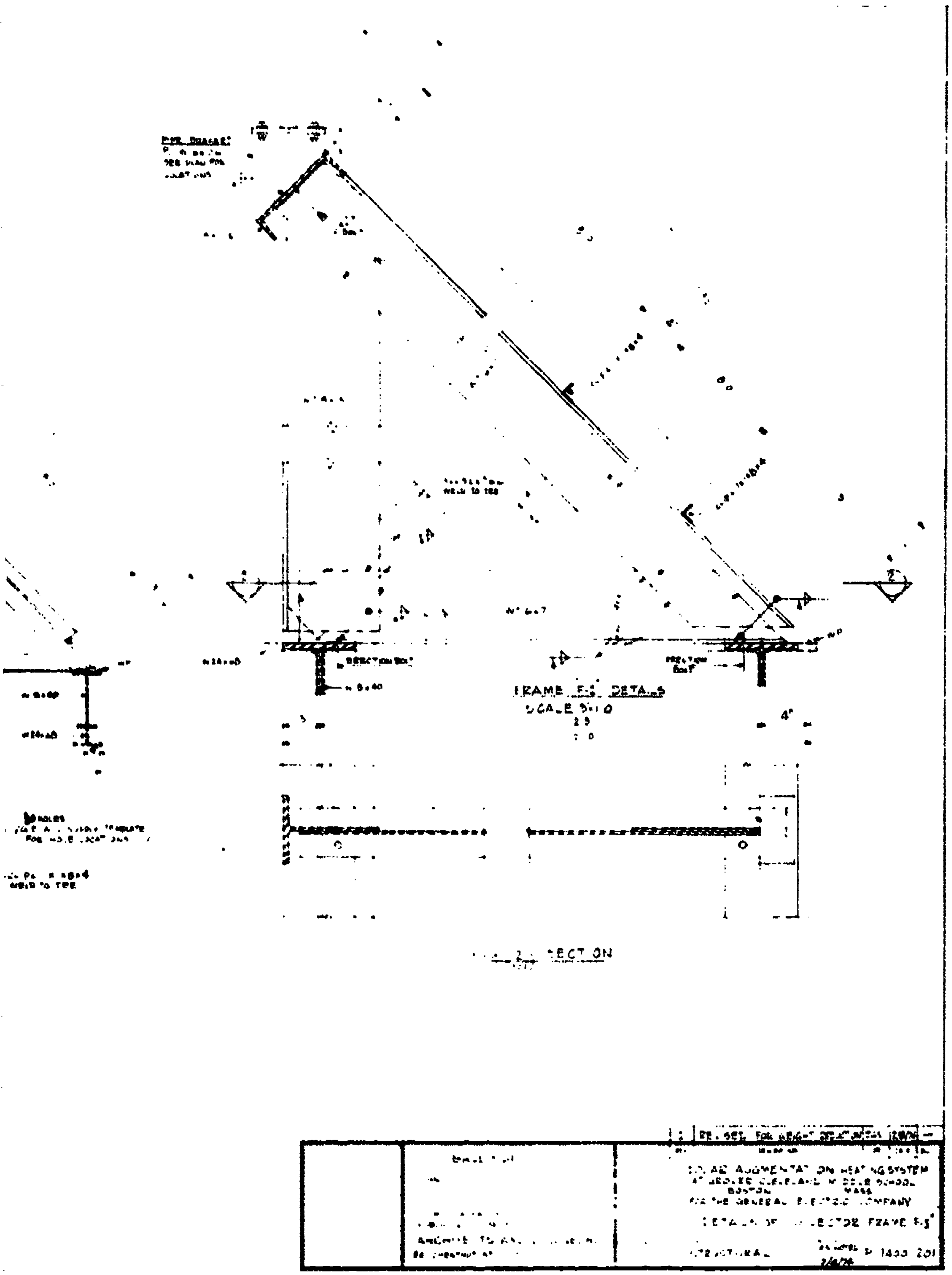
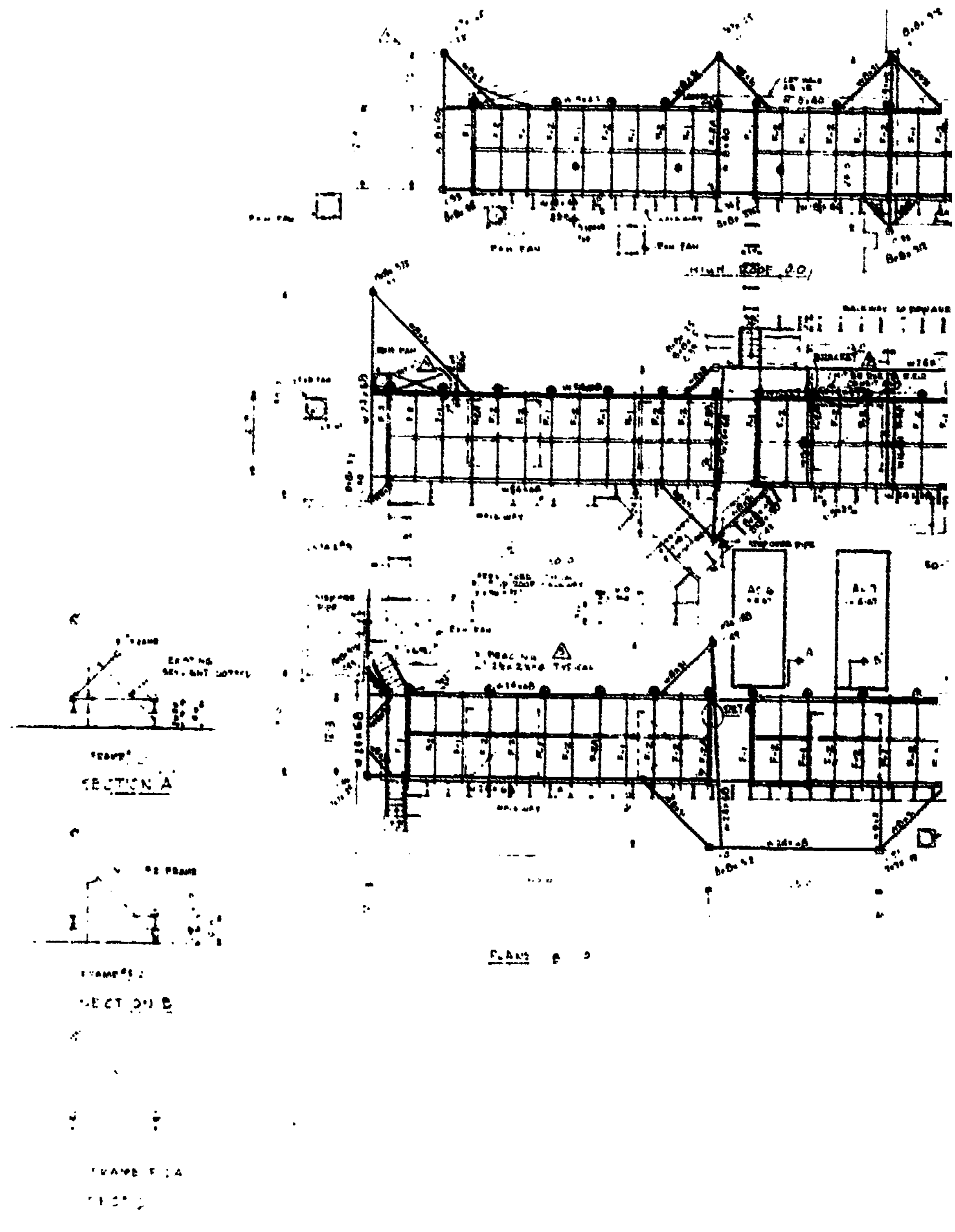


Figure 4-38. Details of Collector Frame F-1, Ballinger Dwg P-7400-201


SECTION A
HIGH ROOF

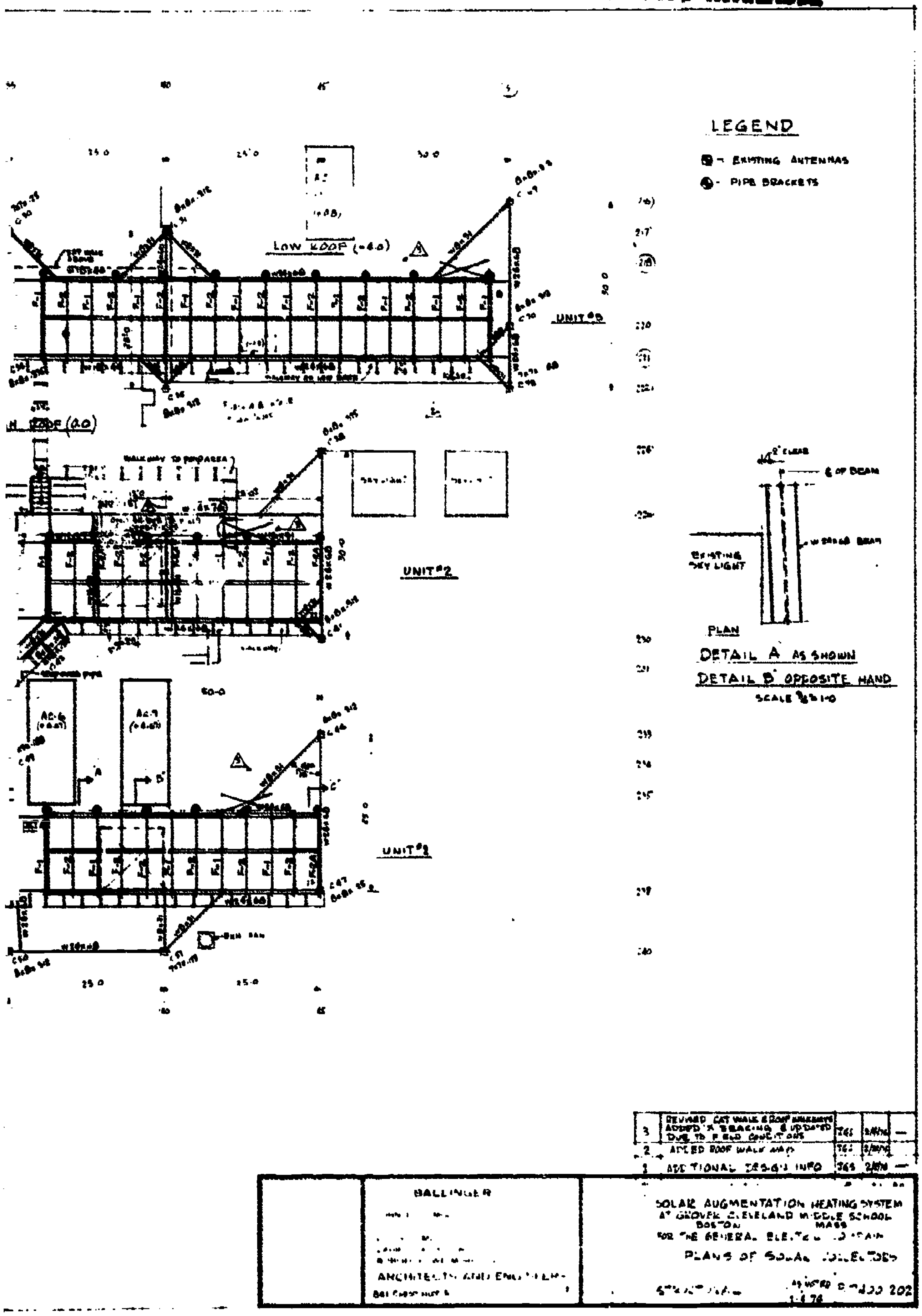
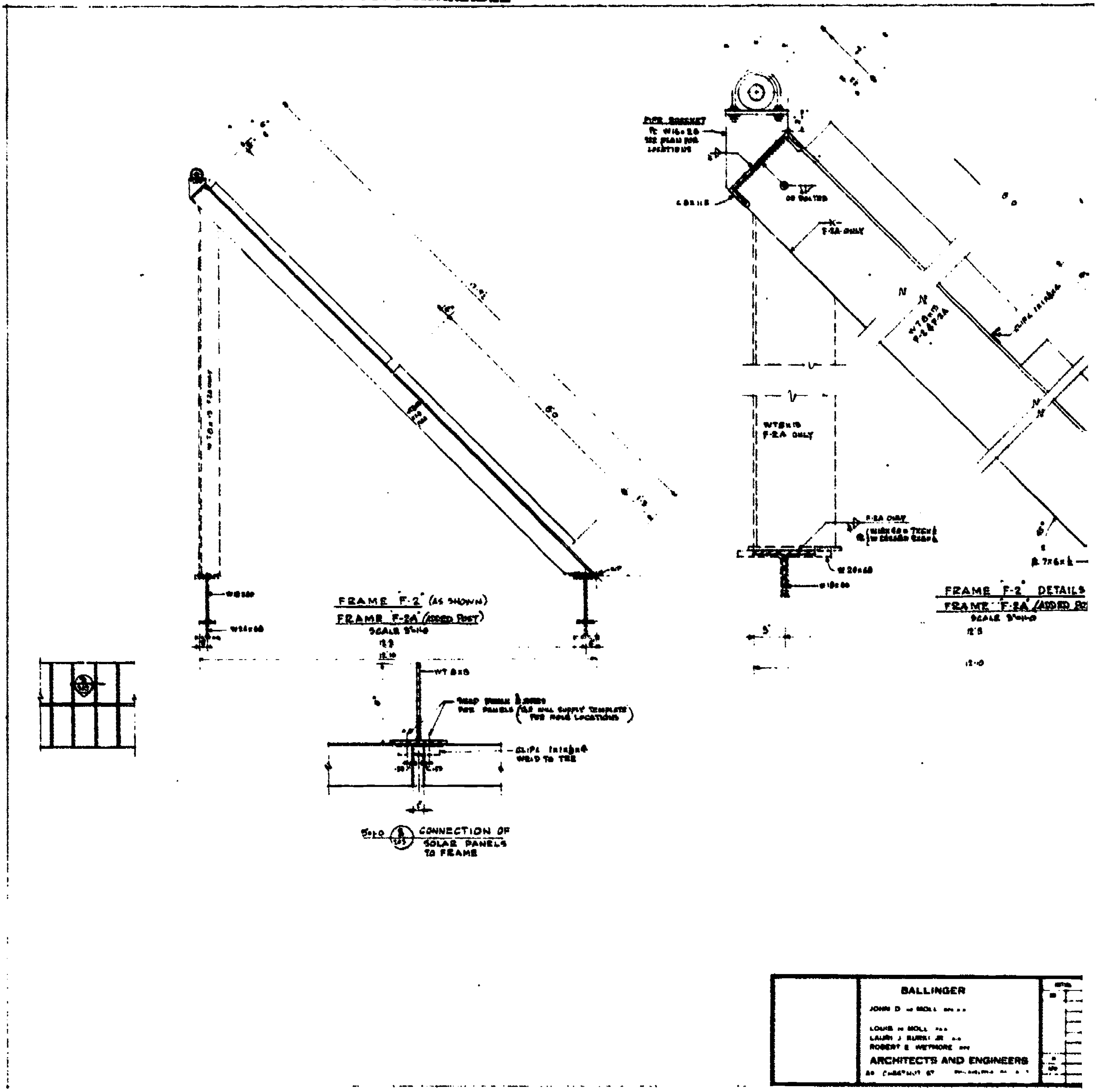


Figure 4-39. Plans of Solar Collectors, Ballinger Dwg P-7400-202


PIPE BRACKET
F-2A ONLY
F-2A ONLY
FRAME F-2 (AS SHOWN)
FRAME F-2A (ADDED POST)
CONNECTION OF SOLAR PANELS TO FRAME
FRAME F-2 DETAILS
BALLINGER
ARCHITECTS AND ENGINEERS

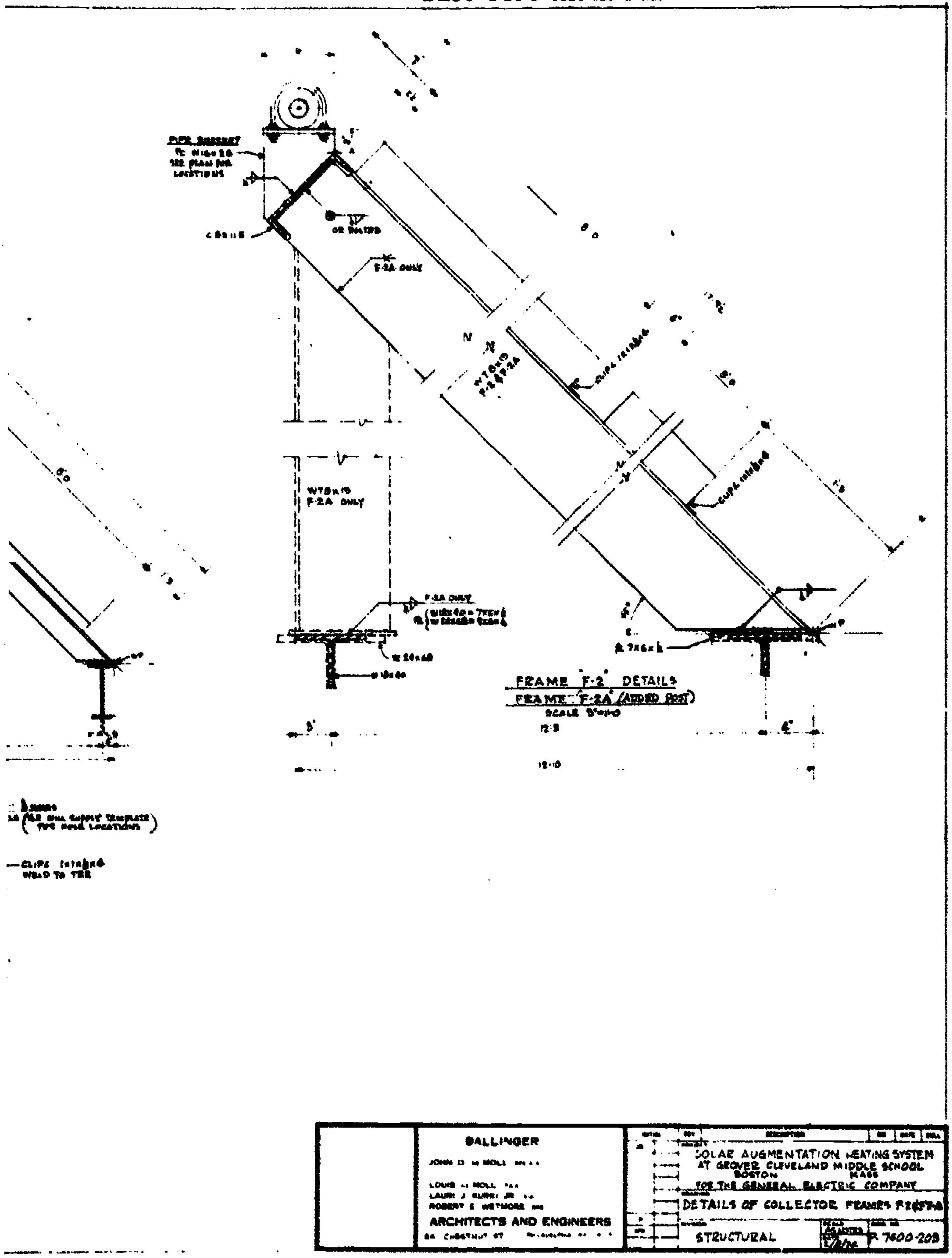


Figure 4-40. Details of Collector Frames F2 & F2-A, Ballinger Dwg P-7400-203

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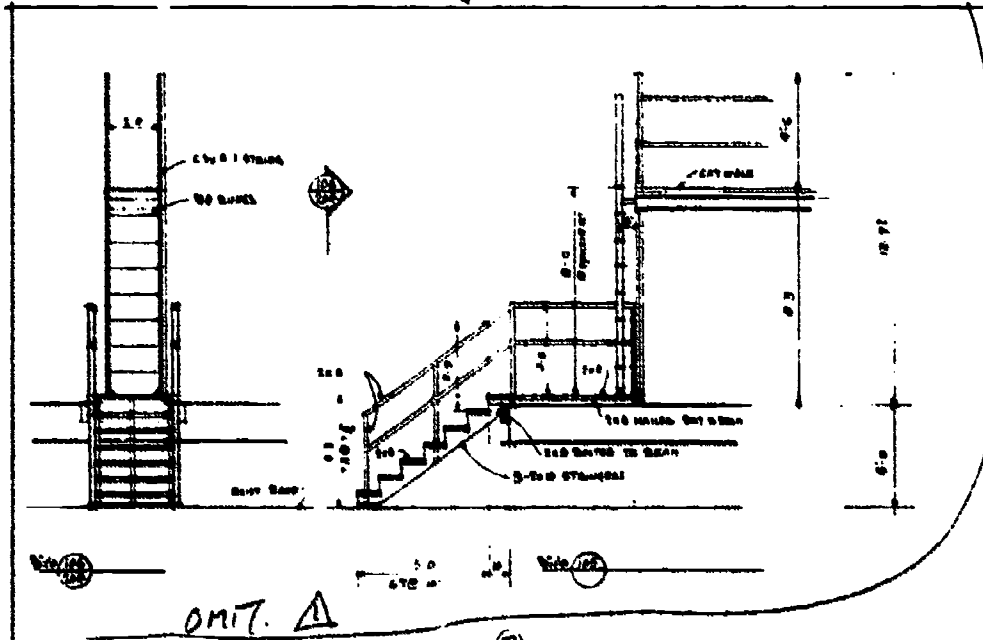
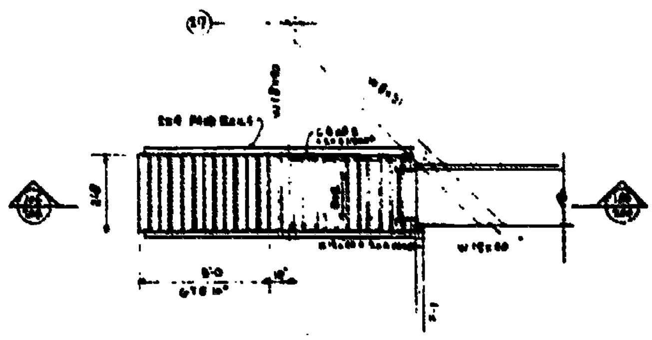
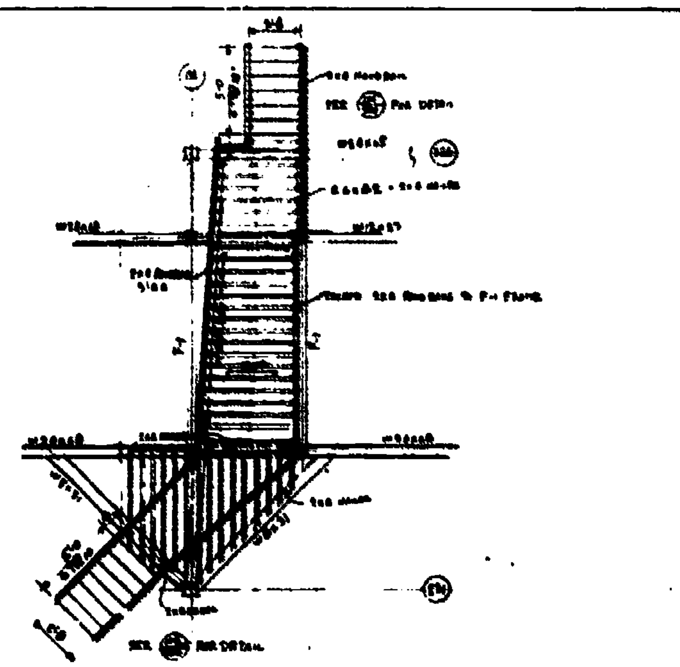


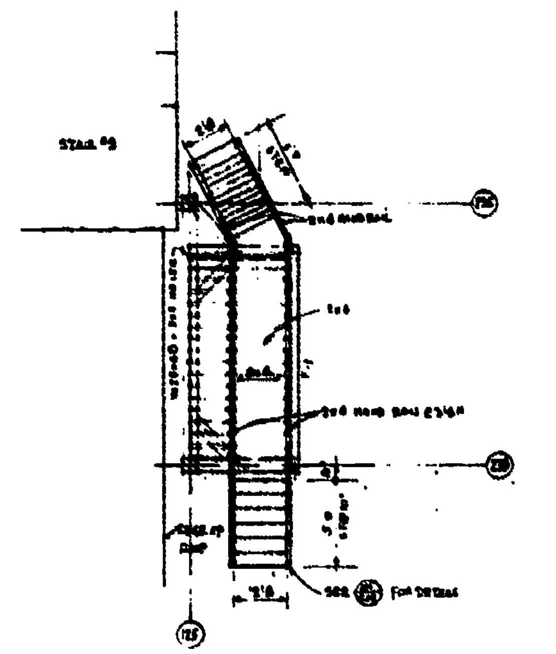


PLAN

STAIR TO CATWALK @ UNIT #3



PLAN OF WALKWAY @ UNIT #2



PLAN OF WALKWAY @ UNIT #1

BALLINGER

ARCHITECTS AND ENGINEERS

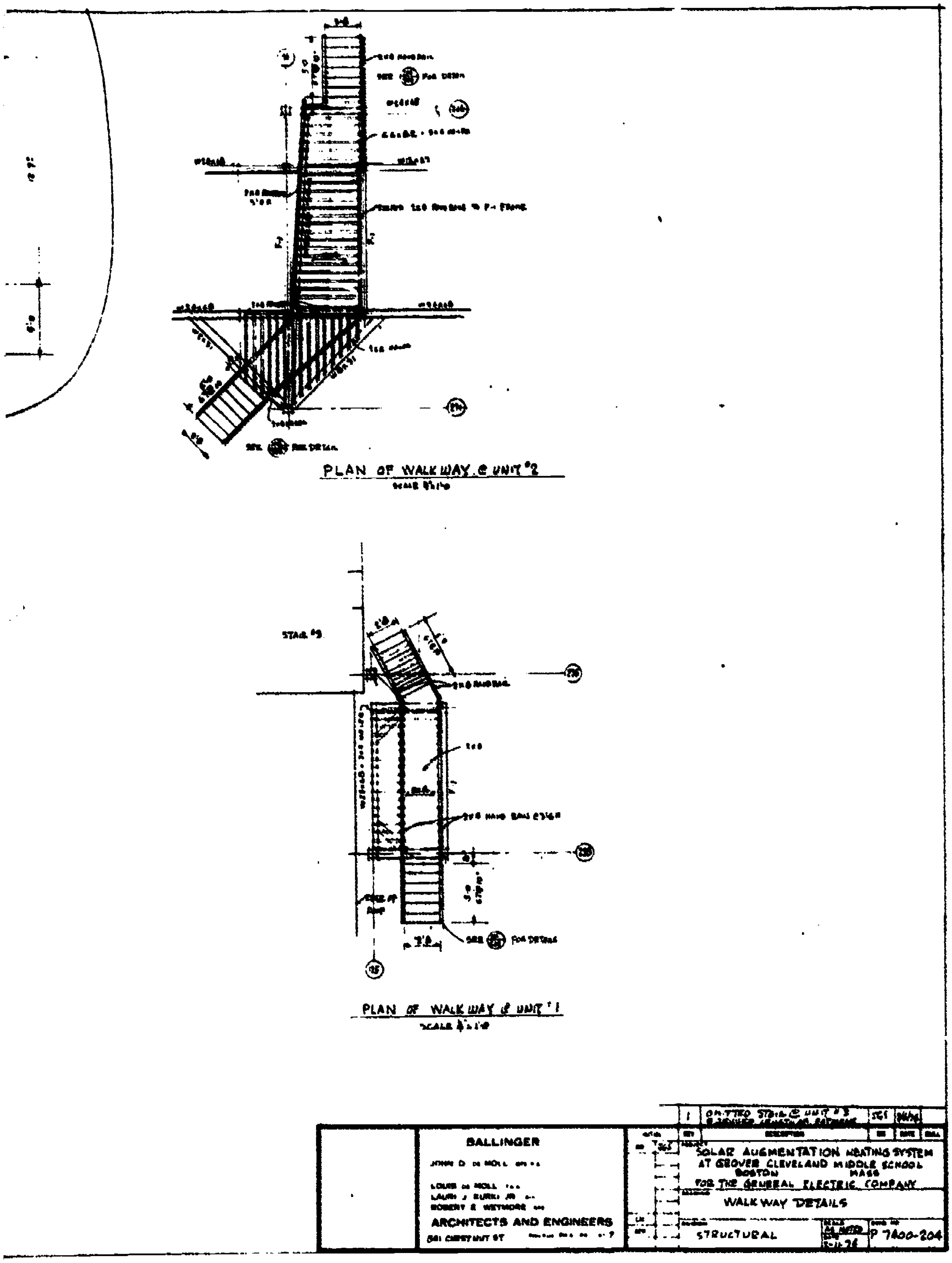


Figure 4-41. Walkway Details, Ballinger Dwg. P-7400-204

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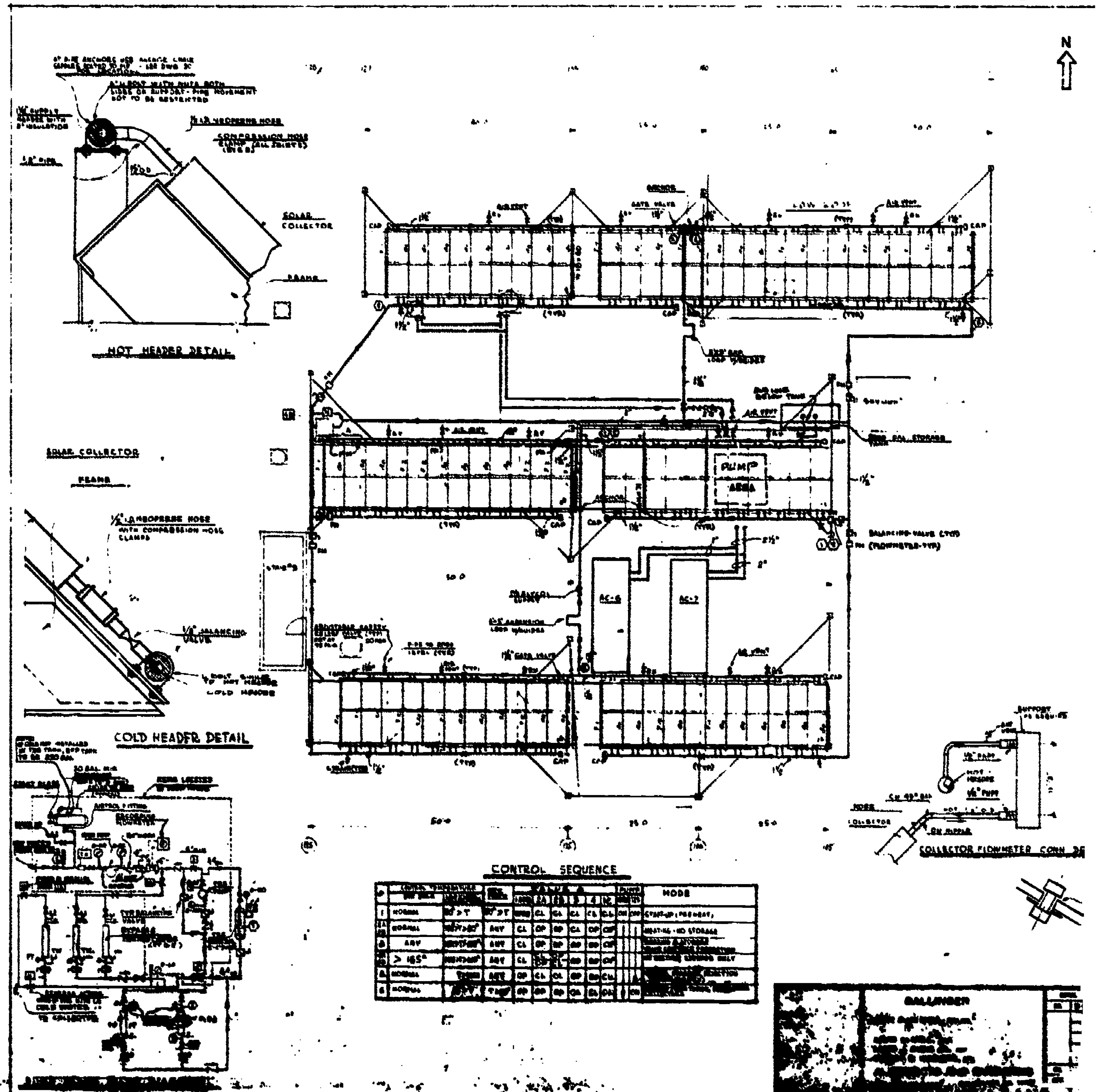

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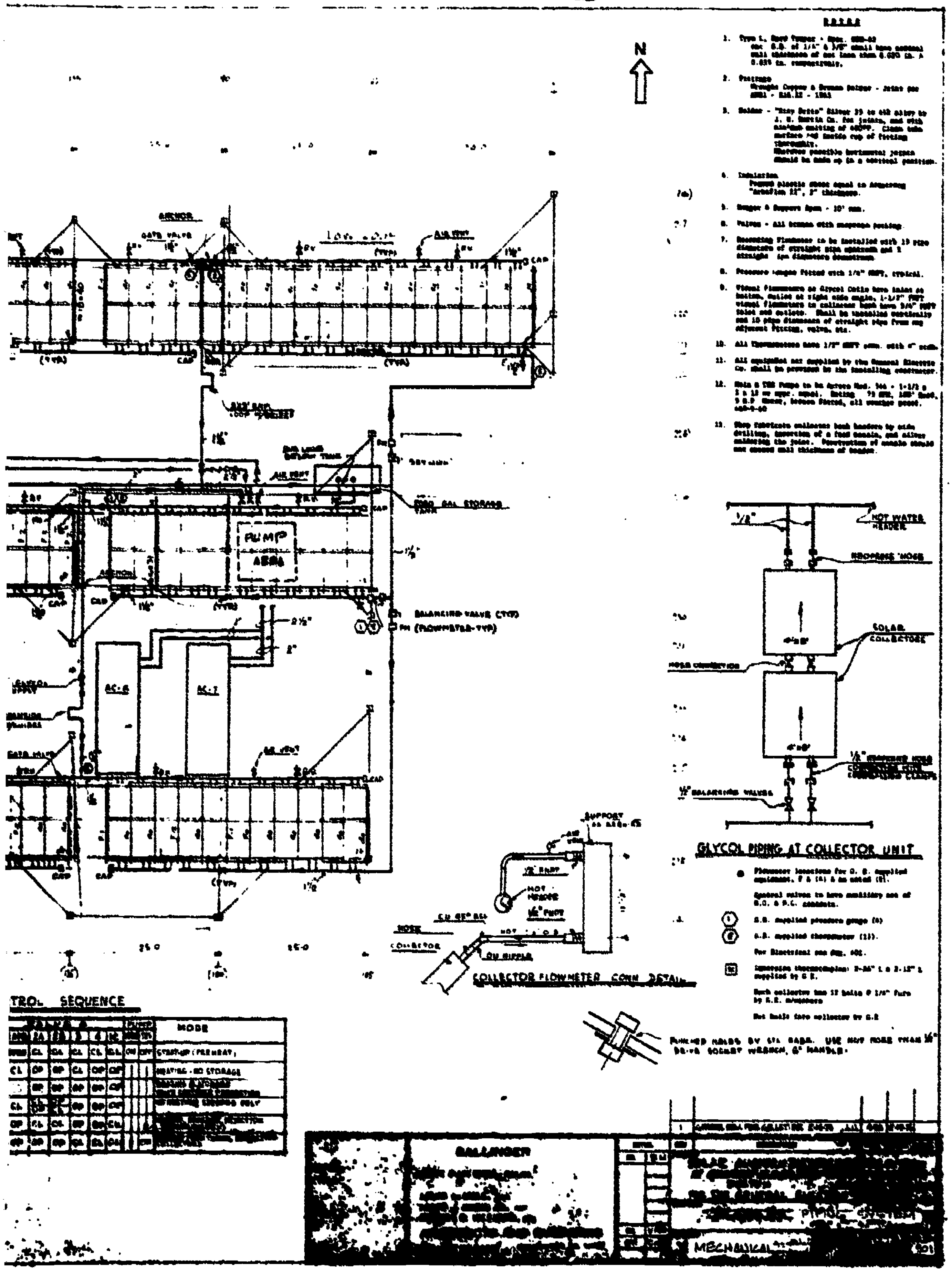

Figure 4-42. Plans of Piping System, Ballinger Dwg P-7400-301

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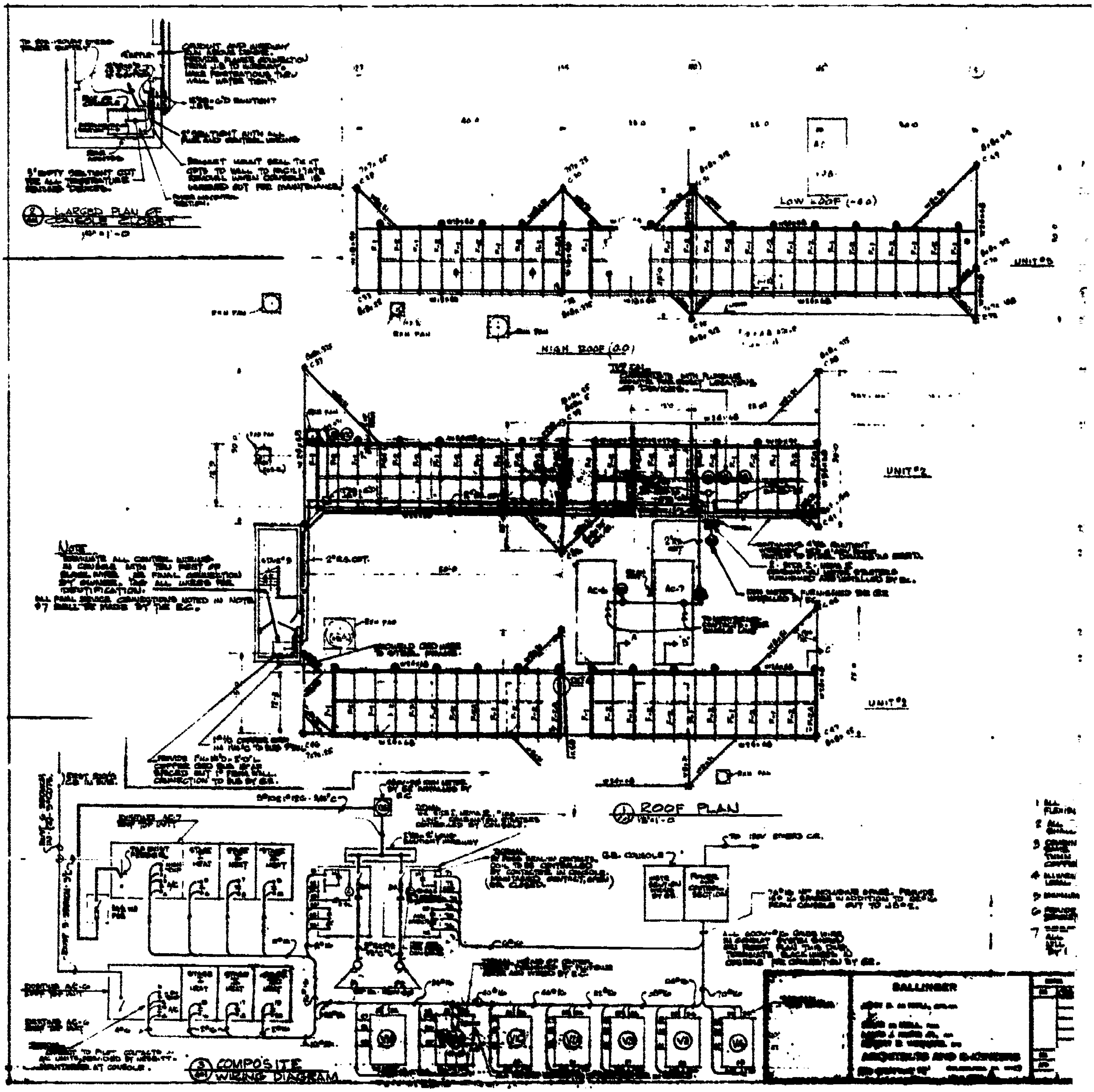

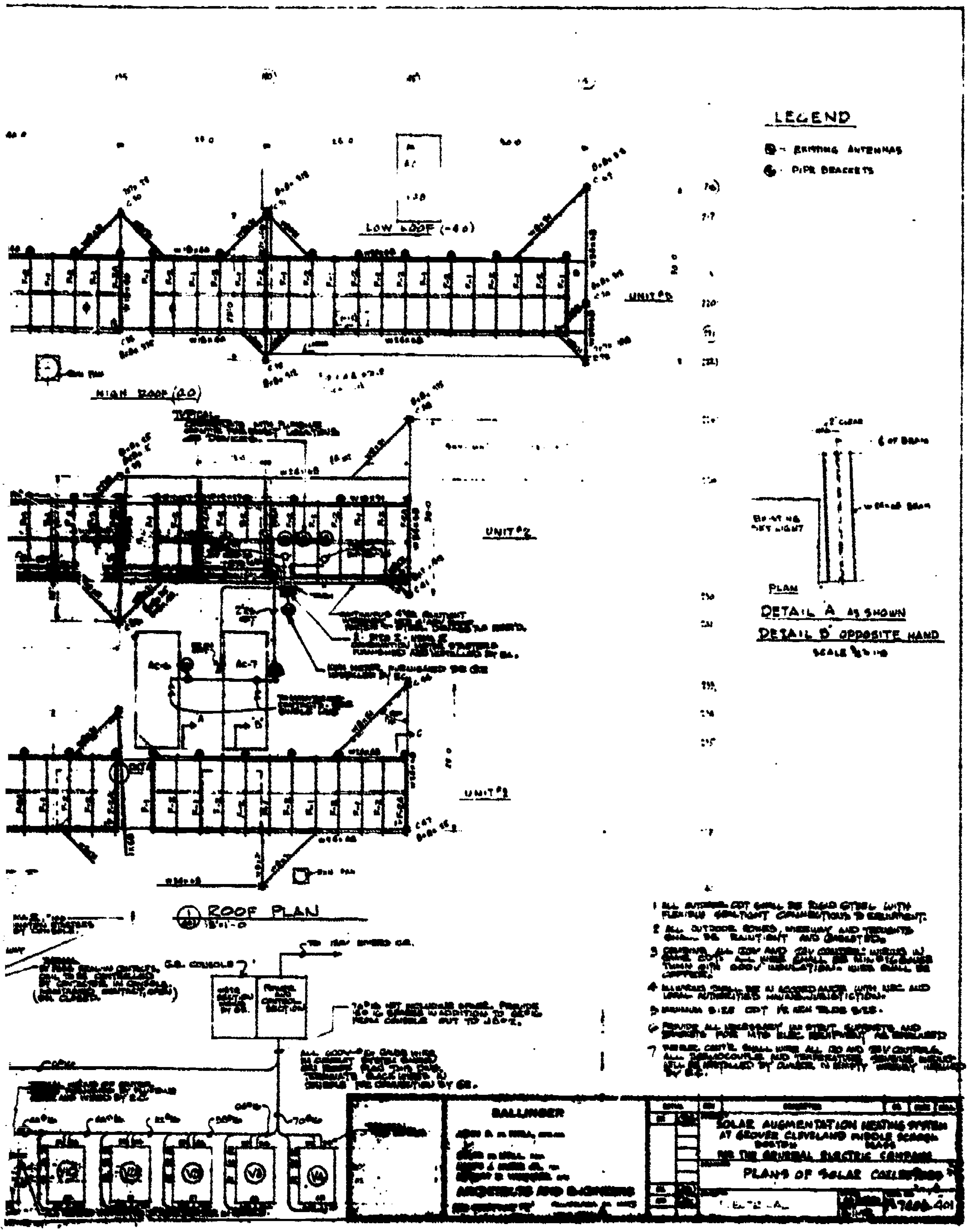

Figure 4-43. Plans of Solar Collectors, Ballinger Dwg P-7400-401

SECTION 5 **BEST COPY AVAILABLE**

SYSTEM FABRICATION AND INSTALLATION

The schedule for the fabrication and delivery of various components and the installation/construction of the experiment on the roof of the Grover Cleveland School is given in Figure Figure 5.1.

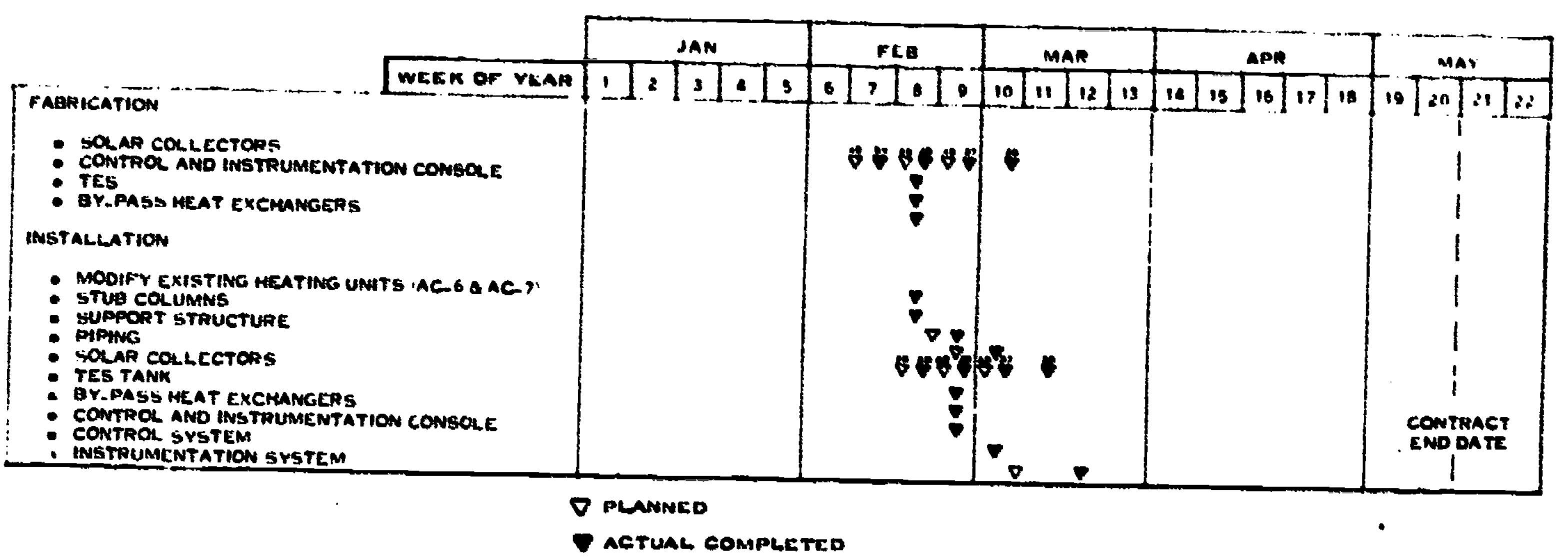

Figure 5-1. System Fabrication and Installation Schedule

5.1 COLLECTOR FABRICATION EXPERIENCE

Considering the fact that the first prototype collectors were completed only five weeks after program start, fabrication problems were minimal. Problems worthy of note are discussed briefly below.

5.1.1 WINDOWS

After approximately a week's delay in material shipment due to the trucking strike in January, the Lexan sheet stock was received at the forming facility. Some initial processing and equipment problems in achieving desired window flatness were overcome with the assistance of General Electric Plastics Department engineeri , personnel. In subsequent production, tolerances on outer window length and width (measured inside the sealing lip) had to be relaxed to meet schedule commitments for the desired production rate. In the case of some windows which were undersize, a subsequent problem was encountered in the field; this is discussed in Paragraph 6.2.5. With this exception window yield was good and the flexible lightweight windows were found to be simple to handle and install.

On initial assemblies, the inner window was retained by a few relatively short Lexan angle clips which held it against the Kydex shelf and were riveted to the Kydex wall above the shelf. Because of bowing or lifting of the inner window between these clips in the initial P3-0 thermal tests, more clips were added in subsequent production groups. Ultimately, as soon as material could be obtained, continuous edge retention of the inner windows was provided on all remaining units of the 148 collectors produced. The angles are installed in a manner which permits free thermal expansion and contraction of the inner window without permitting inter window convection losses via gaps around the edges of the inner window.

Because of the flatness problems experienced in early production outer windows, it was not possible to depend on the adhesion of the sealant to ensure a reliable long term continuous bond between the outer window and the collector pan. For this reason, several retaining screws were inserted into the pan sides through expansion-clearance holes in the sealing lip of the outer window.

5.1.2 ABSORBER ASSEMBLIES

Only one experimental collector was cast with foam insulation before "production" collectors were produced. Some sealing problems relating to liquid (uncured) foam containment were experienced and solved as a result of the first casting, and a usable absorber assembly resulted from the second foam attempt. This unit was subsequently assembled with two early production windows which had been rejected for non-flatness, and became the first full scale P3 test collector (P3-0). This unit is still used in testing at Valley Forge.

Fluid connection tubing nipples were inserted into the welded adapters on the absorber plates through cutouts in the frame pan after foaming. Lack of adequate control on tightening torque on these parts of assembly resulted in some loose joints which developed leaks in the field.

There was considerable variation in the amount of foam applied to each absorber due to the lack of time to develop a more consistent procedure/equipment combination. This was not initially thought to be a problem but ultimately aggravated a panel/window separation problem (discussed in Paragraph 6.2.5).

5.2 SYSTEM INSTALLATION

5.2.1 CONSTRUCTION PHILOSOPHY/APPROACH

The location of the experiment,being in Boston and remote from the General Electric Space Division,complicated the project. This was of special concern for the critically timed construction/installation phases. As a consequence, it was decided that the most prudent approach was to employ a general contractor who would:

1. Be familiar and provide guidance regarding local conditions, i.e., regulations, suppliers, labor unions, etc.
2. Recommend and coordinate subcontractors.
3. Provide on site supervision and miscellaneous labor as required.

Ballinger, the Philadelphia based architectural engineering subcontractor, had previous experience with various contractors in the Boston area and was relied on to provide recommendations. Two qualified general contractors were interviewed in Boston by General Electric and Ballinger and one, Vappi and Co., selected. The major reasons for their being selected were (1) their quite positive commitment to meet cost and schedule requirements, (2) the quality level (reputation) of their subcontractors, and (3) their past record of high performance/quality work.

Discussions with Vappi led to a decision to prefabricate all possible components, i.e., steel frames with mounting holes, headers, etc. This was done to minimize the susceptibility to inclement weather and in the expectation that it would speed the overall progress of the job.

It was apparent during these initial discussions that this would be a virtually all union labor type of installation. In subsequent meetings with Vappi personnel and their subcontractors schedule demands were further emphasized and the possible consequences of a union dispute discussed. The "solar collector panel" constituted a new item and there was a question as to which trade would have jurisdiction. This was ultimately settled with the steamfitters being the applicable craft. In order to minimize the possibility of any other jurisdictional disputes arising and slowing the job, Vappi coordinated the subcontractors to minimize instances when related crafts were on the job site, i.e., sheetmetal workers and insulation installers. As a result, no actual disputes occurred.

Interestingly though, there was an afternoon of discussion as to why the collectors with their formed, sheet aluminum pans were not in the province of the sheetmetal workers. The question was settled with the fact that the collectors came from out of state in a fully assembled condition. However, it was apparent that on site assembly would have required two or possibly three trades.

One of the reasons for choosing the Cleveland School was the ability to physically isolate the work from the active school areas. By and large, this was accomplished. However, there were two activities which were potentially disruptive:

1. The cutting of holes in the roof to structurally tie into the building.

2. The modification of the heating units required three days when no heat could be supplied.

Fortuitously, there was a one week mid-winter school vacation scheduled for February 18 to 22 which was the time this work was scheduled.

Another major area of coordination was intended to be crane utilization. Since the school roof was basically accessible only from the street in front, the intent was to group all the steel erection and heavy lifts together to minimize the time (and cost) that large cranes would be required. This was successful in terms of the large ($1000/day) type crane but circumstances combined to make multiple usage of smaller cranes necessary, i.e., truckers strikes, steel delay, etc.

5.2.2 INSTALLATION SEQUENCE

The overall schedule for this phase was given in Figure 5-1. The relationship of the various activities is shown in Figure 5-2.

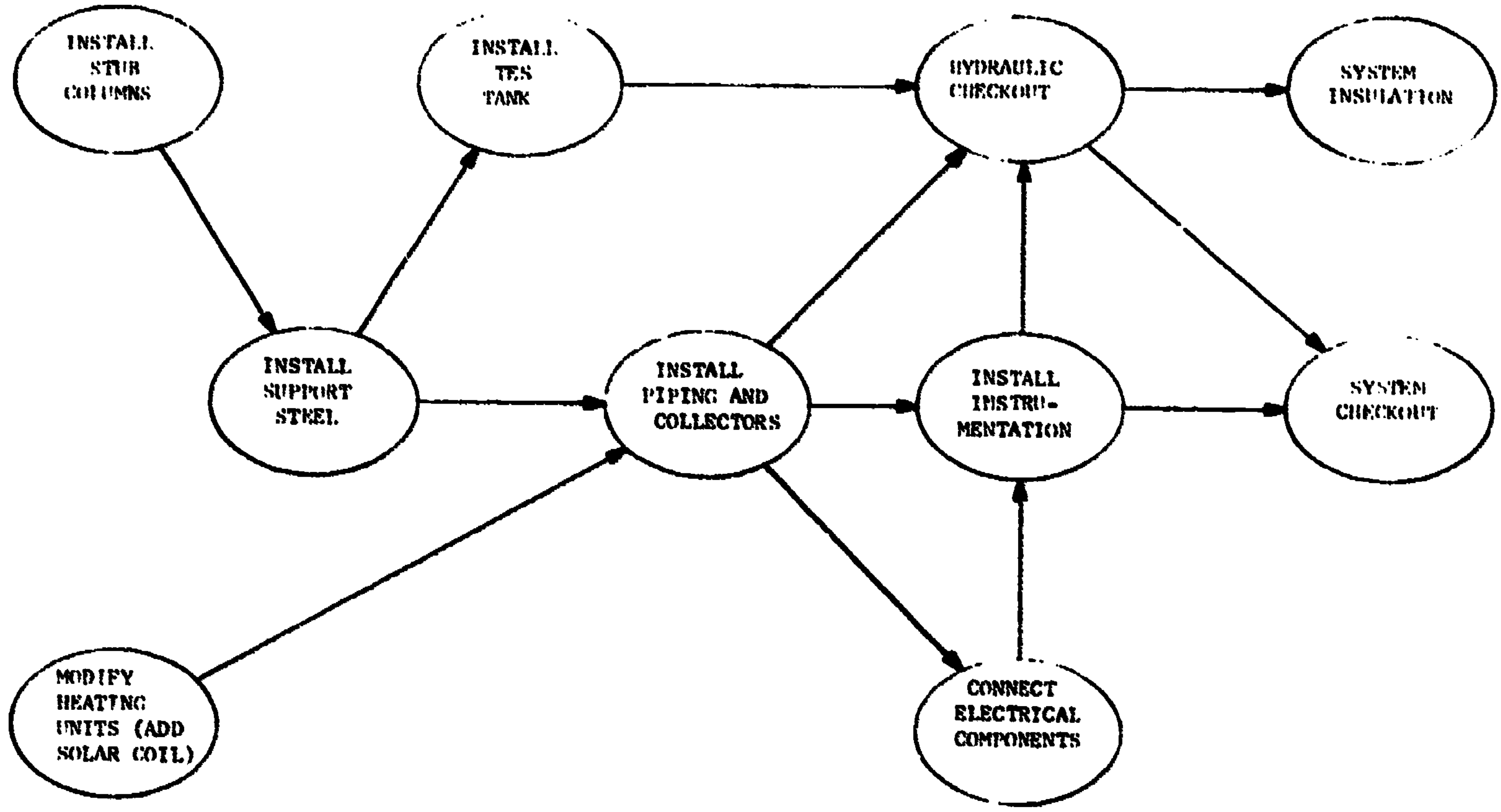

Figure 5-2. Relationship of Installation Tasks

The initial point was the installation of stub colum extensions to extend the selected building columns through the roof and provide attachment pads for the collector support steel. Figures 5-3, 5-4 and 5-5 show respectively the stub columns, cutting an access to a building column, and welding on a stub. The first column was put in on February 13 and this phase was completed February 20.

The modification to insert the hot water ("solar") coil into the two rooftop heating units was also accomplished in this time frame. Figure 5-6 shows the hot deck region prior to modification. The hot deck exit dampers are on the right edge of the figure and it can be seen that the electric coil does not entirely occupy the hot deck volume upstream of the dampers. Figure 5-7 shows the electric coil removed from the hot deck (the adjacent AC-6 heating unit can be seen through the resulting opening in the far side of AC-7). The electric coil was inverted which placed the void volume noted in Figure 5-6 on the upstream side of the electric coil while maintaining the coil's mounting interface with the cabinet of the heating unit. This void was then filled by inserting the solar coil as shown in Figure 5-8. The completed installation is shown in Figure 5-9 as piping was being installed. Relocation, or re-inversion of some mercury wetted relays and the addition of five instrumentation/control relays was then accomplished in the control cabinet on the opposite side of the unit. Thermocouples were also placed in the airstream upstream of the hot deck, between the solar and electric coils, and in the hot deck exit air plenum.

The steel erection was done in two stages; first, the entire horizontal array of dunnage beams was put in place and, second, the triangular collector supporting trusswork was erected on the dunnage beams. A large crane was utilized to place the dunnage beams, lift the TES tank and, because of its long reach capability, to set much of the supporting steel for the center and rear (north) rows of collectors. The plan was to finish the center row first since all of the mechanical equipment was concentrated there and it was the hardest to reach by crane from the street (the rear row could be reached with some difficulty using a small crane from a very narrow back street). The front row was finished second because of its accessibility and visibility, with the rear row being left to last. The erection technique was to place the triangular bents which occur on nominally 8 foot centers along the dunnage beam, tie them together with the top header support channel, and then attach the intermediate tee beams which fall between the bents thus providing attachment points for the 4 foot wide collectors. Figure 5-10 shows a small crane lifting a section of header support channel to the front row. Figures 5-11 and 5-12 show the attachment of a channel. In Figure 5-12 it can be seen that the center row of steel is all in place. Figure 5-13 shows the front row of steel after completion.

The TES tank at approximately 4500 pounds was one of the heavier individual lifts. Figure 5-14 shows the tank set in place behind the center row support steel and Figure 5-15 shows it with the piping in progress.

The bypass heat exchangers were also installed in this time frame. Figure 5-16 shows the two main coils in place around the ventilating blowers, but without the conical covers in place. The conical cover was made up in Boston based on "as installed" dimensions to insure a good fit. Rubber hose was utilized to connect the aluminum coils to the copper piping to preclude direct copper/aluminum contact and minimize the likelihood of galvanic corrosion. The hoses shown in Figure 5-16 did not prove adequate, and had to be replaced with a reinforced version. Figure 5-17 shows the finished installation.

The collector panels were shipped to the site in specially made reusable crates, each holding 10 collectors. The loaded crates had a gross weight of about 1400 pounds and were hoisted onto the roof using a small crane as shown in Figure 5-18. The collectors themselves were covered with black polyethylene as the last operation of final assembly. This was done to minimize the absorber plate temperatures which would be experienced during installation prior to initiating water flow. Black polyethylene was less desirable than white for the purpose but was more available. The collectors assembled late in the program utilized clear polyethylene over white "butcher paper." Figures 5-19, 5-20, and 5-21 show collectors being removed from the crates, carried to the center row of steel, and slid into position. Since the collectors weigh nominally 100 pounds apiece, these operations can be done by two men; however, three were frequently used to facilitate guiding the panel into position over the pre-drilled mounting holes. The upper panels were somewhat more difficult to install due to the height inconvenience as typified by Figure 5-22. The first bank installed (Bank B) in its nearly complete state is shown in Figure 5-23.

As soon as a complete bank of collectors was in place, the prefabricated headers were installed and connected to the piping network. Again rubber hoses were used to connect and electrically isolate the aluminum absorber plates and copper headers. The bank was then checked for leaks using Boston fire hydrant water pressure (25 to 30 psig on the roof) and with the bank isolated from the main liquid loop. Following the leak test the bank was drained, refilled with a water/glycol solution, flow initiated, and the polyethylene covers removed so that the bank would become operational. Figure 5-24 shows banks B and E ready for removal of the covers on March 6. Again the height of the top collectors somewhat inconvenienced cover removal as shown in Figure 5-25.

The electrical work nearly paralleled the collector installations since use of the main pump and cycling of the motorized valves were required to operate the loop.

The installation of instrumentation was only slightly behind the collector installation activity. Thermocouple wire was strung through conduit and routed to the intended location. At the selected location a thermocouple bead was formed by welding and then soldered to the pipe. The three exceptions to this procedure were the use of immersion thermocouples to measure collector outlet liquid temperature at the main pump inlet and the stagnant TES liquid temperature and also the use of prepared thermocouples inside the Nesbitt heating units. The school loaned use of their shop area for a few hours to facilitate assembly of the weather station shown in Figure 5-26. It and the Epply Model 8-48 pyranometer were installed high on the west end of Bank B as shown in Figure 5-27. The instrumentation, which was an integral part of the piping network, i.e., flow meters and immersion thermometers, was, of course, installed as the piping network was assembled.

Insulation was normally the last physical act of installing on a given section of the system. Of necessity, it had to follow both the leak check and instrumentation operations. The insulation consisted of a semi-rigid fiberglass sleeve with a protective aluminum sheath being applied over top of it for straight runs of pipe. All fittings were insulated with fiberglass batting encased in formed to fit, protective plastic sheaths. The flow balancing valves and connecting hoses to the collectors were left uninsulated since it appeared the cost and resulting complication were not warranted by the potential heat saving. The TES tank was insulated in the same manner as the pipes except that two inches of insulation were utilized and the ends were plastered with a mastic compound to provide a weather seal. This is shown in progress in Figures 5-28 and 5-29.

System checkout was basically control console related and consisted of connecting instrumentation leads, verifying valve controller operation, and checking the general integrity/capability of the system for unattended operation.

The system went operational March 6 with banks B and E on line. Bank F followed about two days later with Bank C a few days after that. The effects of a truck strike in the northeastern states and a crane operator's strike in Boston then slowed progress and the last banks (A and D) did not become operational until March 20.

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Figure 5-3.

Figure 5-5.

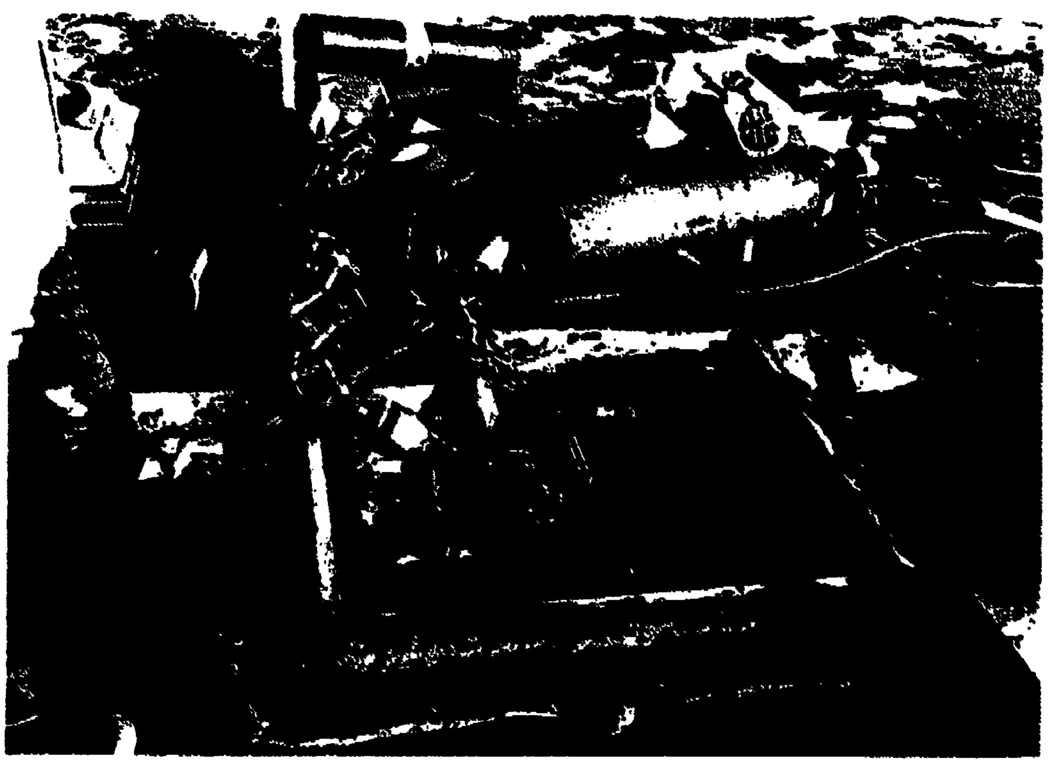


Figure 5-4.

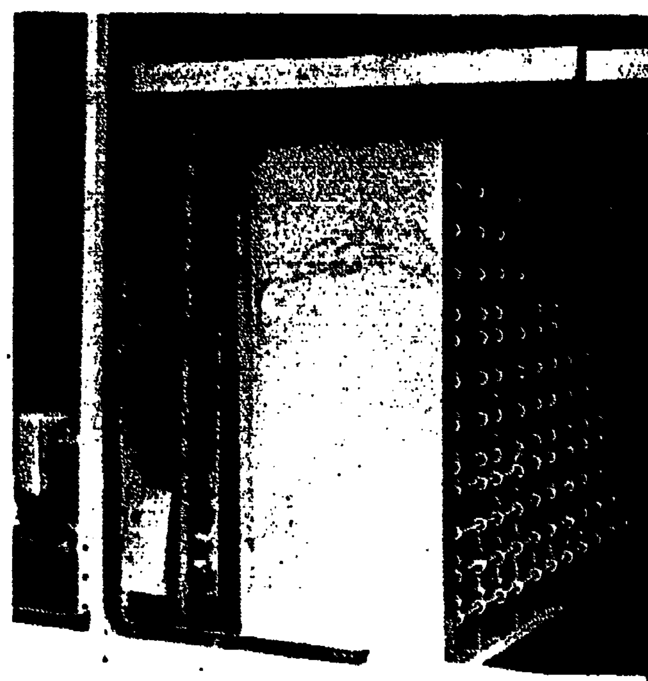
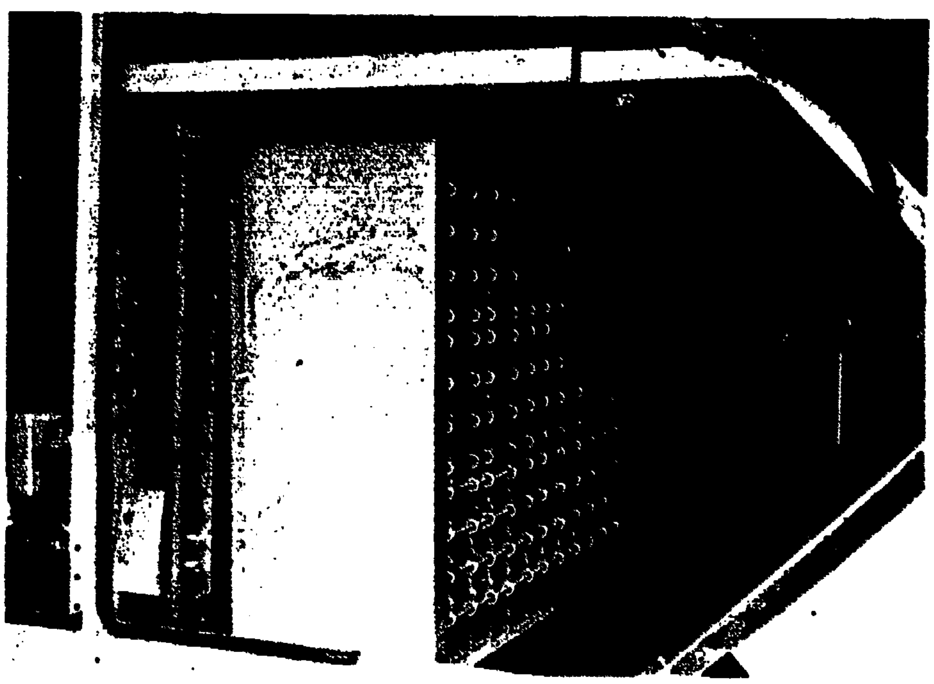


Figure 5-6.

Figure 5-5.



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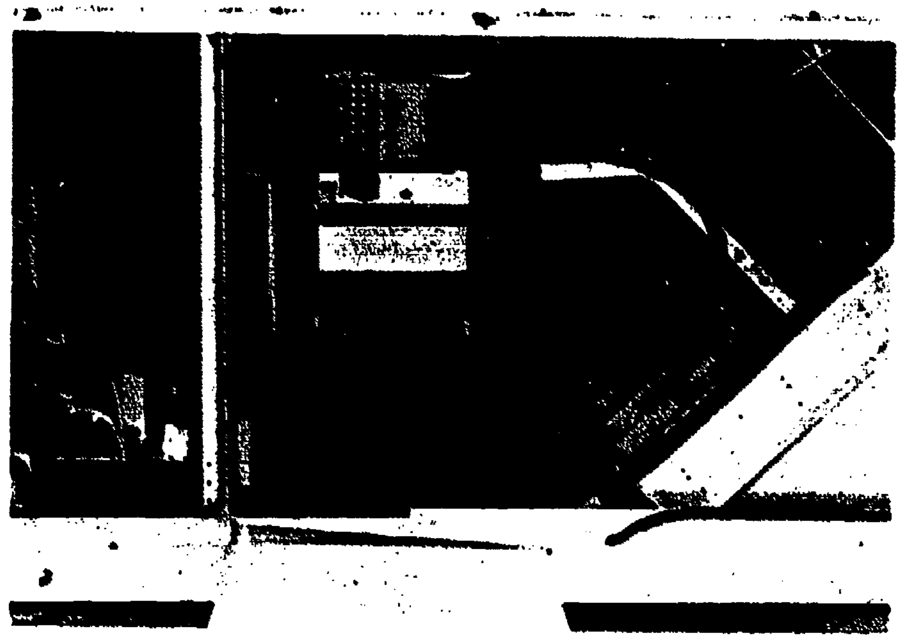

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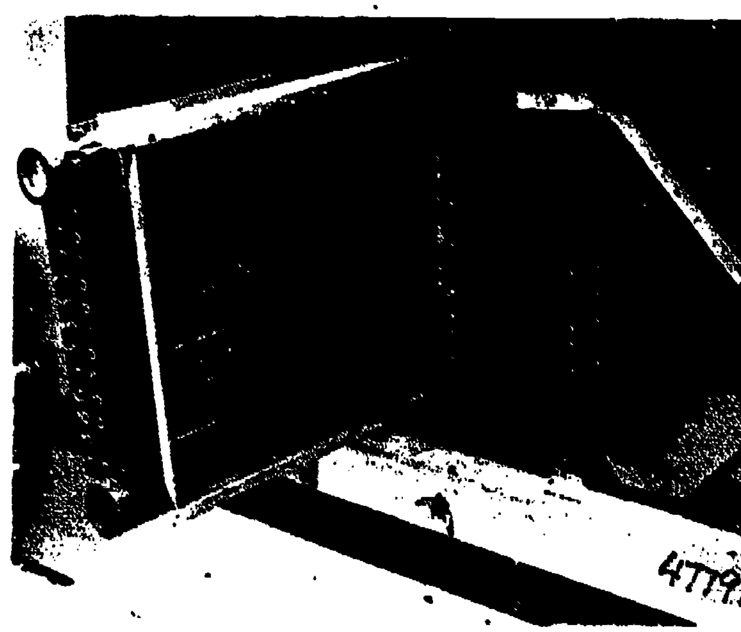

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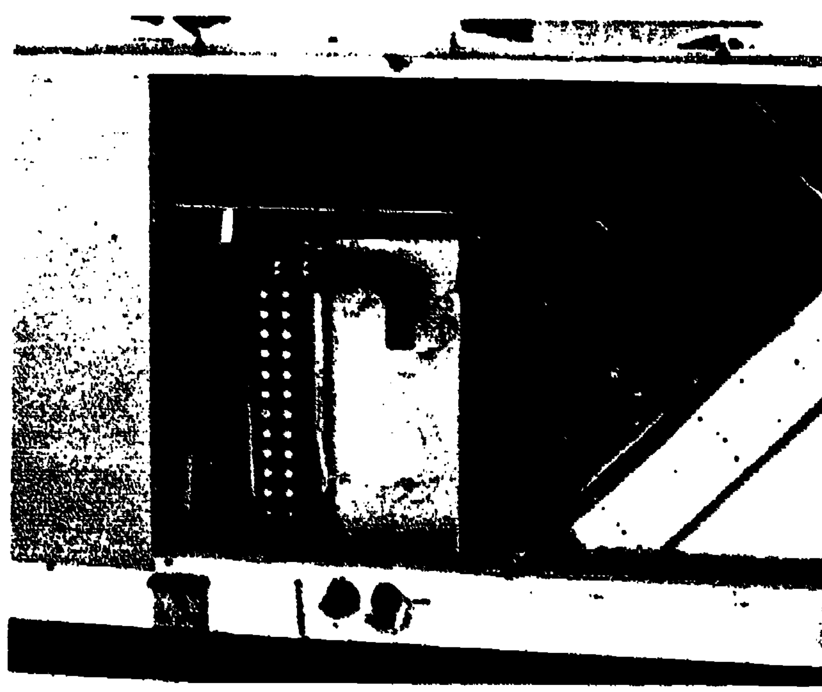

Figure 5-9.

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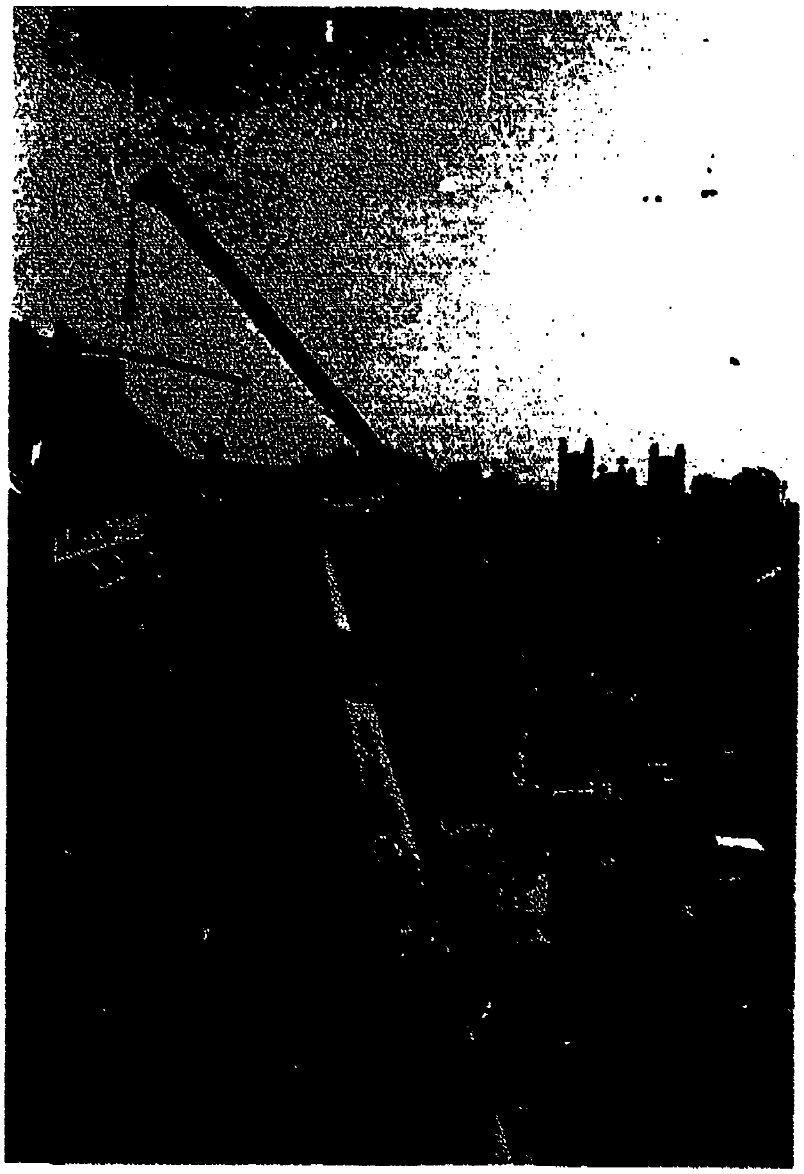

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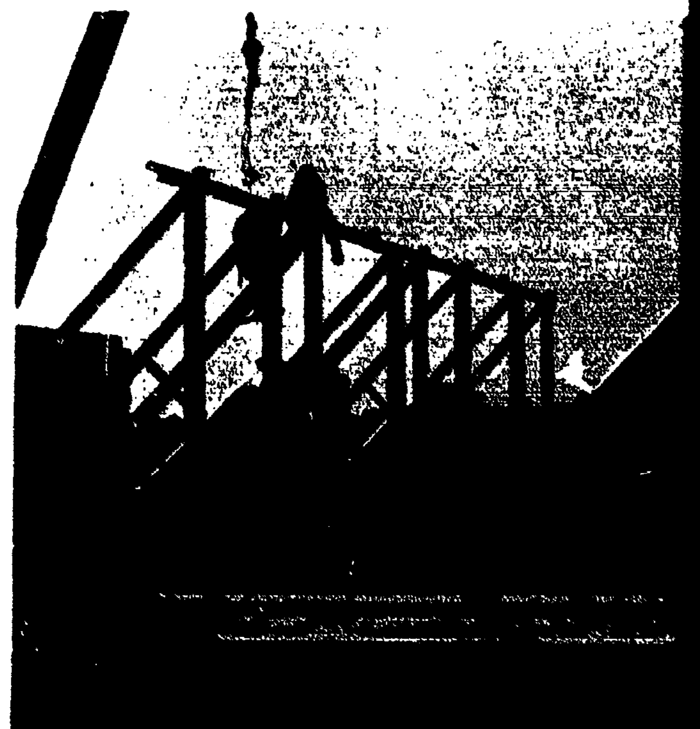

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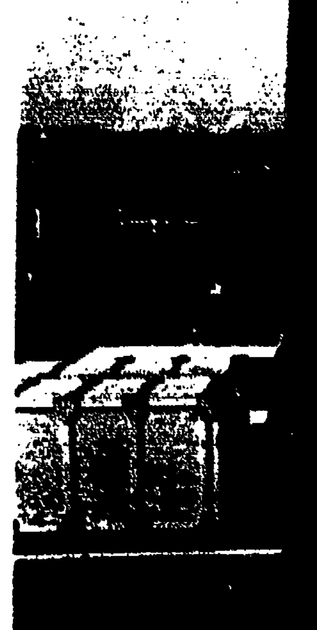


Figure 5-11.

Figure 5-12.

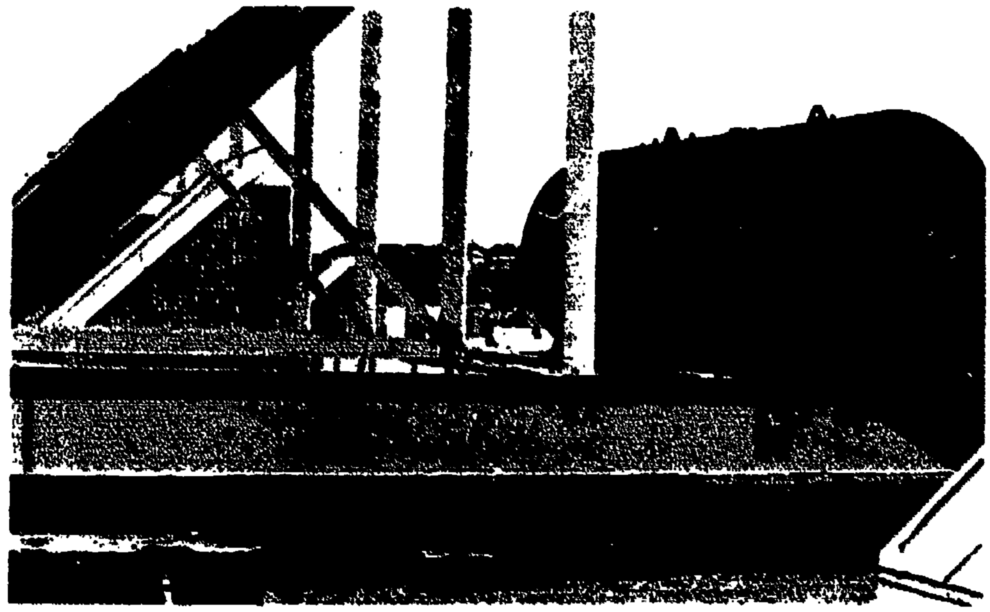
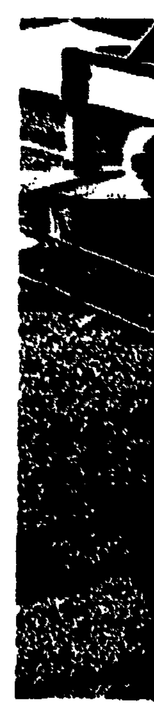


Figure 5-14.

Figure 5-16.



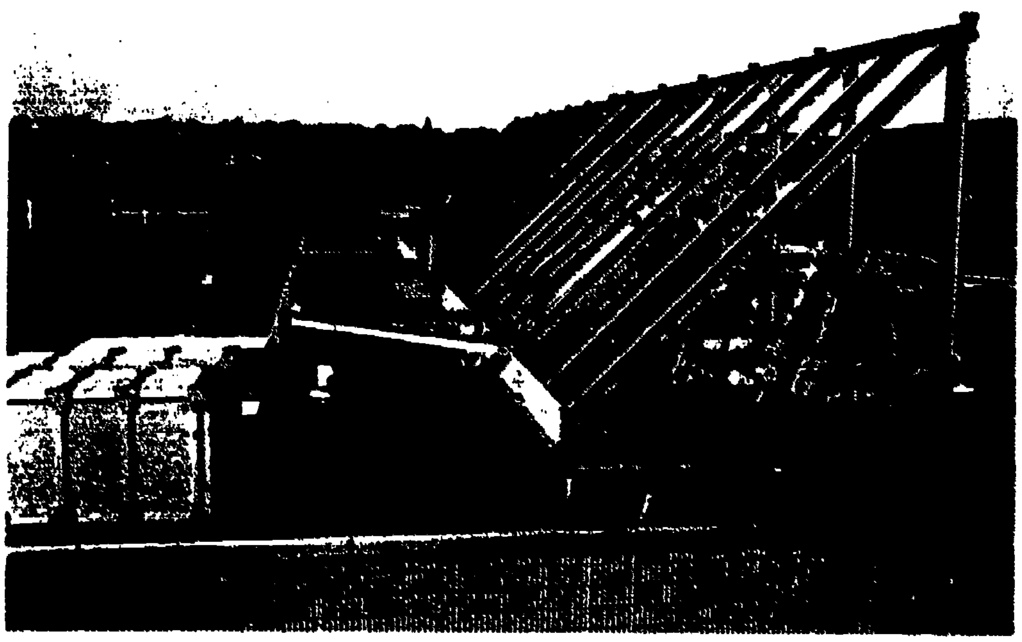
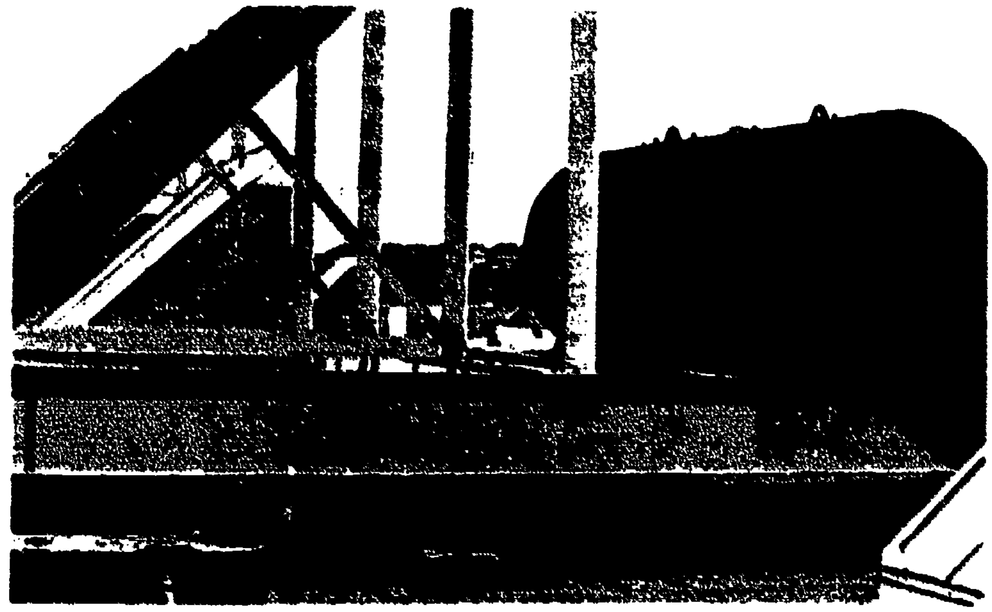


Figure 5-13.

Figure 5-12.



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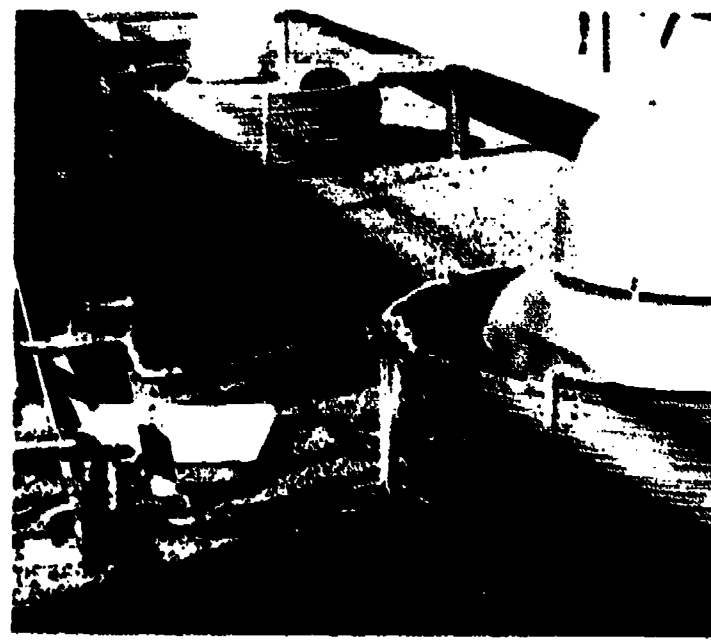

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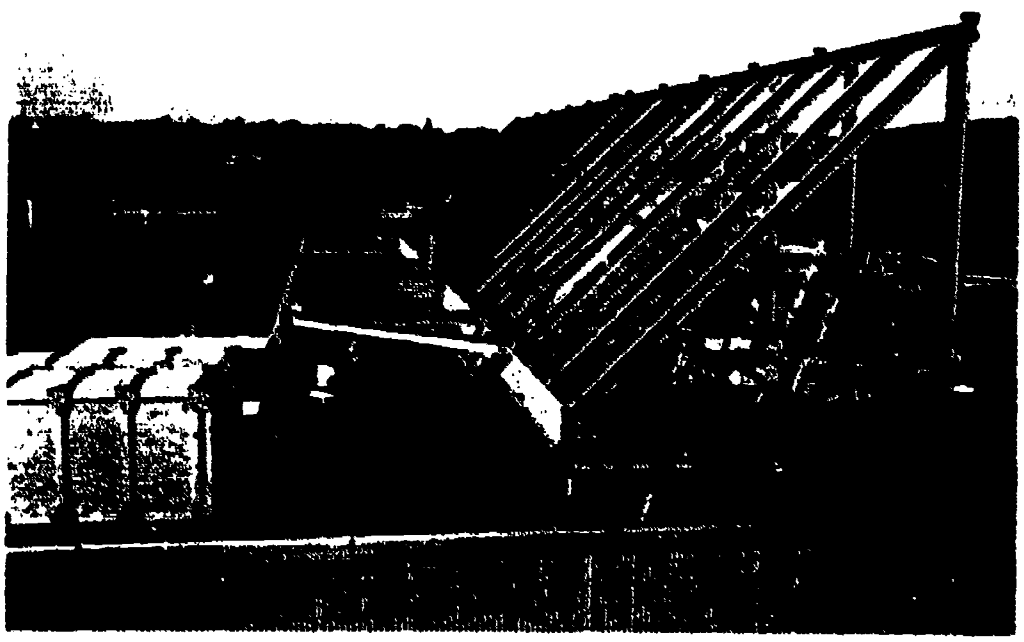

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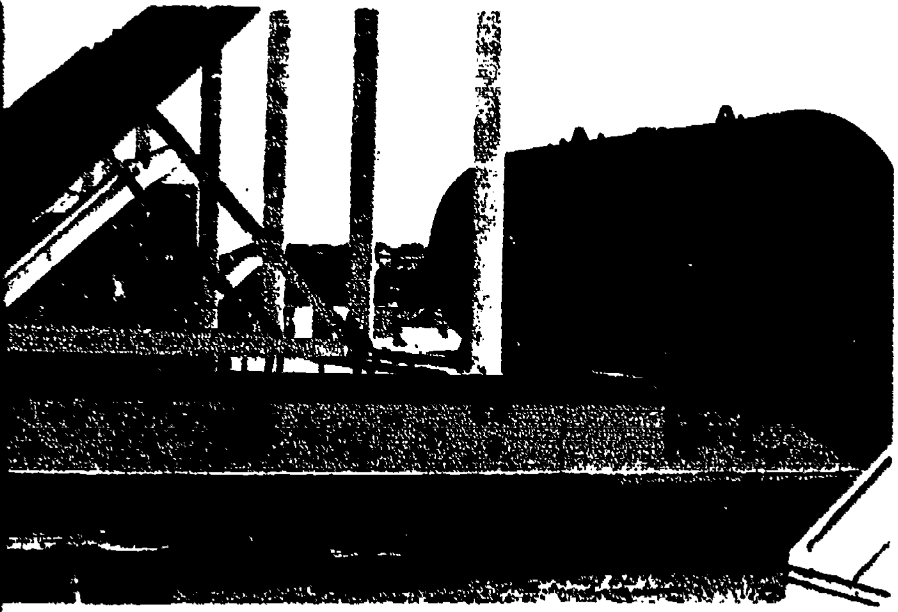

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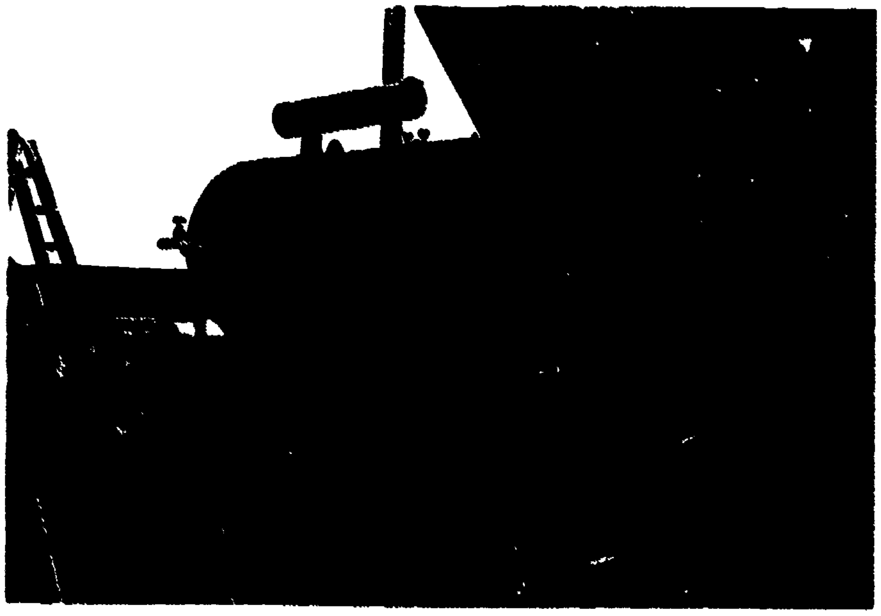

Figure 5-15.

Figure 5-16.

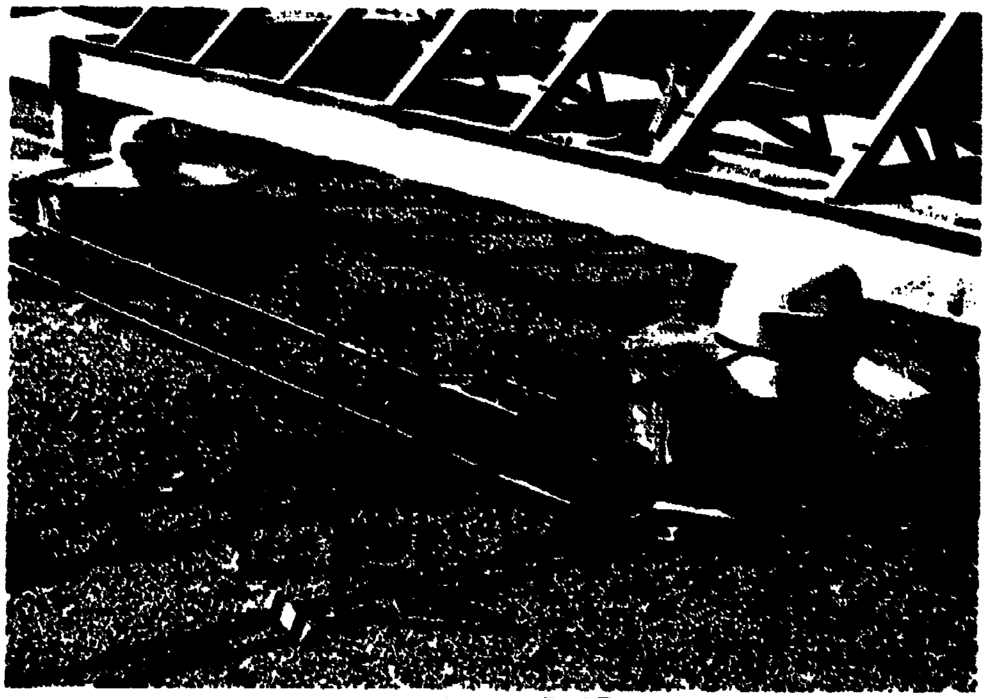

Figure 5-17.

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Figure 5-19.

Figure 5-18.

Figure 5-20.

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5-20.

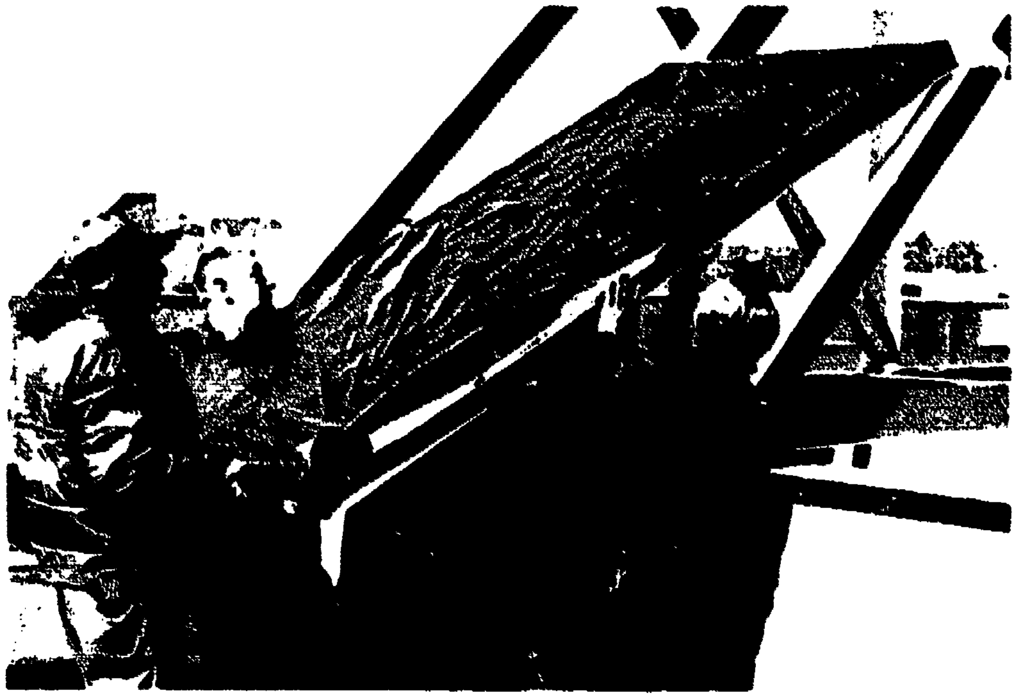

Figure 5-21.

Figure 5-22.

Figure 5-23.

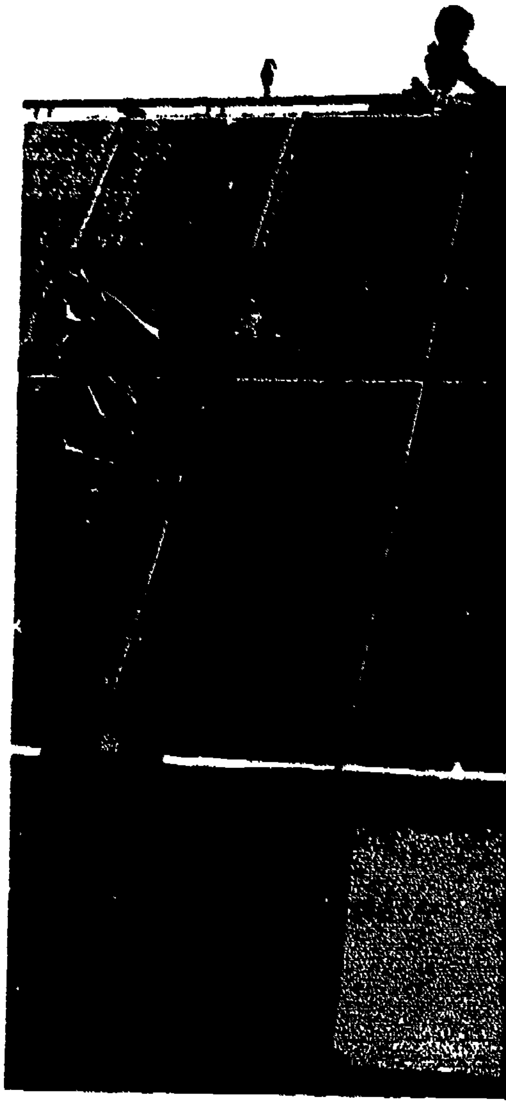

Figure 5-25.

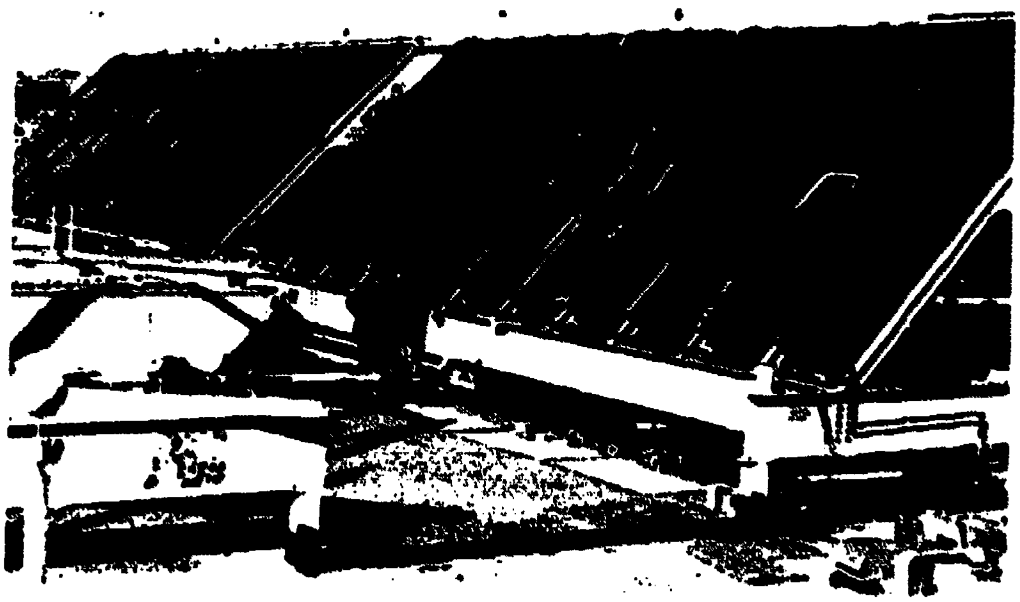

Figure 5-24.

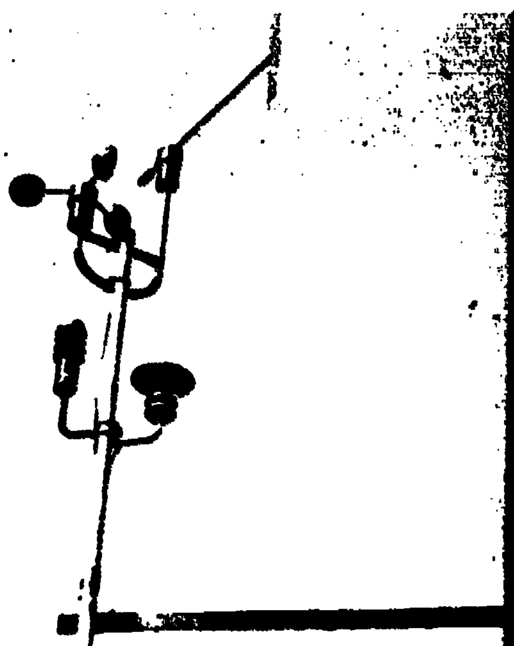

Figure 5

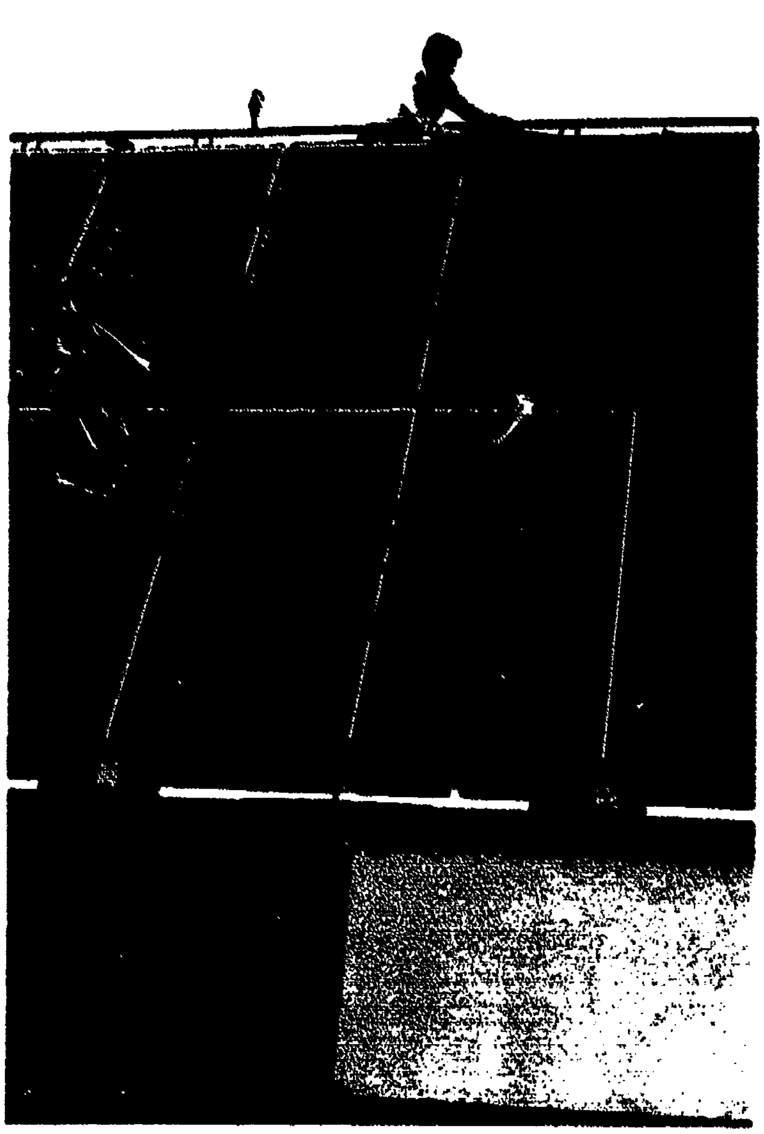

Figure 5-25.

Figure 5-26.

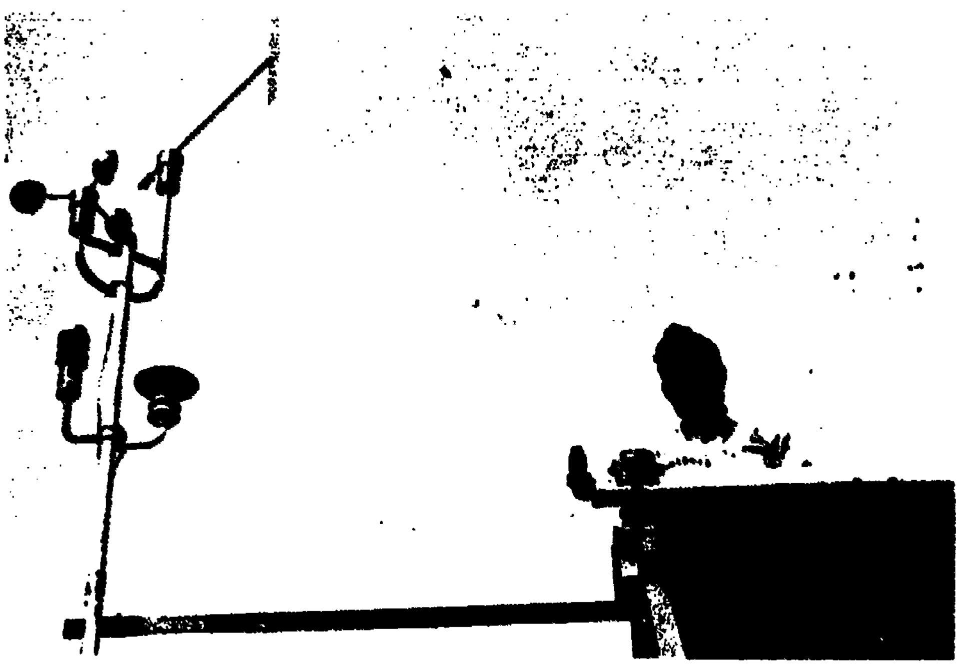

Figure 5-27.

Figure 5-28.

Figure 5-26.

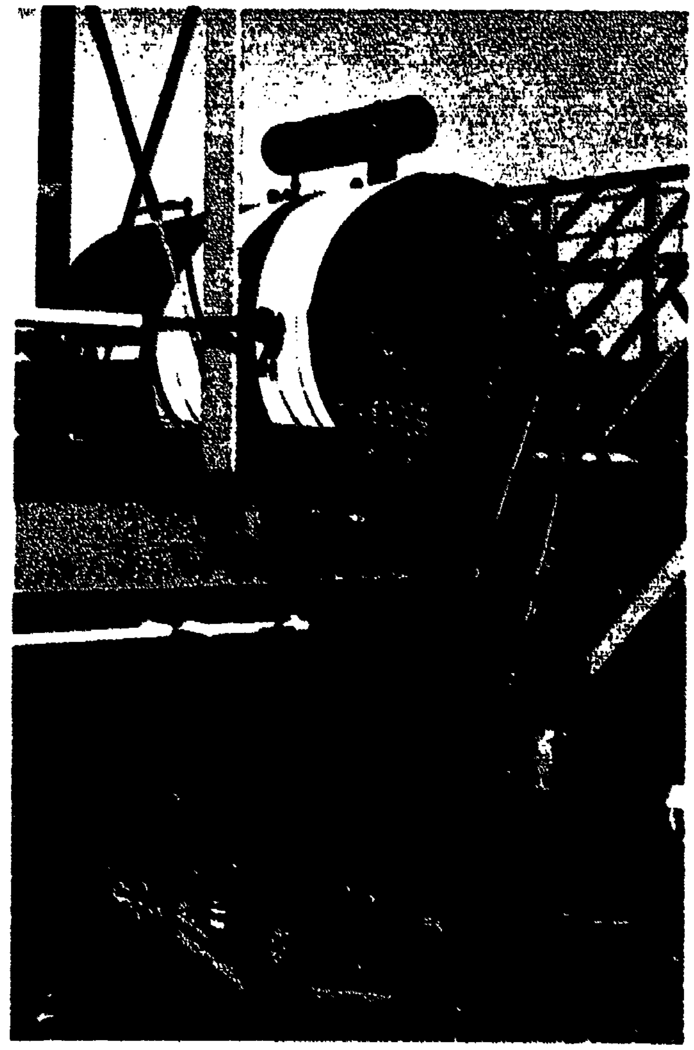

Figure 5-29.

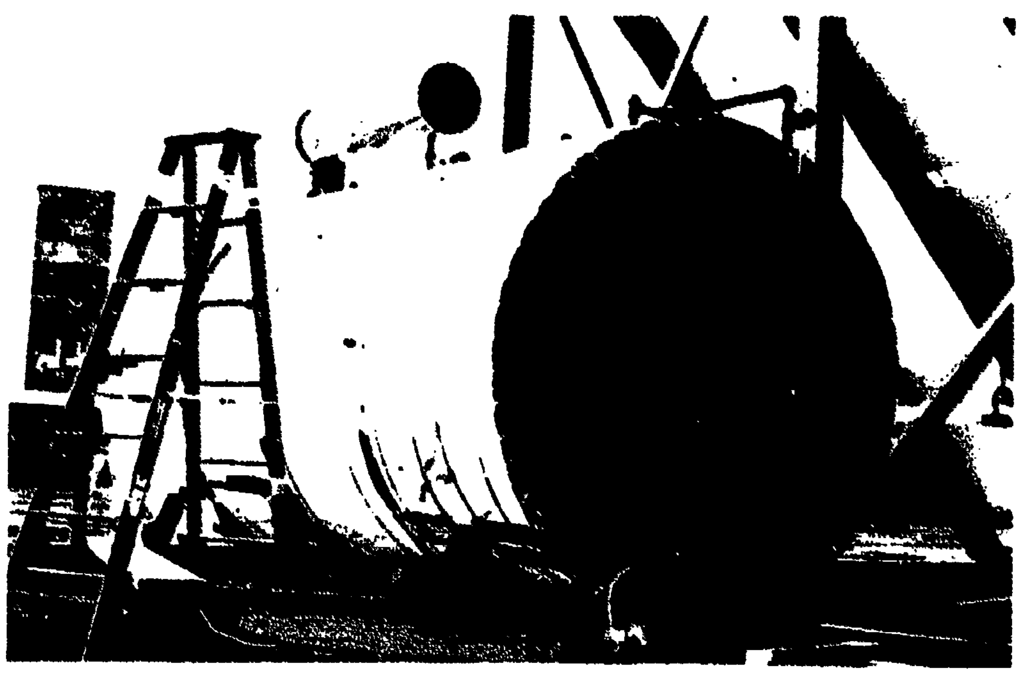

Figure 5-28.

5.2.3 INSTALLATION SUPERVISION AND REPORTING

As mentioned previously, Vappi provided a supervisor who was on the job site virtually full time and was responsible for the conduct of the installation. In addition, General Electric provided the program manager, the project engineer, and the instrumentation/controls engineer on site throughout most of the installation/checkout period. Their role was to:

1. Provide consultation as required to make "on the spot" decisions.
2. Install and checkout the control console, thermocouples, and data acquisition subsystem.
3. Provide whatever interfacing was required to keep the city and school personnel abreast of the project.
4. Insure that the system was installed in the manner intended.

Daily tabulations were kept and weekly time sheets were submitted by Vappi which itemized the time, materials and labor categories expended during the week.

Each week a one-page top summary report of the most significant items related to the project was submitted to the National Science Foundation. The text of these reports is provided in Table 5-1.

5.3 COSTS OF FABRICATION AND INSTALLATION

The costs associated with a project such as this solar heating experiment are always of considerable interest. However, the costs incurred in this project are not expected to be representative of future solar heating installations. This was the first solar heating installation for all of the subcontractors and costs associated with "learning" and new product assembly line startup were experienced. In addition, some urgency was attached to the project in order to obtain real data during the 1973/1974 heating season.

Other construction cost producing factors were:

- The heavy but readily available steel support structure which compressed design time and municipal approval cycles. Additional indirect costs are also attributable to this design structure, i.e., crane costs.

PROGRESS REPORT No. 1 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
January 25, 1974

1. GE engineers and Ballinger, the A&E subcontractor, made a detailed inspection of the Grover Cleveland School on 22 January.

2. GE and the Public Facilities Division of the City of Boston jointly prepared a working agreement on 23 January. Both parties are reviewing the agreement prior to final signing.

3. The solar heating system design is proceeding according to schedule. Purchase orders have been placed for all long lead time items. Delivery dates support the operational date.

4. The structural design is progressing on schedule. The Vappi Construction Company has been selected to perform the construction and installation.

PROGRESS REPORT No. 2 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
February 1, 1974

1. The Solar Collector Panel layout has been completed.

2. The Piping Schematic and sizing has been completed.

3. The Control System Logic Design is in work and is on schedule.

4. The Instrumentation System Design is completed. All parts are on order.

5. The Solar Collector assembly process is progressing satisfactorily. All parts except the windows have been received. The window delivery dates are on schedule.

6. Preliminary structural drawings were transmitted to the Construction Contractor for measurements. Final drawings will be completed and taken to the City of Boston and the Contractor approximately 5 February.

PROGRESS REPORT NO. 5 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
February 22, 1974

1. Construction is progressing extremely well. The center Row A-frames are installed. The "I" beams are installed for the front row and installation of the support structure has begun on row 3.

2. The thermal energy storage tank was delivered to the school on Friday for installation.

3. Solar Collector Assembly is proceeding. 57 panels are in Final Assembly and will be shipped to Boston over the weekend. Need date is Monday, Feb. 25.

4. The Control and Data System fabrication is 90% completed and will be shipped to Boston for emplacement on Monday, Feb. 25.

PROGRESS REPORT NO. 6 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
March 1, 1974

1. Center row of collectors is all installed. System will be filled between 4-5PM today. Systems checkout will continue.

2. All steel is in place.

3. Thermocouple instrumentation is being installed.

4. Control and data system is being checked out.

5. The thermal energy storage tank has been installed and the instrumentation is being installed.

PROGRESS REPORT No. 9 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
March 22, 1974

1. The solar heating system on the Grover Cleveland School was dedicated Tuesday, March 19, 1974.

2. All 144 solar collectors are installed. Ninety are fully operational; the other 54 are being checked out and will be brought on line Monday, March 25, 1974.

3. The system has supplied heat to the Grover Cleveland School every day since March 6, 1974, except for two cloudy days.

4. All instrumentation is installed and is being checked out.

5. The control system is functioning in the automatic mode.

PROGRESS REPORT NO. 10 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
March 29, 1974

1. All collectors are installed. The system has been operating in automatic mode all week.

2. Construction clean-up is still in process. Insulation and roofing work are the major remaining tasks.

3. Solar collector Serial #138 developed a leak at the input connection. The collector will be removed and replaced with a new collector. Serial #138 will be returned to Valley Forge for failure analysis.

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PROGRESS REPORT No. 3 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
February 8, 1974

1. The material for the windows of the solar collector was delayed by the trucker's strike. The material has been delivered and the vendor is proofing his tooling prior to production.

2. Meetings were held with the General Construction Contractor (Vappi) and his subcontractors to explain the task and schedule. Initial estimates of cost are higher than anticipated. The cost estimates are being refined and should come down as more details are made available to the subcontractor. All subcontractors indicate they should be able to meet initial systems operational date of 1 March, providing there are no further delays of material shipments.

3. The final structural drawings were shipped to the construction contractor and the City of Boston. The mechanical drawings and the electrical drawings will be shipped by Monday, February 11.

4. The control system and instrumentation design and fabrication is proceeding on schedule.

PROGRESS REPORT NO. 4 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
February 14, 1974

1. Construction at the Grover Cleveland School has started. One stub column was installed on February 13. The water and snow on the roof created an unexpected delay in opening the roof for welding.

2. The steel support structure for Row 2 of the collectors is being fabricated in Boston. Erection is scheduled to start on Tuesday.

3. A Thermal Energy Storage tank supplier has been found. Delivery date has been promised to support the operational need date.

4. The tooling for forming the windows for the solar collectors has been proofed. Production of windows has started.

5. The Control Panel and Data System are being fabricated.

PROGRESS REPORT NO. 7 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
March 8, 1974

1. Since the center row of collectors is operational, solar heat was applied to the Grover Cleveland School on March 6, 1974 at 4:10 pm.

2. Twenty-six of the collectors in the front row are installed and connected. Filling is in process. Installation has started on the remaining collectors on the front row.

3. The electrical installation is essentially complete. Clean-up tasks are in process.

4. The control system is 90% complete and is operating in the manual mode.

5. The data system is approximately 50% connected. Installation is still in process.

6. The thermal energy storage tank is being filled.

PROGRESS REPORT NO. 8 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
March 15, 1974

1. The Grover Cleveland School has received heat from the solar heating system every day since March 6, 1974.

2. Ninety solar collectors are installed and working.

3. The thermal energy storage system is installed and heated to 150°F.

4. The system has been operating in the automatic mode, check-out is continuing.

5. The remaining collectors are on site and are being installed.

PROGRESS REPORT NO. 11 NSF-C-869
Solar Heating Experiment
Grover Cleveland Middle School
Boston, Massachusetts
April 5, 1974

1. The system installation is complete, and has operated in automatic mode all of this report period.

2. Construction clean-up (roof repair and painting) is still in process.

- The selection of subcontractors was based on past ability, ability to support the schedule, and enthusiasm for working on a solar project instead of a normal competitive bidding.

- The "wildcat" trucking strike which necessitated circuitous routing of materials around various violence prone regions of Pennsylvania and New Jersey and the use of vehicles transporting partial loads.

- Some increase in estimated costs can be attributed to changes in work scope which occurred as the job progressed.

The differences between the estimated costs and actual costs as shown in Table 5-2 reflects the impact of these factors.

Table 5-2. Cost Summary for Grover Cleveland School Solar Experiment

Item	Estimate ~ $K	Actual ~ $K
Solar Collectors (mat'l and mfg labor for 4608 ft^2)	69.2	75.6
General Contractor (VAPPI)	18.0	22.0
Steel Fabrication	27.0	36.2
Steel Erection	10.0	8.6
Plumbing	35.0	41.2
Electrical	3.0	7.0
Roofing	3.0	4.3
Totals	165.2	194.9

SECTION 6
SYSTEM OPERATION

The system became operational on March 6, running in the manual mode with only Banks B and E on line. Successively, the automatic control system, the TES tank, and the remaining banks were brought on line with the full system in operation on March 25. However, control valve 1A was erratic and did not respond to a close command. Various solutions were attempted but finally the motor subassembly was replaced and the system began functioning in the expected manner starting April 16. The principal effect of valve 1A remaining open was to dump heat via the main bypass heat exchangers while heating the school and/or storing heat in the TES tank.

Since March 20, the system has operated basically in an unattended, fully automatic mode. General Electric personnel were on site for most of the month of March with the principal activities being physical site cleanup and minor modifications to improve the overall system reliability. There were two relatively major failures which occurred, fortunately both happened during the period GE personnel were on site; the main pump motor failed one of its bearings and one collector absorber plate weld failed. Other than these instances, which were both early life type failures, the system has operated flawlessly.

It became obvious when checking out the system and first examining the data that good heating systems are not easily used analytical laboratories. Simple arrays of a few panels are much more usable for obtaining actual collector performance data. A "real" heating system must operate in a flexible manner which means multiple operating modes with varying heat loads. This combined with significant thermal inertia terms results in a system which is normally in a transient condition. As a consequence, emphasis must be placed on data integrated over the day with "point" performance figures being interesting but not particularly meaningful.

Much of the data which can only be obtained with this type of experiment -- long term system operational effects -- has yet to be obtained. Hopefully, this will be possible in the future.

The schedule summary for the operational phase of the project is shown in Figure 6-1. Photographs of the completed system are shown in Figures 6-2 through 6-6.

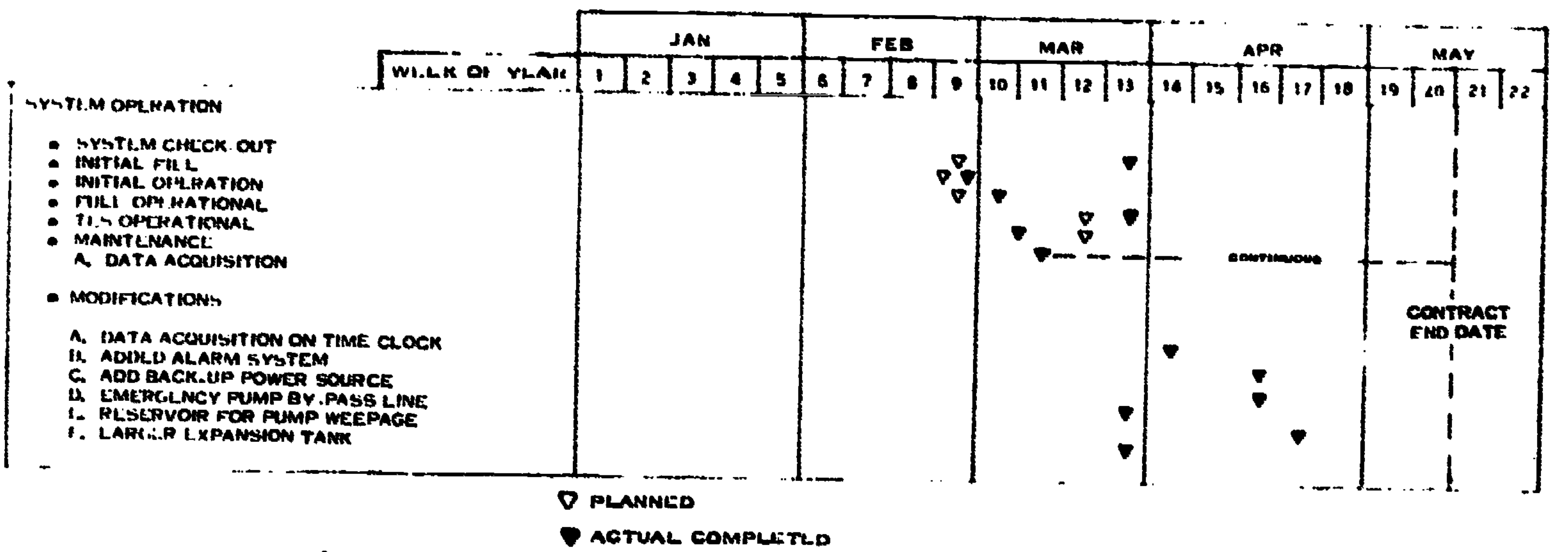

Figure 6-1. System Operation Schedule

6.1 FLUID LOOP CHARACTERISTICS

The working fluid for the system was a solution of Boston water and a commercial grade of ethylene glycol containing corrosion inhibitors and manufactured by BASF Wyandotte. The solution ratio was 70 percent water, 30 percent glycol. Loop liquid inventory was measured via a water meter during the leak checking operations. While there is some uncertainty due to an operational error which occurred, the indicated total loop volume was between 200 and 250 gallons.

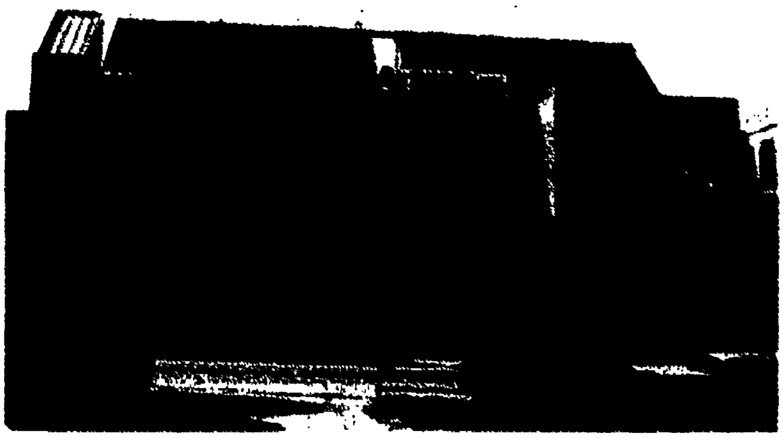

Figure 6-2. Photograph of Completed System (Front of School)

Figure 6-3. Photograph of Completed System (First Two Rows)

Figure 6-4. Photograph of Completed System (Rear Row)

Figure 6-5. Photograph of Completed System (Aerial View)

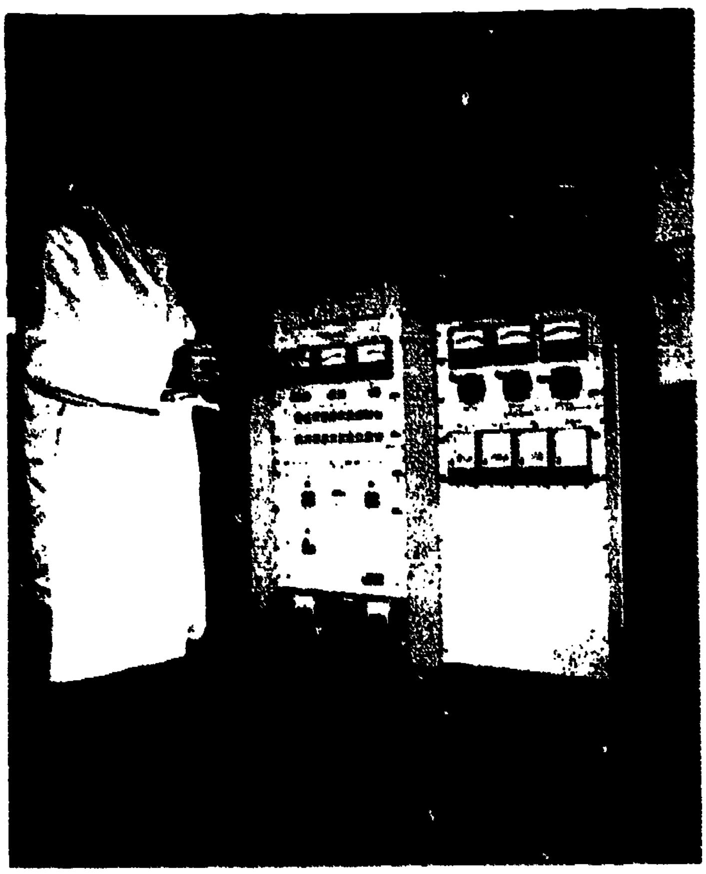

Figure 6-6. Photograph of Completed System (Control Console)

6.1.1 SCHOOL HEAT LOAD

The two roof mounted heating units have identical 410,000 BTU/hr heating capacity and according to the plans were thought to have identical heating demands. As a consequence, the solar heating system was designed based on identical 30 gpm liquid flows through each solar heating coil. During the initial days of operation, it was noted that the solar heating system could satisfy the heat requirements of AC-7 rather easily; however, electrical heating in addition to solar heat was required by AC-6 for several hours after the AC-7 heating load was carried by the "solar" system. As a consequence, during the system checkout phase the AC-6/7 flow distribution was intentionally unbalanced, the intent being to determine a point which resulted in both units' heat loads being totally assumed by the "solar" system at about the same time. This was done to maximize the effect of the "solar" system on the electricity consumed for heating and also to equalize the temperature drops. This also slightly lowered the average liquid temperature and slightly raised the loop efficiency. Unfortunately, it appeared that a flow imbalance ratio of approximately 4:1 would be required which was not deemed practical due to:

1. The reducing effect of the additional parasitic pressure drop on total loop flow rates
2. The very low loop flow which would result in the event of a normal heating condition (mode 3) with AC-6 on air conditioning (valve 2A closed)

The second reason is actually a little remote since the exhibited air conditioning demands on AC-7 were found to be larger than those on AC-6 and thus AC-6 would normally only go into an air conditioning mode <u>after</u> AC-7. However, the condition is possible and these two reasons caused us to limit the flow to a 3:1 ratio. With this ratio the total heating load of AC-6 was satisfied by the solar system typically 20 minutes after AC-7 was satisfied. The flow imbalancing introduced a delay in satisfying AC-7, but it appeared small, of the order of 10 minutes or less.

6.1.2 FLOW DISTRIBUTION

One bank (Bank C) was more highly instrumented than the others, having both collectors with internal instrumentation and flow meters with which to read flow through each of four collector tandem pairs. As mentioned in the Design Section (Paragraph 4.2.2.1), an improperly designed header in a "Z" flow path network would result in a large flow through the end collectors and a low (or possibly zero) flow through the middle collectors. The performance of the headers in this system was checked using the flow meters on Bank C.

Before discussing the test it is important to understand the geometry. Referring back to the instrumentation schematic, Figure 4-35, it may be seen that collector flow meters are in series with the total outlet flow from the first, second, fifth, and eleventh collectors from the west end of Bank C (specifically, collectors #102, 104, 110 and 122). Since the flow meters are comparatively large devices with various mounting restrictions and a significant distance separating the inlet and outlet ports, a different outlet flow path resulted in these four locations. The comparison of the collector to outlet header connection with and without flow meters is shown in Figure 6-7. The net effect of this difference and the flow meter itself were found to produce a significantly higher pressure drop coefficient for the collectors with flow meters. This effect was nearly obvious after the fact but unfortunately was overlooked in the design phase. As a consequence, the header performance had to be based on three separate tests, the first two of which were done prior to removal of the polyethylene covers.

In the first test all balancing valves were opened completely with the result that all four flow meters read zero. This meant that the pressure drop through the metered collectors was significantly higher than either the non-metered collectors or the header.

In the second test, the balancing valves feeding the non-metered collectors were closed leaving the header serving only the first, second, fifth and eleventh pairs of collectors. The following flow rates were recorded:

Collector	Flow
102	7.0 liters/min.
104	~ 7.0* liters/min.
110	6.6 liters/min.
122	6.8 liters/min.

*Could not be read exactly due to visibility problem.

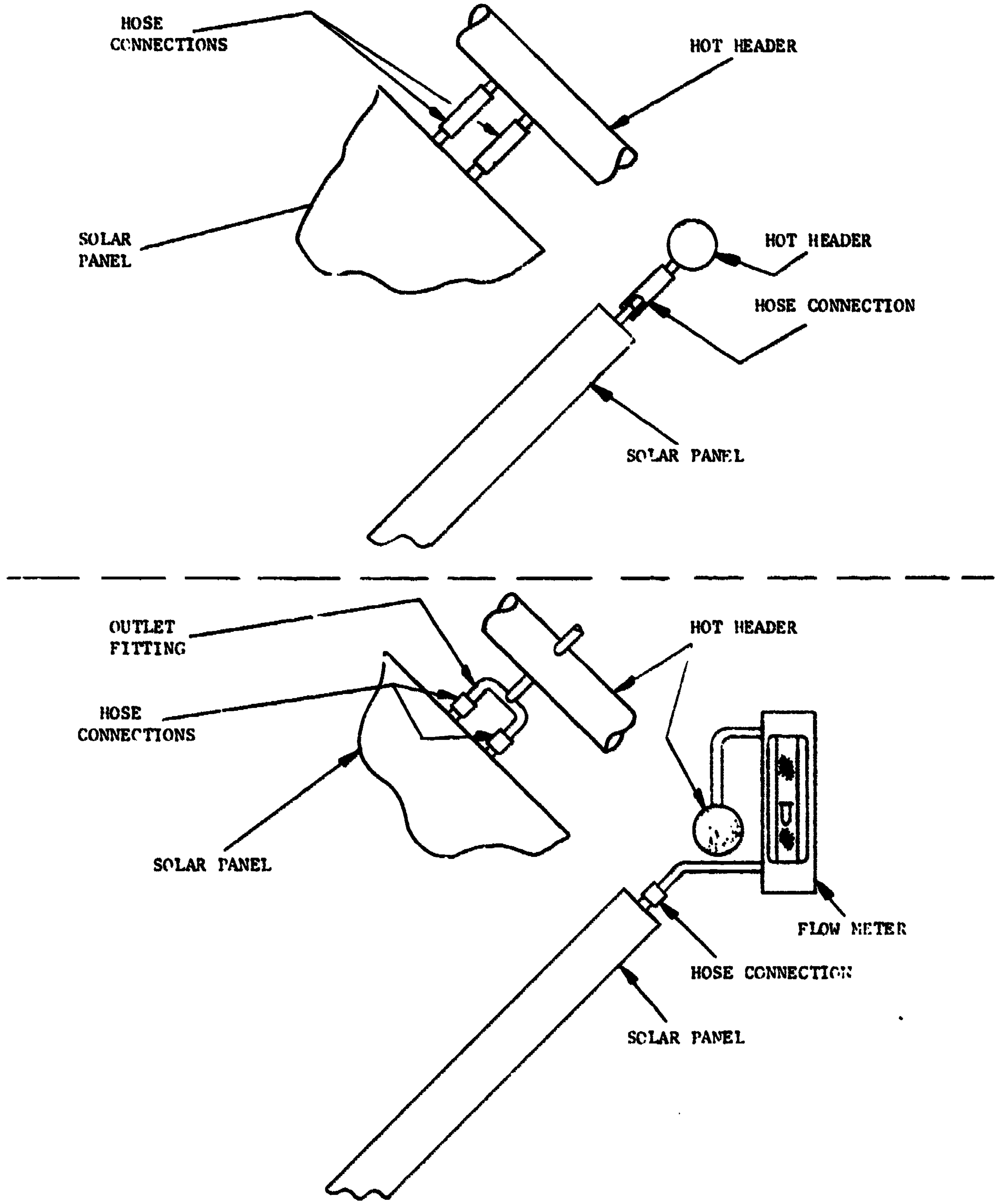

Figure 6-7. Comparison of Collector Header Connection with and without Flow Meter

While the total header flow was slightly lower than the normal operation point, the closeness and pattern of the readings implied a naturally uniform flow distribution.

The bank was then operated for approximately three weeks until leakage problems with the collector flow meters forced their removal. During this time period the flow through Bank C was balanced by adjusting the balancing valves to obtain uniform readings of temperatures as measured by a probe contacting the outlet hoses. This was not the most satisfactory of procedures but it sufficed and the indicated spread was 120° to 132°F. The position indexes on the balancing valves fell into two very uniform groups: ~ 5 for the non-metered collectors and ~ 15 for the collectors with flow meters.

The third test was probably the most meaningful. It was made possible by the removal of the collector flow meters and substitution of a length of pipe. This retained the length of the metered flow path and the twice "normal" flow rate but removed the pressure drop associated with the flow meter poppet itself. For this test each of the 22 outlet hoses were instrumented identically, close to the collector using clamped-on thermocouples. The exterior of the hose was then insulated to make the readings more representative of the outlet liquid temperature and all balancing valves were opened completely. Outlet temperature readings were taken during a condition when a large temperature rise across the collectors existed. Table 6-1 presents these readings. As can be seen the total spread with the identical full open valve settings is approximately 56°F, with collectors 102, 104, 110, and 122 all being above the average of the non-metered panels as would be expected (lower than average flow rate due to a higher than "normal" outlet pressure drop which results in a greater than "normal" temperature rise). Not surprisingly, panel 110 had the highest temperatures. The comparatively low readings on the west outlet of collector 102 and both on 104 (relative to 110 and 122) is not known; it may have been the slight breeze from the west, ill fitting insulation or a combination. In any event, the significant conclusion was that the seven non-metered collectors exhibited good uniformity ranging from 152° to 162°F. Based on these results it was deemed unnecessary to attempt improving the flow distribution in the other banks by use of the balancing valves. It was also decided to leave the distribution at Bank C as it was (valves wide open) and monitor the collectors to observe any hot panel effects which might occur.

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Table 6-1. Bank C Collector Outlet Hose Temperature Distribution

Panel Number	West/East Hose Temperature - °F
102*	168/194
104*	159/164
106	161/159
108	157/160
110*	204/204
112	161/162
114	159/161
116	156/158
118	156/158
120	152/160
122*	195/186

*Former location of a collector flow meter.

Some indication of a probable poor flow distribution within the collectors was obtained with the collector flow meters prior to their demise. The original design point flow rate was 0.8 gpm/collector; however, whenever there was bright sun on the system with this flow rate, steam bubbles could be seen rising with the flow stream as it passed through the glass flow meters. This was evidenced numerous times with outlet liquid temperatures as low as 180°F and pressures as high as 7 psig (at the flow meters). The steam bubbles would cease with a 25 percent flow rate increase to approximately 1.0 gpm/collector. The steam bubble flow could not be heard in the hot return feed pipes, indicating their collapse either in the outlet header or the physically lower (and higher static pressure) return feeders. The postulated cause of this phenomena is one or more "slow flow" channels within the absorber plate. As a consequence, nominal flow was increased to 1.0 gpm/collector for the normal heating condition (Mode 3) with the knowledge that the most credible other modes would all produce higher flow rates.

6.1.3 FLOW RATES IN VARIOUS MODES

As noted earlier, the system has five basic operating modes which can be modified by occurrences within either Nesbitt heating unit. These occurrences are the existence of a so called "first stage" overtemperature condition (165°F) in the hot deck or the usage of the refrigeration cycle air conditioning system. The effect of either occurrence is identical; the closure of the corresponding valve 2 to discontinue hot liquid flow through the "solar" coil. As a consequence, there are a total of 11 possible flow path configurations for the system.

During a period with minimal solar flux, the system was cycled through each of the possible configurations manually and the various flow rates measured. The results are given in Table 6-2. It can be seen that there is good agreement between the control panel total flow meter and the sum of the two flow meters on the heating units (in Mode 3) but not as good agreement with the sum of the six bank flow meters. As a consequence, the six bank flow meters were utilized only for balancing bank to bank flow distributions on the assumption that the relative readings were more likely to be accurate.

Table 6-2. System Flow Characteristics

System Operating Mode	Liquid Flows ~ gpm									Pressure ~ psig	
	Solar Panel Banks						Heaters		Panel Meter	Main Pump	TES Pump
	A	B	C	D	E	F	AC 6	AC 7		Out/In	Out/In
1	12.75	12.25	11	14	11.25	11.50	0	0	70	51 /8.75	29/29
2	12.75	12.25	11	14	11	13.50	19	6	70	50 /8.50	63/49
2 With 2A Closed	↓	↓	↓	↓	↓	↓	0	11.50	↓	50 /8.50	62/49
2 With 2B Closed	↓	↓	↓	↓	↓	↓	22.25	0	↓	50 /8.50	61/47.50
3	12	12	10.75	12.25	10	11.75	47.75	15.50	64	51/8.75	28/28
3 With 2A Closed	4.25	4.25	6.50	4.75	4	4.50	0	21.25	24	56/9.50	15/15
3 With 2B Closed	11.25	10.75	10	11	9	10	54	0	57	52/9	25/25
4	14.25	14.50	12.25	14.75	11.50	11.75	37	11.50	77	49/8.25	46/46
4 With 2A Closed	11.50	10.50	10.25	11	9.25	10.50	0	17.25	58	51.5/8.50	51/51
4 With 2B Closed	14.75	13.25	11.75	14	11	13.50	41.75	0	74	49/8	47/47
5	16.75	14	12	16.50	12.75	15.50	0	0	81	48/8.25	46/46

Test Conditions: Sky Overcast, 70°F Loop Temp, April 24, 1974

6.1.4 OPERATING MODE TRANSITION POINTS

The functions of the control system were described in Paragraph 4.2.4.1. However, two control or mode transition points had to be determined empirically, specifically:

1. The minimum point at which sufficient "extra" temperature was available such that the heat storage in the TES could begin and not result in a shortage of heat to either AC-6 or 7.

2. The minimum TES temperature at which the liquid circulated through the TES coil will be at least as effective in supplying AC-6 and 7 as the main loop supplying 80°F liquid.

The first is the determination of the transition point between Modes 3/4 and the second is the transition point between Modes 1/2/3.

When the Mode 3/4 transition occurs, the flows through AC-6 and 7 are reduced by about 30 percent and the total flow increases by approximately 20 percent. (The difference between the total and the sum of AC-6/7 being the flow through the TES coil). With the intentionally unbalanced AC-6/7 flow rates (Paragraph 6.1.1), it was found that generally 130°F inlet water was required to assume the total heating load of AC-6 and 7 (this compared to the design point of 120°F with equal 30 gpm flows). By trial and error it was determined that delaying the transition until the loop control temperature reached 145°F would nearly always provide adequate heat to AC-6 and 7 at the reduced Mode 4 flow rates. This determination was made by observing whether the electric coils came back on after the transition was artificially induced (via controller adjustment).

The intent of Mode 2 is to only supply heat from the TES when the TES can be at least as effective as the main loop at its minimum useful operating point, 80°F. The combined effect of the unfortunately misoriented TES coil and the low flow rates in Mode 2 is to require that the TES control instrumentation be reading a high temperature (relative to 80°F) in order to provide a significant heat input. The actual effect of the misoriented coil is to greatly increase the so called approach temperature available in Mode 2 (see Paragraph 4.2.3.3 for more discussion). The actual flow through the TES coil in Mode 2 is horizontal (rather than the intended vertical upward) and is heavily influenced by the thermal stratification which occurs in the TES fluid. The net result was that the difference between control instrumentation, which measures TES fluid temperature approximately 4 inches below the top of the TES coil envelope, and the circulated liquid outlet temperature was about 20°F.

At the low flow rates existing in Mode 2 it was estimated that 110°F liquid was producing the same cyclic effect of the AC-6/7 electric heating stages as was produced by 80°F liquid in Mode 3. Consequently, the Mode 1/2/3 transition point was set at 130°F. This transition point is much higher than the 90°-110°F range which was expected when the TES tank was designed. It also makes the system less efficient than it should be since, to be useful, the TES fluid temperature level must be kept inordinately high, thus both increasing the heat losses and limiting the periods during which heat can be stored. In the future it is anticipated that a reevaluation of this transition point can be made and that incorporation of a recirculation scheme for the TES fluid will nullify this minor problem.

6.1.5 TYPICAL DAY'S PERFORMANCE

As an illustration of the system's daily performance, the data collected on April 16 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 6-8, initially both the collector outlet temperature and the TES temperature were less than the transition temperature levels (80 & 130°F) at which either source could be 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 AM, hence at earlier times the heating demand was answered by the three electrical stages. All three of these heaters were on till approximately 7:30 AM at which time Heater No. 3 began to shut off. Just before 8:00 AM Heater No. 2 began to cycle and by 8:30 AM Heater No. 1 also began to cycle. At this time, 8:30 AM, the collector outlet temperature had reached the 80°F transition point and, as can be seen in Figure 6-8, the electrical heating stages were off or cylcing and Valve No. 2a was opened, permitting the hot fluid to flow through the solar coil in AC-6. At 9:30 AM the electrical heating ceased for the day and the solar system carried the heating load.

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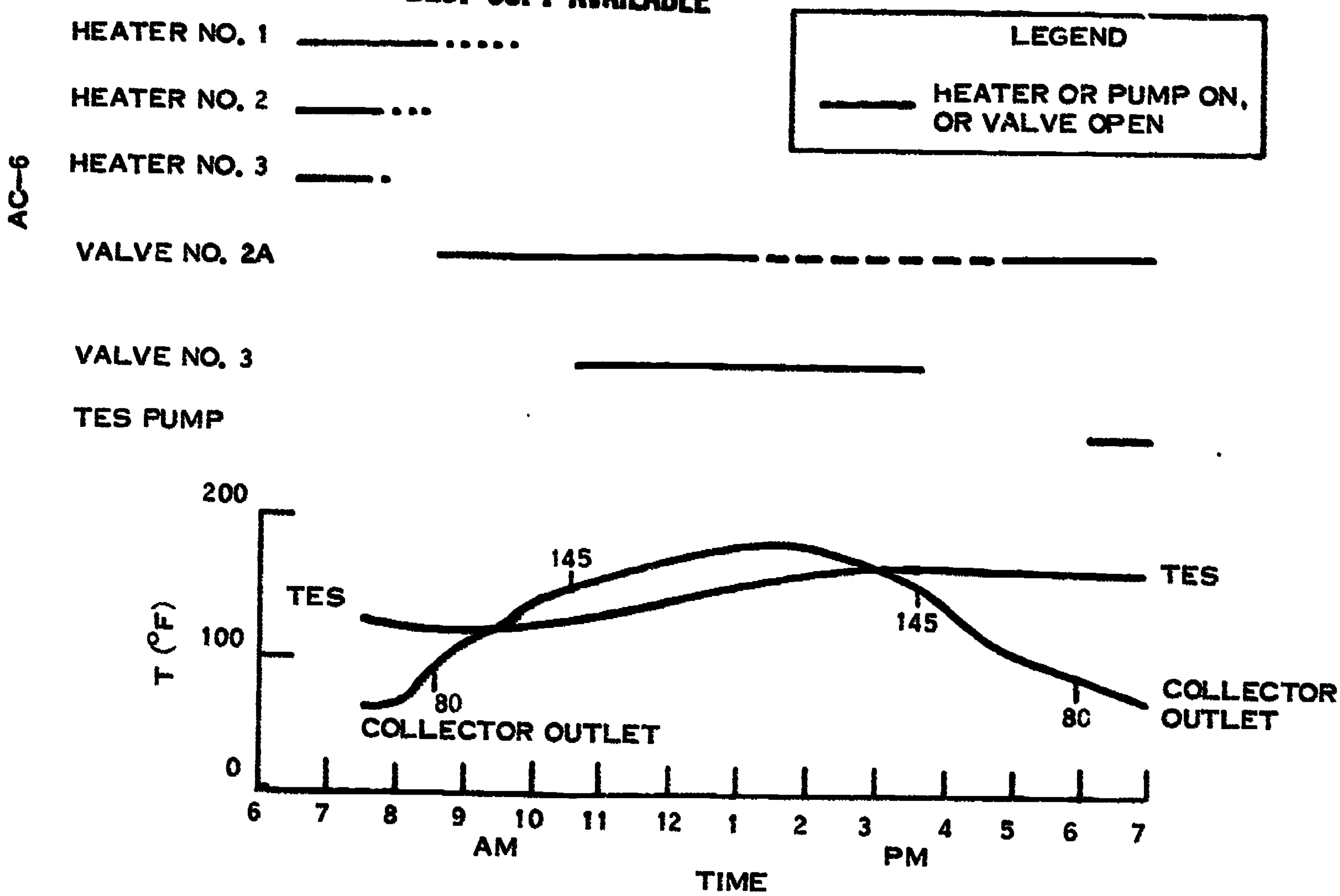

Figure 6-8. System's Daily Performance

This mode of operation then persisted till about 10:30 AM at which time the collector fluid reached its second transition temperature, 145°F, causing Valve No. 3 to open and permitting the collector fluid to transfer some of its energy to the TES tank. As can be seen in Figure 6-8, at 10:30 AM the TES temperature began to rise.

At shortly after 1:00 PM, Figure 6-8 shows Valve No. 2a alternately opening and closing till about 5:00 PM. 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 PM, the collector outlet temperature has again passed through its 145°F transition point. The solar flux 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 6-8, this results in the closing of Valve No. 3 and a rather constant TES tank temperature thereafter.

From 5:00 PM till 7:00 PM, Valve No. 2a is constantly open. During this time interval the collector outlet temperature is initially high enough (greater than 80°F) to supply the heating demand. However, by about 6:00 PM the collector outlet temperature had reduced to the 80°F Mode 1/3 transition point and is no longer used to supply heat. Nevertheless, the TES temperature is above the Mode 1/2/3 transition temperature of 130°F and consequently Valve No. 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 6-8. Under certain conditions, Valves 2a and 3 will be opened 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 80°F point and a transition from Mode 1 to 3 occurs, Valve No. 2a will open. 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 80°F. This would result in Valve No. 2a being closed and an increase in the collector fluid temperature, which would again cause Valve No. 2a to open. Such cyclical behavior obviously did not occur in the performance shown in Figure 6-8.

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 145°F 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. The relatively smooth behavior of the system is due to (1) the placement of the control thermocouple immediately upstream of all thermal loads, (2) the $\approx$ 3 minutes required for an element of fluid to circulate the loop, (3) the small overall magnitude of heat load changes occurring at the various mode transitions (except 3/4).

6.2 LOOP PERFORMANCE

6.2.1 PERFORMANCE SUMMARIES

Daily "point" readings of various data are taken by the school custodian between noon and 1 PM and telephoned to GE engineering personnel. The data actually reported is data/time, pyranometer reading, ambient conditions, collector inlet and outlet temperatures, flow rate, TES tank temperature and operational mode. Values of solar flux, incident energy, collector ΔT, energy delivered by the collectors, and a "spot" efficiency are then calculated as described in Table 6-3. Table 6-3 also defines all of the elements in the "noon" data summary charts shown in Figures 6-9 through 6-15.

Figures 6-16 through 6-43 represent, in graph form, the system operational data as a function of time and gives the pyranometer reading ⊙ in millivolts, the flow rate ⊡ in gpm, collector outlet temperature ▽ as given by T/C 43 of Bank "D", and collector temperature difference △ (Bank "D" outlet - inlet) along with the temperature of the thermal energy storage tank ◇ in ^{o}F.

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Table 6-3. Method of Calculating Operational Performance Summary Table Values

Column (1) Date and Time - Day, date and time of day data was taken. Normal time data is around 12:30PM.

Column (2) Pyranometer Reading - A millivolt reading from the pyranometer read from the data logger channel (1).

Column (3) Solar Flux - Designated by the symbol Φ and given in units of BTU/Hr/Ft^2.

Φ = Conversion constant X pyranometer reading (P_R) in millivolts (MV)

$\Phi = K P_R$

K = Conversion constant = 29.5 $\frac{BTU}{Hr\ Ft^2\ MV}$

Column (4) Incident Energy - Is the measure of energy in $\frac{BTU}{Hr}$ striking the collectors at approximate normal incidence.

Incident Energy E_I = Absorber area (A_p in ft^2) X number of panels (N) X Solar Flux (Φ)

$= A_p N \Phi \left(\frac{BTU}{Hr}\right)$ $\quad A_p = 30.03$ ft^2, $N = 114$

Thus E_I = [illegible] Φ

Column (5) Ambient Temp., Wind and Sky - Ambient outside air temperature obtained from the solar panel control console weather station instruments. Ambient temperatures are recorded continuously as well as wind, direction and velocity. Sky condition is a subjective measure of the sky cover, i.e., clear, no clouds - 0, 30% scattered clouds - ◔, 60% cloud cover ◑, 100% overcast ●.

Column (6) Collector Inlet - °F - The T/C reading (channel 10) of the up stream side of the inlet manifold for Bank "D". Bank "D" is the most representative of the average panel reading for the entire six banks.

Column (7) Collector Outlet - °F - The T/C reading (Channel 13) of the downstream side of the outlet manifold for Bank "D".

Column (8) ΔT - °F - The numeric difference between the inlet and outlet temperature of the collector panels. Column (7) - Column (6)

Column (9) Flow Rate - gpm - The collector fluid flow rate as recorded on Channel 2 of the data logger.

Column (10) Energy Delivered - Determines the amount of energy collected by the loop fluid due to a temperature increase from collector inlet to outlet.

Energy Delivered E_D = units conversion (8.021) x

fluid density (ρ $\frac{lbs}{ft^3}$) x

specific heat of fluid C_p ($\frac{BTU}{lb\text{-}°F}$) x

temperature rise across collector bank (ΔT °F) X

loop fluid flow rate Q (gpm)

$E_D = 8.021 \rho C_p \Delta T Q$

Since the loop was initially thought to operate between 30 and 170 °F the fluid conditions were taken at an average temperature of 100 °F for a 40% mixture of glycol to water.

ρ = 64.[illegible] lb/ft^3 $\quad C_p$ = .91

E_D = 467.1 ($\Delta T Q$)

Column (11) System Spot Efficiency - This is an instantaneous efficiency based on the data logger chart and is obtained by dividing the energy delivered E_D by the incident energy E_I. This number is accurate only so long as the conditions, mainly solar flux Φ, have remained constant over the period of the last data logger scan.

$$\text{System Spot Efficiency} = \frac{E_D \text{ (Column 10)}}{E_I \text{ (Column 4)}}$$

Column (12) TES - °F - This represents the T/C reading of the thermal energy storage tank and is read from Channel 71 of the data logger scan for the reporting time.

Column (13) Mode - An indication of whether the collector system control panel is in manual or automatic mode.

	SKY CODE	
R = RAIN	○	= CLEAR
K = SMOKE	⦶	= SCATTERED ≈ 30%
S = SNOW	⦷	= BROKEN ≈ 60%
H = HAZE	⊕	= OVERCAST

SOLAR COLLECTOR SYSTEM OPERATIONAL DATA
FOR
GROVER CLEVELAND SCHOOL
BOSTON, MASSACHUSETTS

-1974-

Dist:
A. Arker
C. Fowler — J. Notestein
S. Haas — K. Pater
W. Haggerty — J. Poland
S. Keer — W. Terrill
K. McFarland

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	DATE	PYRANOMETER READING	SOLAR FLUX (BTU/HR/FT^2)	INCIDENT ENER. X10^{-5} BTU/HR	AMBIENT TEMP. WIND & SKY	COLLECTOR INLET °F	COLLECTOR OUTLET °F	Δ T - °F	FLOW RATE GPM	ENERGY (Btu/Hr) DELIVERED X10-5	SYSTEM SPOT EFFICIENCY%	TES -°F	MODE				REMARKS
MON	4/1	2.61	77.0	3.28	46 10NW ⦷	120	138	18	cool. trans 58	4.88	148	80	A				142 panels operate, eff. questionable. Solar flux not consistent with loop temp.
TUES	4/2	0.69	20.4	.869	38 5E ⦷	75	75	0	cool. trans 60	0	0	130	A				142 panels - no collector output
WED	4/3	8.37	246.9	10.67	68 5W ○	176	205	29	64	8.6	81	163	A				144 - No problems Leaking panels replaced.
THUR	4/4	0.88	26.0	1.12	50 10SW R ⦶	85	85	0	73	0	0	153	A				144 - no problems
FRI	4/5 Last Fri. update	0.88	26.0	1.12	65 20SW ⊕	100.5	108.2	8.3	73.0	2.83	251	135.4	A				144 panels. No problems. Eff. not consistent with loop ΔT.
SAT																	
SUN																	

1:00 P.M. Time

P_R = PYRAMETER READING
A_p = PANEL AREA - FT.^{2}
N = NUMBER OF PANELS
ρ = LOOP FLUID DENSITY $\frac{LBS.}{FT.^3}$

C p = LOOP FLUID SPECIFIC HEAT $\frac{BTU/}{LB\ \text{-}°F}$
ΔT = COLLECTOR TEMP. DIFF.
Q = GPM

SOLAR FLUX (Φ) = 29.5 P_R
INCIDENT ENERGY = $A_p N \Phi$ = 4324 (Φ)
ENERGY DELIVERED = 467.1 (Δ T) (Q)
SPOT EFFICIENCY = $\frac{\text{DELIVERED ENERGY}}{\text{INCIDENT ENERGY}}$

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Figure 6-9. Solar Collector System Operational Data for Grover Cleveland School, Boston, Massachusetts

	SKY CODE	
R = RAIN	○	= CLEAR
K = SMOKE	⦶	= SCATTERED = 30%
S = SNOW	⦷	= BROKEN = 60%
H = HAZE	⊕	= OVERCAST

SOLAR COLLECTOR SYSTEM OPERATIONAL DATA FOR GROVER CLEVELAND SCHOOL BOSTON, MASSACHUSETTS

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	DATE	PYRANOMETER READING	SOLAR FLUX (BTU/HR/FT^2)	INCIDENT ENER. X10^{-5} BTU/HR	AMBIENT TEMP. WIND & SKY	COLLECTOR INLET °F	COLLECTOR OUTLET °F	Δ T - °F	FLOW RATE GPM	ENERGY (Btu/Hr) DELIVERED X10^{-5}	SYSTEM SPOT EFFICIENCY%	TES - °F	MODE				REMARKS
MON	4/8	2.88	85.0	3.68	45 5E ⦷	93.5	98.5	5.0	94.0	2.19	59.7	115.1	A				No problem. 144 panels. System found in manual mode on return from roof inspection. Suspect student inter. Proced. changed.
TUES	4/9	0.37	10.91	0.472	26 25NE ⊕	52.9	52.1	-	71.0	0	0	112.2	A				No problems
WED	4/10	2.29	69.6	3.0	25 5E ⊕	75.6	78.1	3.5	72.0	1.2	39	105.5	A				No problems
THUR	4/11	8.25	243.4	10.5	50 20NE ○	155.3	172.3		75.0	5.96	56.7	135.5	M				Manual mode - No problem, see J.Poland
FRI	4/12	8.13	248.73	10.36	50 5E ⦷	132.0	137.0	5.0	62.92	1.5	14.5	141.8	A				144 collectors. No problems.
SAT																	
SUN																	

NOTE:

1:00 P.M. Time

P_R = PYRAMETER READING
A_P = PANEL AREA - FT.^{2}
N = NUMBER OF PANELS
ρ = LOOP FLUID DENSITY $\frac{LBS.}{FT.^3}$

Cp = LOOP FLUID SPECIFIC HEAT $\frac{BTU/}{LB\ -°F}$
ΔT = COLLECTOR TEMP. DIFF.
Q = GPM

SOLAR FLUX (Φ) = 29.5 P_R
INCIDENT ENERGY = $A_P N \Phi$ = 4324 (Φ)
ENERGY DELIVERED = 467.1 (Δ T)(Q)
SPOT EFFICIENCY = $\frac{\text{DELIVERED ENERGY}}{\text{INCIDENT ENERGY}}$

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Figure 6-10. Solar Collector System Operational Data for Grover Cleveland School, Boston, Massachusetts

	SKY CODE	
R = RAIN	○	= CLEAR
K = SMOKE	⦶	= SCATTERED ≈ 30%
S = SNOW	⦶	= BROKEN ≈ 60%
H = HAZE	⊕	= OVERCAST

SOLAR COLLECTOR SYSTEM OPERATIONAL DATA FOR GROVER CLEVELAND SCHOOL BOSTON, MASSACHUSETTS

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Day	DATE	PYRANOMETER READING	SOLAR FLUX (BTU/HR/FT2)	INCIDENT ENER. X10-5 BTU/HR	AMBIENT TEMP. WIND & SKY	COLLECTOR INLET °F	COLLECTOR OUTLET °F	△ T - °F	FLOW RATE GPM	ENERGY (Btu/Hr) DELIVERED X10-5	SYSTEM SPOT EFFICIENCY%	TES -°F	MODE				REMARKS
MON	4/15	----PATRIOTS DAY ---○----- HOLIDAY IN MASSACHUSETTS - NO READINGS TAKEN----															
TUES	4/16	8.56	253	10.92	55 20NE ○	161.8	177.6	15.8	84	6.2	56.7	125.0	A				Automatic. No problems.
WED	4/17	2.29	67.56	2.92	25 10S ⊕	75.6	78.1	2.5	72	.842	1.245	105.5	A				Automatic. No problems.
THUR	4/18	8.40	247.8	10.71	65 10SE ○	174.9	189.7	14.8	75	5.19	48.4	174.5	M				Manual mode - maintenance
FRI	4/19	1.74	51.33	2.22	40 5NE ⊕	102.5	108.1	5.6	N/A	-	-	155.4	M				Manual - Operating on back-up pump.
SAT																	
SUN																	

1:00 P.M. Time

P_R = PYRAMETER READING
A_p = PANEL AREA - FT.^{2}
N = NUMBER OF PANELS
ρ = LOOP FLUID DENSITY $\frac{LBS}{FT.^3}$

C_p = LOOP FLUID SPECIFIC HEAT $\frac{BTU}{LB\ °F}$
ΔT = COLLECTOR TEMP. DIFF.
Q = GPM

SOLAR FLUX (Φ) = 29.5 P_R
INCIDENT ENERGY = $A_p N \Phi$ = 4324 (Φ)
ENERGY DELIVERED = 467.1 (Δ T) (Q)
SPOT EFFICIENCY = $\frac{\text{DELIVERED ENERGY}}{\text{INCIDENT ENERGY}}$

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Figure 6-11. Solar Collector System Operational Data for Grover Cleveland School, Boston, Massachusetts

SKY CODE

R = RAIN ○ = CLEAR
K = SMOKE ⦶ = SCATTERED = 30%
S = SNOW ⦷ = BROKEN = 60%
H = HAZE ⊕ = OVERCAST

SOLAR COLLECTOR SYSTEM OPERATIONAL DATA FOR GROVER CLEVELAND SCHOOL BOSTON, MASSACHUSETTS

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K. McFarland Page____

	Date	Pyranometer Reading	Solar Flux (BTU/HR/FT²)	Incident Ener. X10^{5} BTU/HR	Ambient Temp. Wind & Sky	Collector Inlet °F	Collector Outlet °F	ΔT - °F	Flow Rate GPM	Energy (Btu/Hr) Delivered X10-5	System Spot Efficiency %	TES -°F	Mode					Remarks
MON	4/22	3.85	113.5	4.91	75 10SW ⊕	167.5	171.8	4.3	48	.960	19	164.3	A					Automatic. Some leak Bank A&D
TUES	4/23	5.17	152.5	6.59	70 10SW ⦷	126.6	144.6	18.0	49	4.10	62	152.7	A					Automatic. Leaks fixed. Everything OK.
WED	4/24	1.61	47.5	2.05	50 5N ⊕	83.6	84.9	1.3	73	0.44	21	111.5	A					Automatic. No problems.
THUR	4/25	2.35	69.33	2.99	44 10E ⊕	93.1	96.5	3.4	64	1.01	34	102.3	A					Automatic - No problems.
FRI	4/26	8.97	264.62	11.43	51 5NW ⦶	149.3	174.0	24.7	47	5.40	47	132.7	A					Automatic - No problems.
SAT																		
SUN																		

1:00 P.M. Time

P_R = PYRAMETER READING
A_p = PANEL AREA - FT.^{2}
N = NUMBER OF PANELS
ρ = LOOP FLUID DENSITY $\frac{LBS.}{FT.^3}$

C p = LOOP FLUID SPECIFIC HEAT $\frac{BTU/}{LB\ -°F}$
ΔT = COLLECTOR TEMP. DIFF.
Q = GPM

SOLAR FLUX (Φ) = 29.5 P_R
INCIDENT ENERGY = $A_p N \Phi$ = 4324 (Φ)
ENERGY DELIVERED = 467.1 (ΔT)(Q)
SPOT EFFICIENCY = $\frac{\text{DELIVERED ENERGY}}{\text{INCIDENT ENERGY}}$

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Figure 6-12. Solar Collector System Operational Data For Grover Cleveland School, Boston, Massachusetts

150

SKY CODE		
R = RAIN	○	= CLEAR
K = SMOKE	⦶	= SCATTERED ≈ 30%
S = SNOW	⦶	= BROKEN ≈ 60%
H = HAZE	⊕	= OVERCAST

SOLAR COLLECTOR SYSTEM OPERATIONAL DATA FOR GROVER CLEVELAND SCHOOL BOSTON, MASSACHUSETTS

-1974-

Dist:
A. Arker
C. Fowler — J. Notestein
S. Haas — K. Pater
W. Haggerty — J. Poland
S. Keer — W. Terrill
K. McFarland — Page____

	DATE	PYRANOMETER READING	SOLAR FLUX (BTU/HR/FT²)	INCIDENT ENER. X10⁻⁵ BTU/HR	AMBIENT TEMP. WIND & SKY	COLLECTOR INLET °F	COLLECTOR OUTLET °F	Δ T - °F	FLOW RATE GPM	ENERGY (Btu/Hr) DELIVERED X10-5	SYSTEM SPOT EFFICIENCY%	TES -°F	MODE				REMARKS
MON	4/29	7.97	235.1	10.16	76 10SW ⦶	196.5	214.6	18.1	47	3.974	39.1	185.9	A				Auto. No problems.
TUES	4/30	2.24	66.1	2.86	52 10E ⊕	123.7	126.3	2.6	71	0.862	30	125.9	A				Auto. No problems.
WED	5/1	8.32	245.0	10.59	65 20W ○	198.0	213.8	15.8	47	0.347	33	198.3	A				Auto. No problems.
THUR	5/2	8.35	246.3	10.65	50 10NW ○	191.4	209.5	18.1	47	0.397	37	183.9	A				Auto. Some leaks and pump instr vibr.
FRI	5/3	2.66	78.47	3.39	55 5SE ⊕	115.9	118.8	2.9	70	0.948	28	137.1	A				Auto. No problems.
SAT																	
SUN																	

1:00 P.M. Time

P_R = PYRAMETER READING
A_p = PANEL AREA - FT.^{2}
N = NUMBER OF PANELS
ρ = LOOP FLUID DENSITY $\frac{LBS}{FT.^3}$

Cp = LOOP FLUID SPECIFIC HEAT $\frac{BTU/}{LB\ -°F}$
ΔT = COLLECTOR TEMP. DIFF.
Q = GPM

SOLAR FLUX (Φ) = 29.5 P_R
INCIDENT ENERGY = $A_p N \Phi$ = 4324 (Φ)
ENERGY DELIVERED = 467.1 (ΔT) (Q)
SPOT EFFICIENCY = $\frac{\text{DELIVERED ENERGY}}{\text{INCIDENT ENERGY}}$

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Figure 6-13. Solar Collector System Operational Data for Grover Cleveland School, Boston, Massachusetts

SKY CODE		
R = RAIN	○	= CLEAR
K = SMOKE	⦶	= SCATTERED ≈ 30%
S = SNOW	⦷	= BROKEN ≈ 60%
H = HAZE	⊕	= OVERCAST

SOLAR COLLECTOR SYSTEM OPERATIONAL DATA
FOR
GROVER CLEVELAND SCHOOL
BOSTON, MASSACHUSETTS

-1974-

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K. McFarland

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	DATE	PYRANOMETER READING	SOLAR FLUX (BTU/HR/FT2)	INCIDENT ENER. X10^{-5} BTU/HR	AMBIENT TEMP. WIND & SKY	COLLECTOR INLET °F	COLLECTOR OUTLET °F	Δ T - °F	FLOW RATE GPM	ENERGY (Btu/Hr) DELIVERED X10-5	SYSTEM SPOT EFFICIENCY%	TES -°F	MODE				REMARKS
MON	5/6	7.09	209.16	9.04	50 10E ○	133.7	174.6	40.9	72	13.69	152	135.5	A				Auto. No problems. Eff - not consistent w/solar flux.
TUES	5/7	1.52	44.8	1.94	50 5NW ⊕	92.7	95.3	2.6	57	.692	36	129.9	A				No problems.
WED	5/8	8.19	241.61	10.45	55 10W ○	166.5	187.3	20.8	61	5.93	57	163.6	A				Auto. No problems.
THUR	5/9	3.49	102.9	4.45	55 10S ⦷	125.0	128.3	3.3	71	1.09	25	153.5	A				Auto. No problems.
FRI	5/10	0.18	5.31	.229	49 2E R ⊕	64.3	63.6	0	70	0	0	127.3	A				Auto. No problems.
SAT																	
SUN																	

1:00 P.M. Time
P_R = PYRAMETER READING
A_p = PANEL AREA - $FT.^2$
N = NUMBER OF PANELS
ρ = LOOP FLUID DENSITY $\frac{LBS.}{FT.^3}$

C_p = LOOP FLUID SPECIFIC HEAT $\frac{BTU/}{LB\ °F}$
ΔT = COLLECTOR TEMP. DIFF.
Q = GPM

SOLAR FLUX (Φ) = 29.5 P_R
INCIDENT ENERGY = $A_p N \Phi$ = 4324 (Φ)
ENERGY DELIVERED = 467.1 (Δ T) (Q)
SPOT EFFICIENCY = $\frac{\text{DELIVERED ENERGY}}{\text{INCIDENT ENERGY}}$

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Figure 6-14. Solar Collector System Operational Data for Grover Cleveland School, Boston, Massachusetts

SKY CODE	
R = RAIN	○ = CLEAR
K = SMOKE	⦵ = SCATTERED ≈ 30%
S = SNOW	⦶ = BROKEN ≈ 60%
H = HAZE	⊕ = OVERCAST

SOLAR COLLECTOR SYSTEM OPERATIONAL DATA
FOR
GROVER CLEVELAND SCHOOL
BOSTON, MASSACHUSETTS

Dist:
A. Arker
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K. McFarland
J. Notestein
K. Pater
J. Poland
W. Terrill

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-1974-

	DATE	PYRANOMETER READING	SOLAR FLUX (BTU/HR/FT2)	INCIDENT ENER. X10-5 BTU/HR	AMBIENT TEMP. WIND & SKY	COLLECTOR INLET °F	COLLECTOR OUTLET °F	△ T - °F	FLOW RATE GPM	ENERGY (Btu/Hr) DELIVERED X10-5	SYSTEM SPOT EFFICIENCY%	TES -°F	MODE				REMARKS
MON	5/13	3.85	113.6	4.91	60 10W ⦶	129.5	144.5	15.0	55	3.85	78	124.8	A				Auto. Panel 121 showing seepage - 203 possible seepage.
TUES	5/14	7.83	230.9	9.98	65 5W ○	194.9	212.2	17.3	47	3.798	38	186.6	A				Auto - No problems.
WED	5/15	7.92	233.6	10.10	75 30SW ○	185.0	196.7	11.7	80	4.372	43.2	185.8	A				Auto - No problems.
THUR	5/16	8.01	236.3	10.22	75 10W ○	206.7	223.2	16.5	82	6.32	61.8	205.3	A				Auto - No problems. Dumping heat.
FRI	5/17	8.11	239.2	10.34	85 10W ○	179.6	191.6	11.8	80	4.41	42.6	180.3	A				Auto - No problems. No dumping heat.
SAT																	
SUN																	

1:00 P.M. Time

P_R = PYRAMETER READING
A_p = PANEL AREA - $FT.^2$
N = NUMBER OF PANELS
ρ = LOOP FLUID DENSITY $\frac{LBS.}{FT.^3}$

C_p = LOOP FLUID SPECIFIC HEAT $\frac{BTU/}{LB\text{-}°F}$
△T = COLLECTOR TEMP. DIFF.
Q = GPM

SOLAR FLUX (Φ) = 29.5 P_R
INCIDENT ENERGY = $A_p N \Phi$ = 4324 (Φ)
ENERGY DELIVERED = 467 · (△T)(Q)
SPOT EFFICIENCY = $\frac{\text{DELIVERED ENERGY}}{\text{INCIDENT ENERGY}}$

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Figure 6-15. Solar Collector System Operational Data for Grover Cleveland School, Boston, Massachusetts

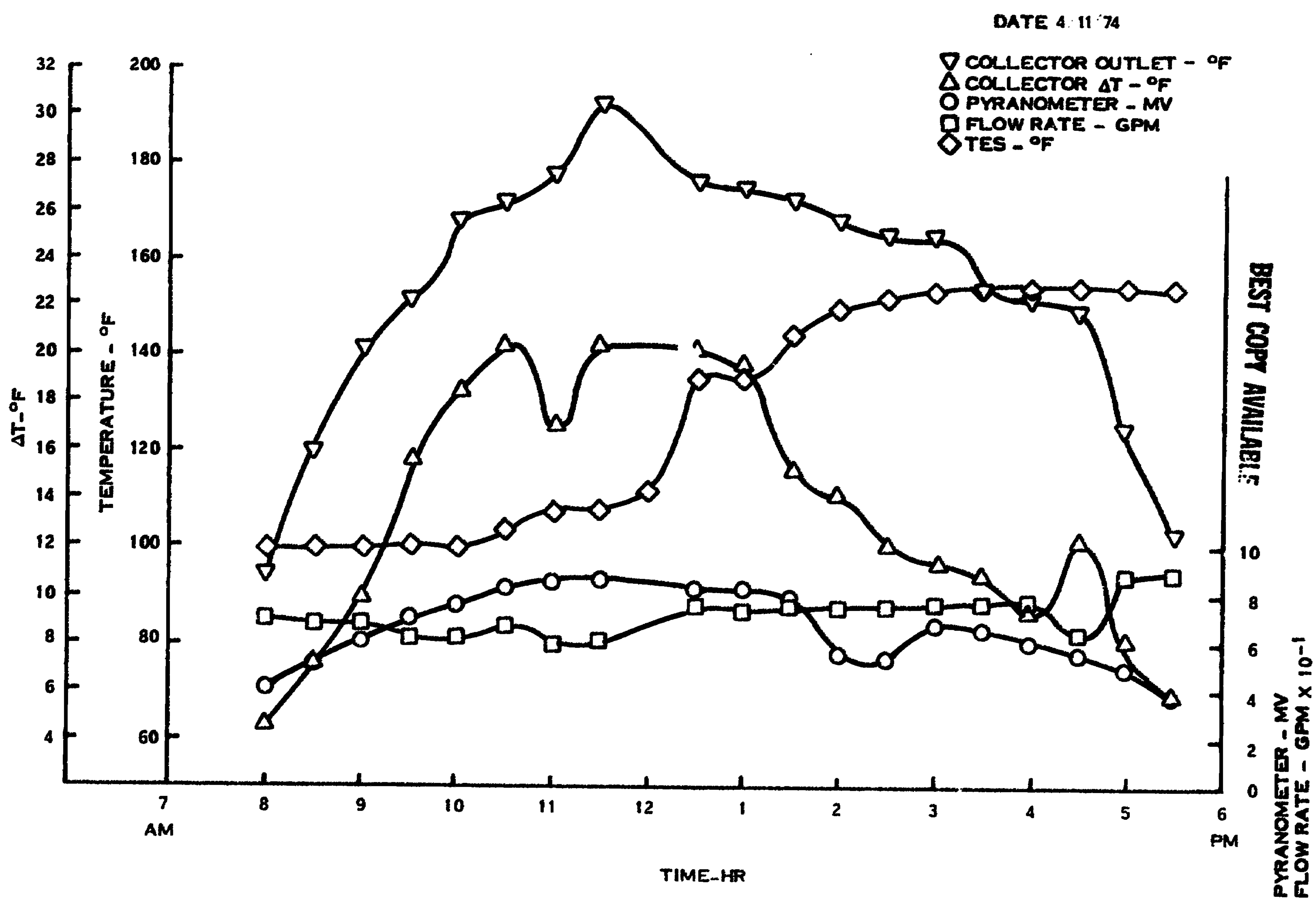

Figure 6-16. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-11-74

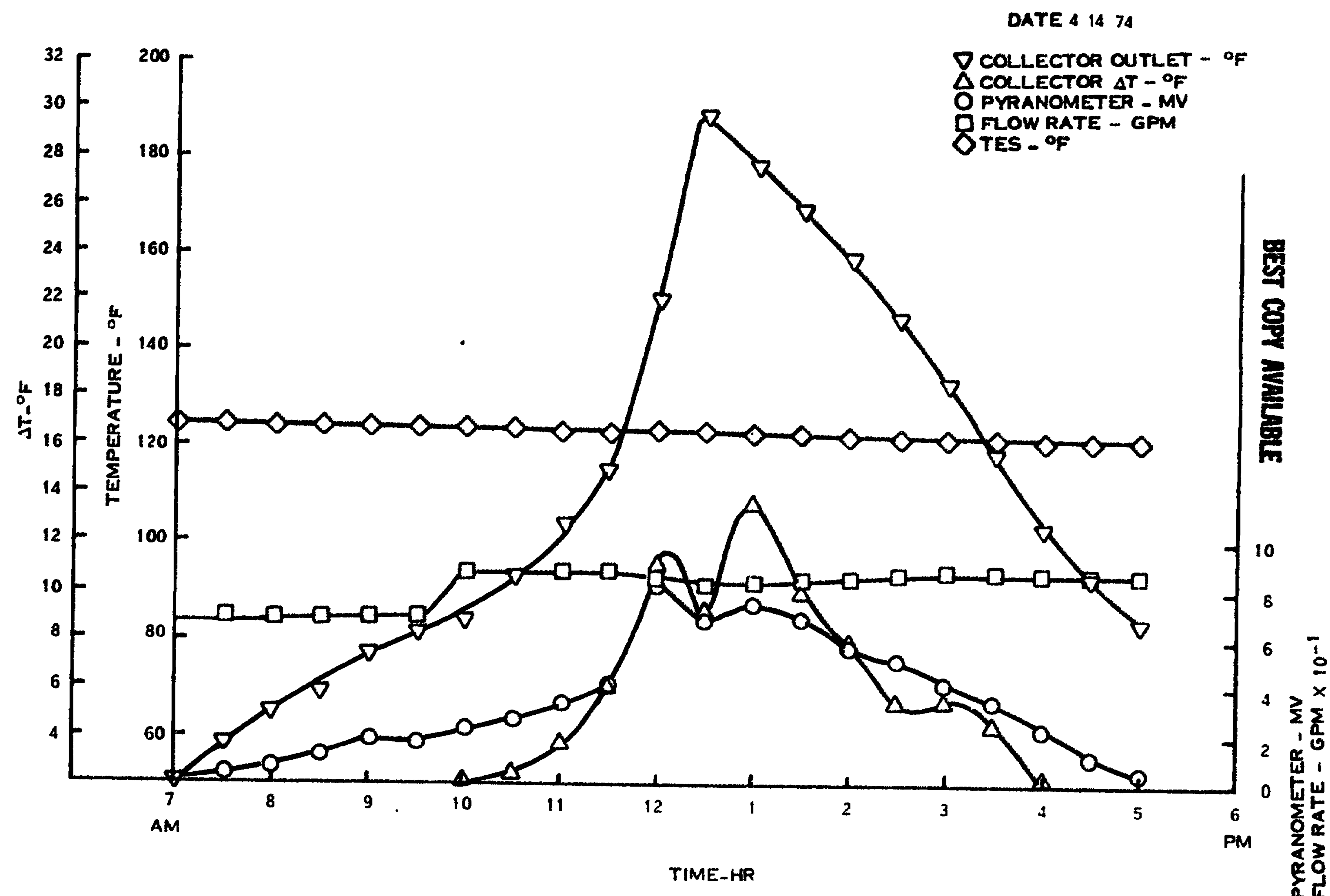

Figure 6-17. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-14-74

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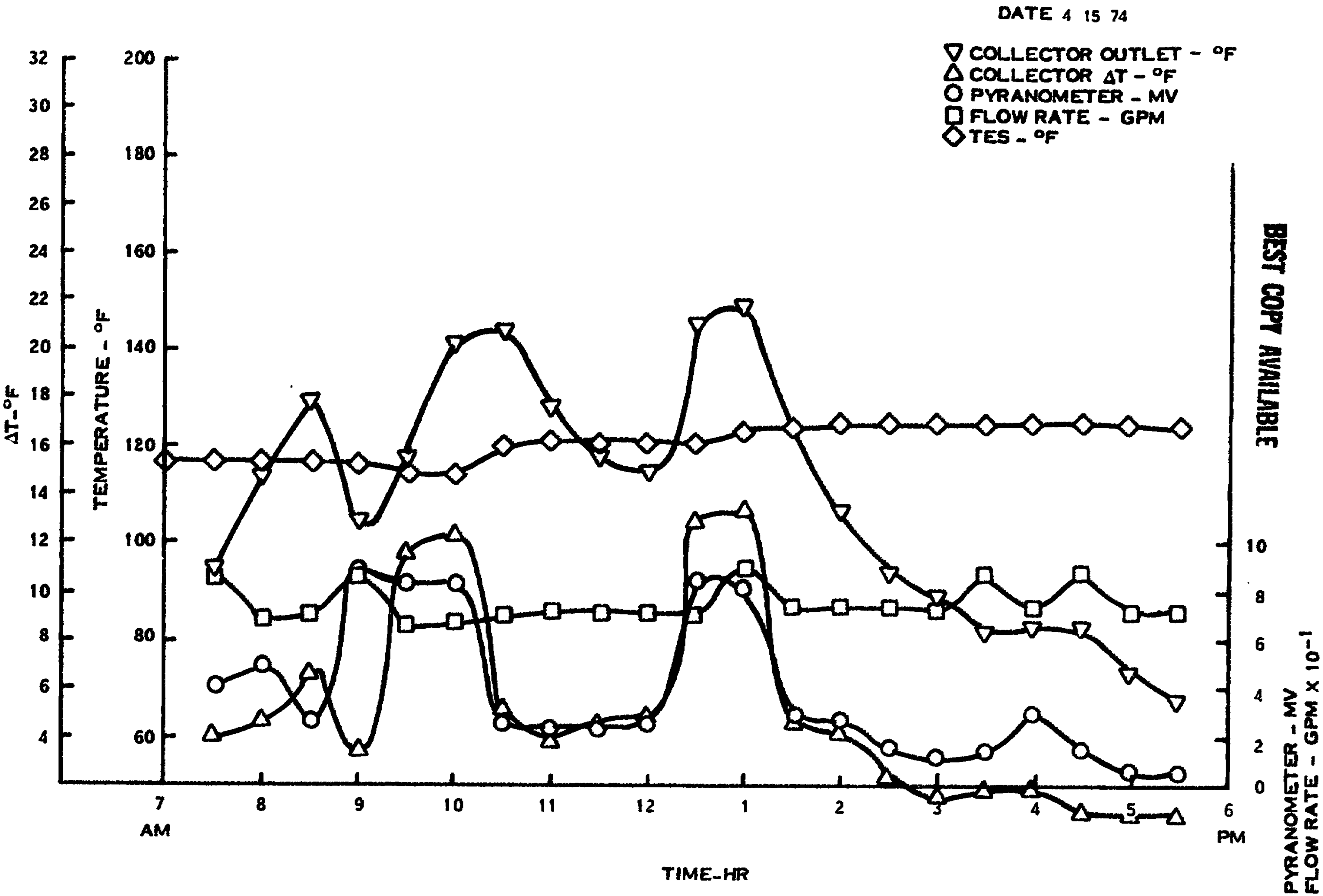

Figure 6-18. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-15-74

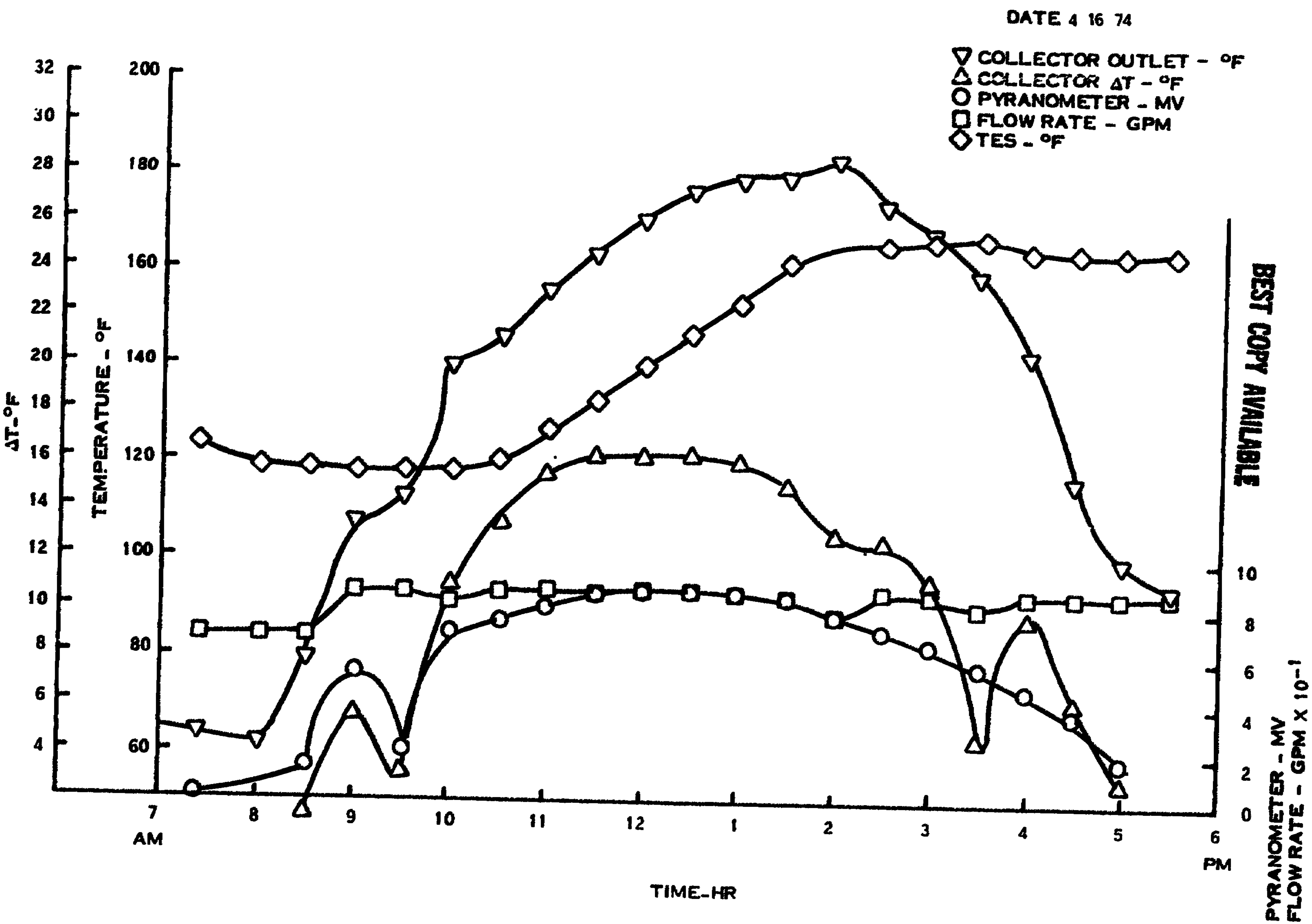

Figure 6-19. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-16-74

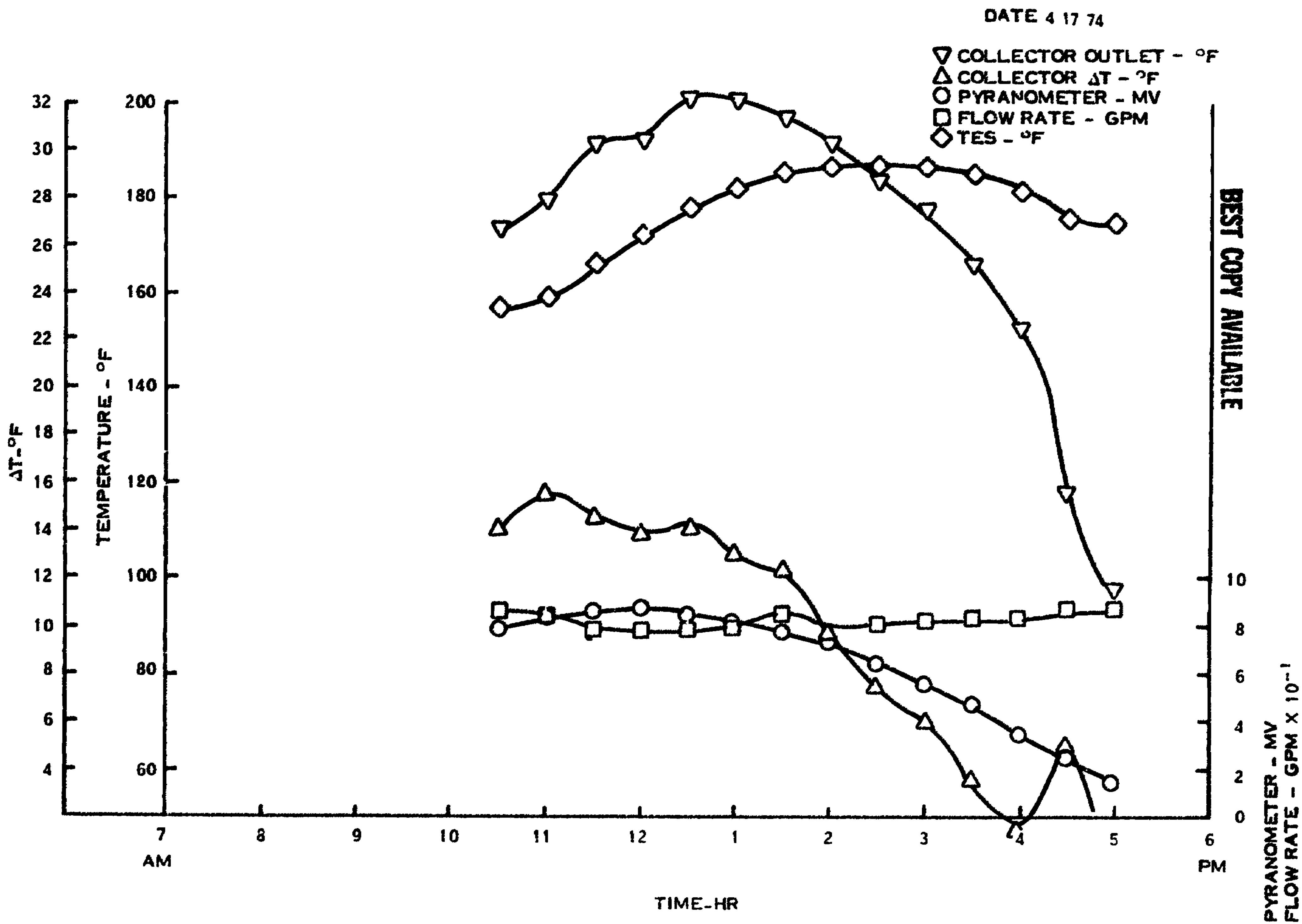

Figure 6-20. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-17-74

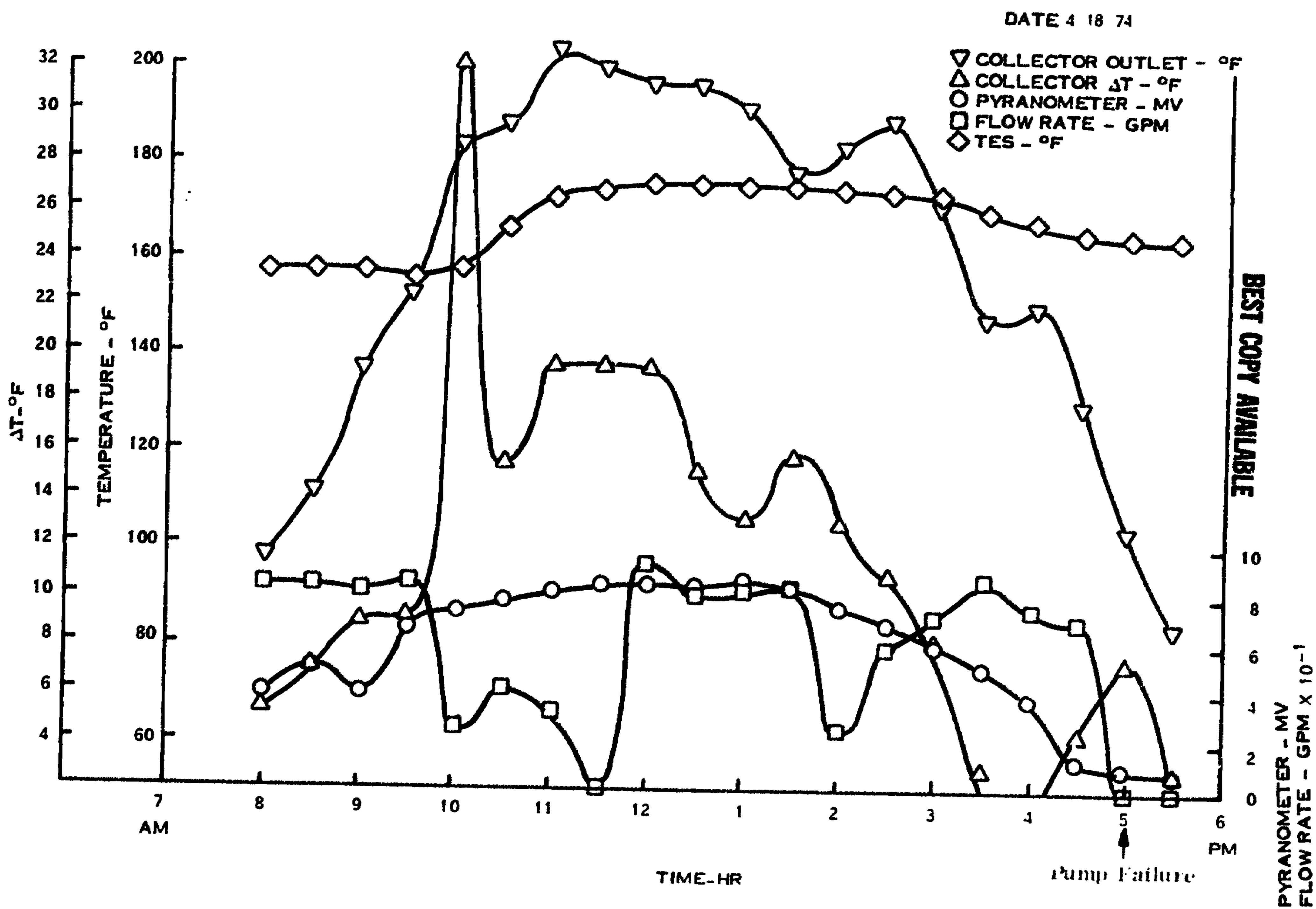

Figure 6-21. Solar Collector Loop Data Grover Cleveland School, Boston, Mass.. 4-18-74

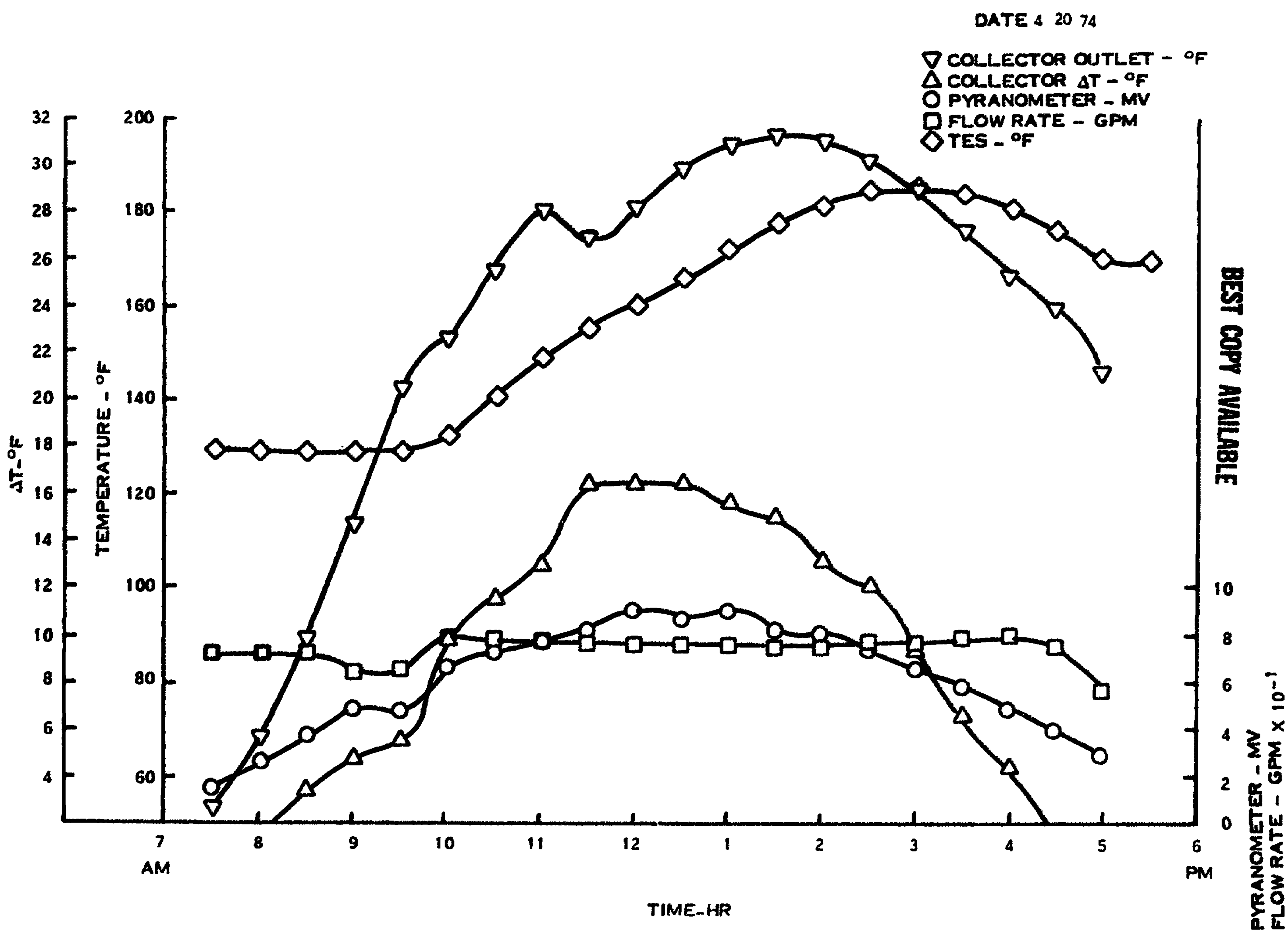

Figure 6-22. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4 20 74

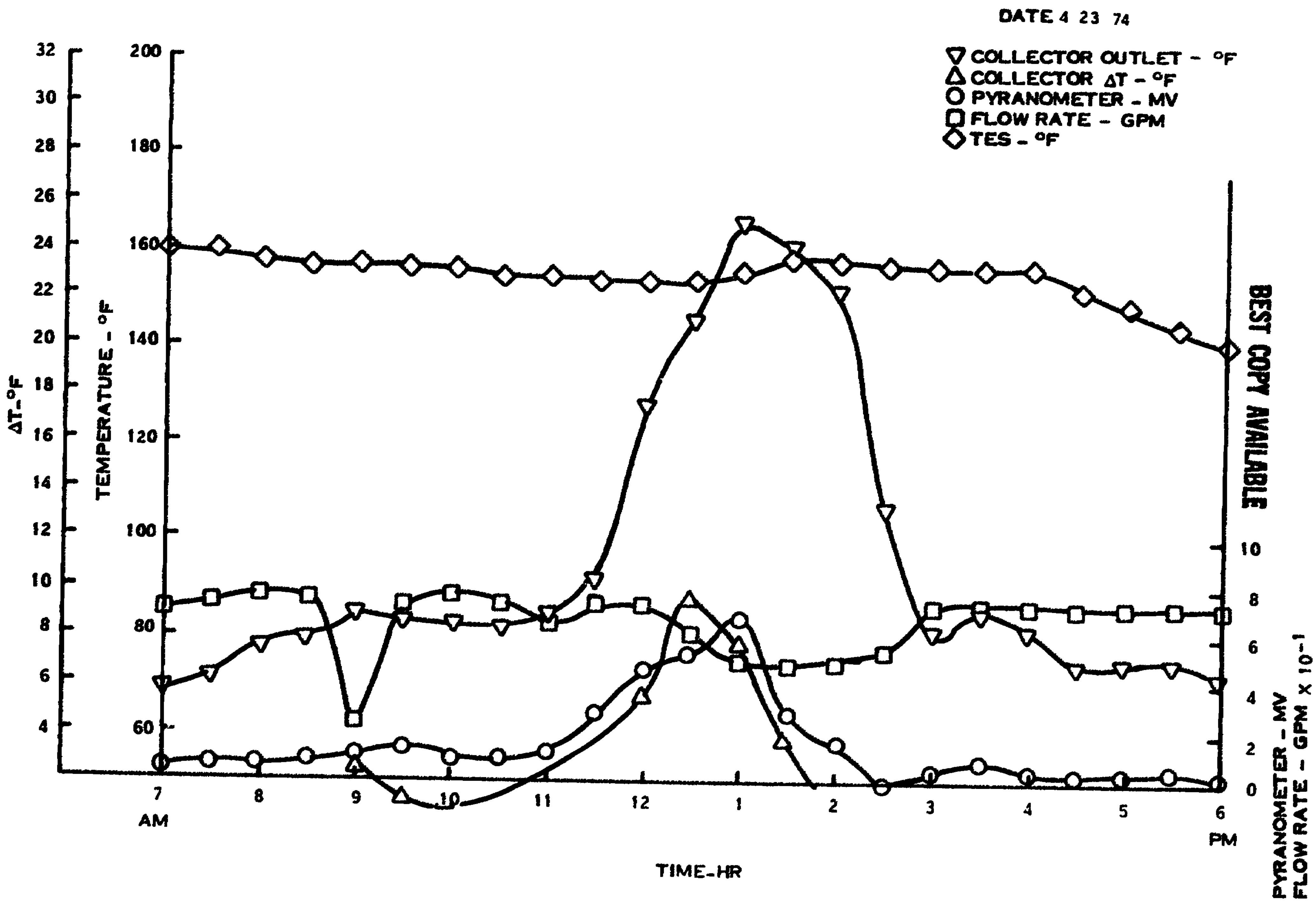

Figure 6-23. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-23-74

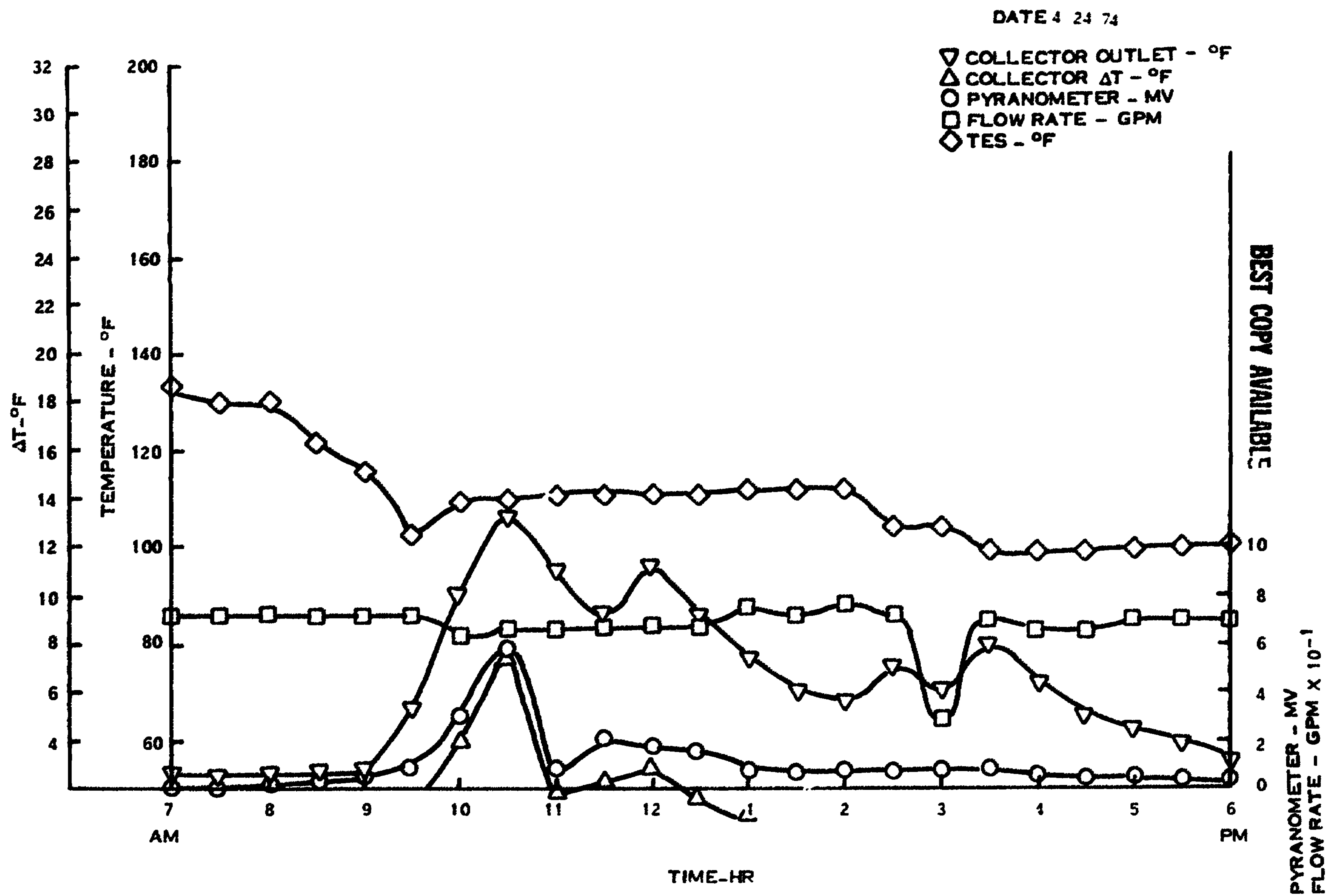

Figure 6-24. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-24-74

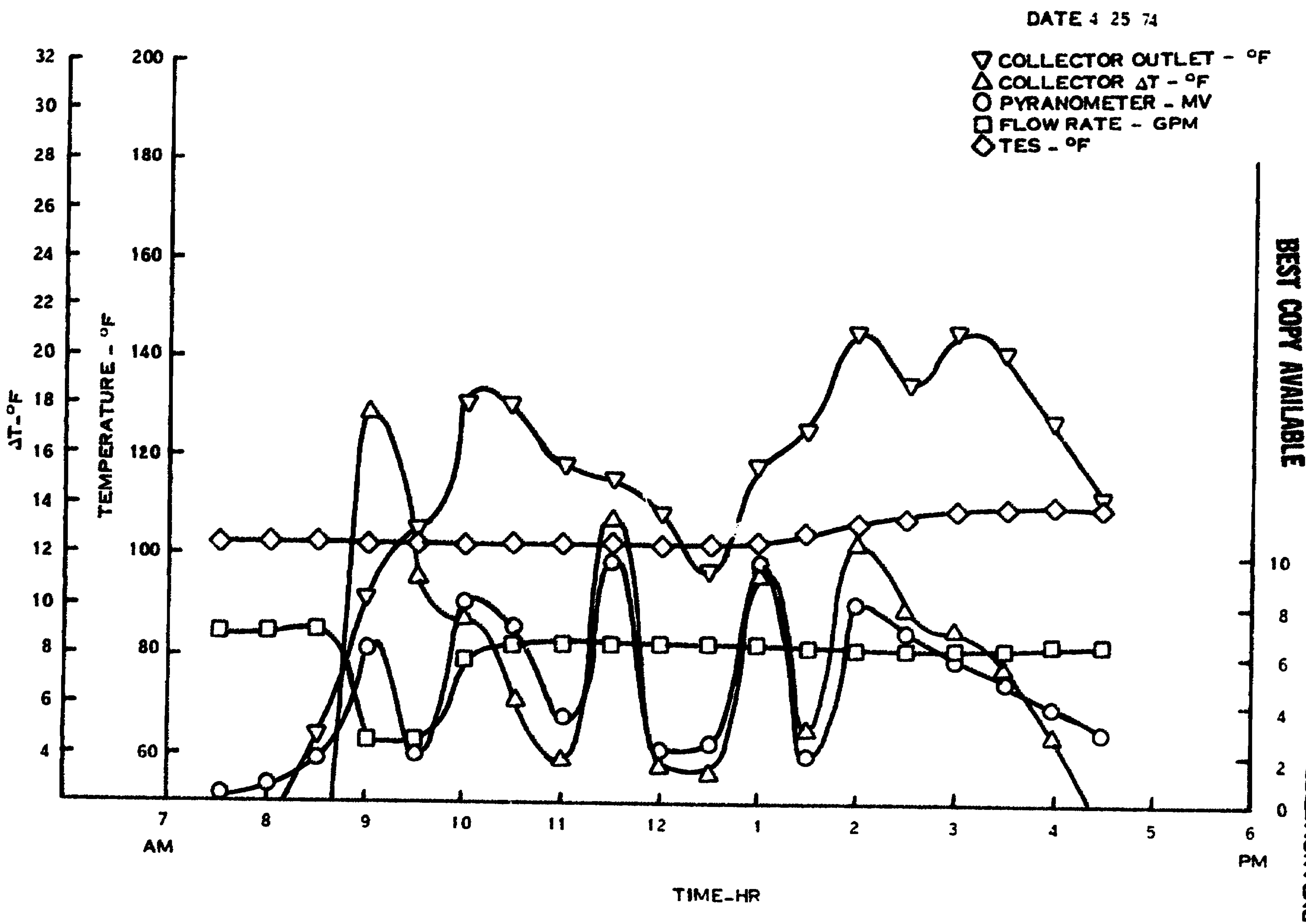

Figure 6-25. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-25-74

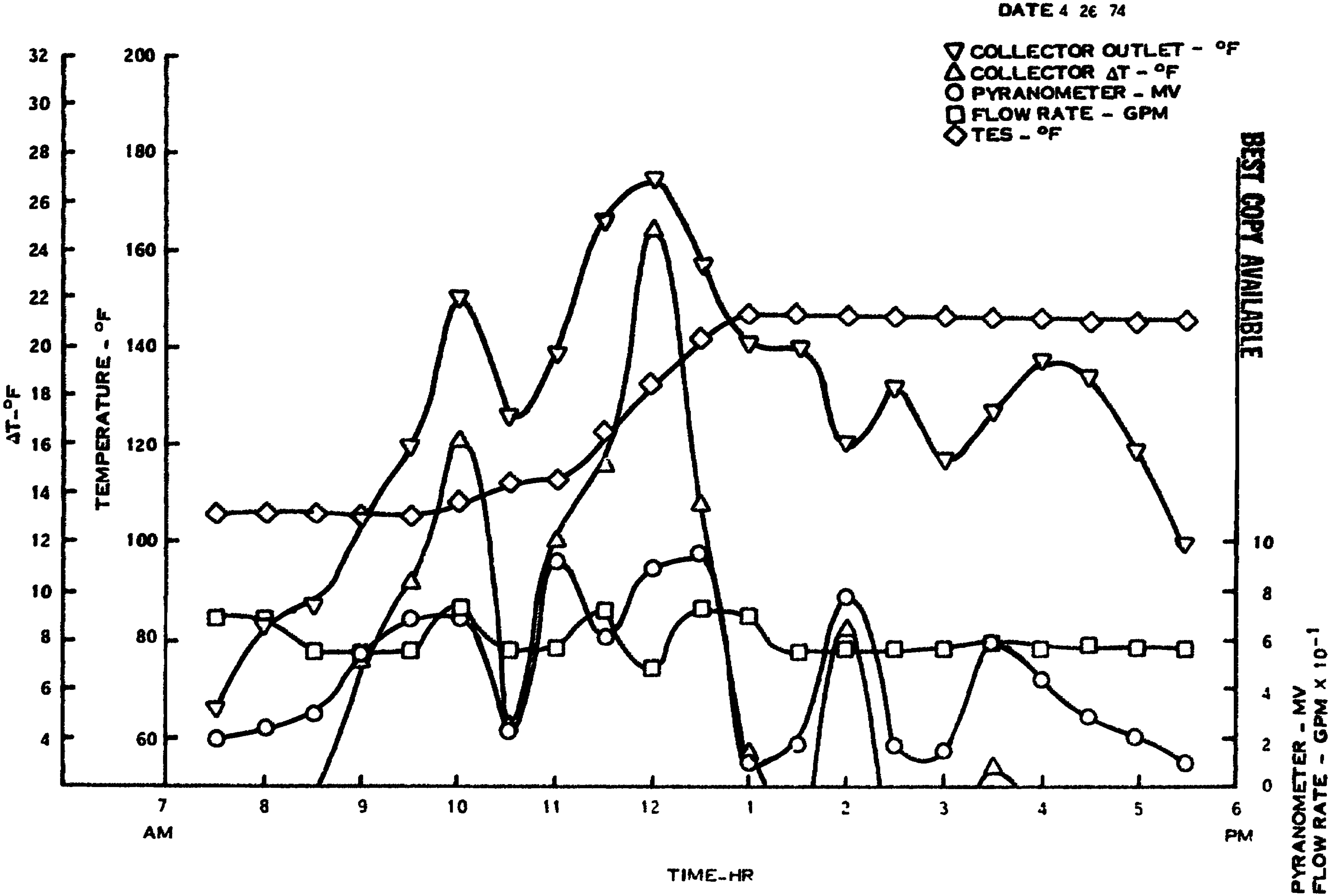

Figure 6-26. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-26-74

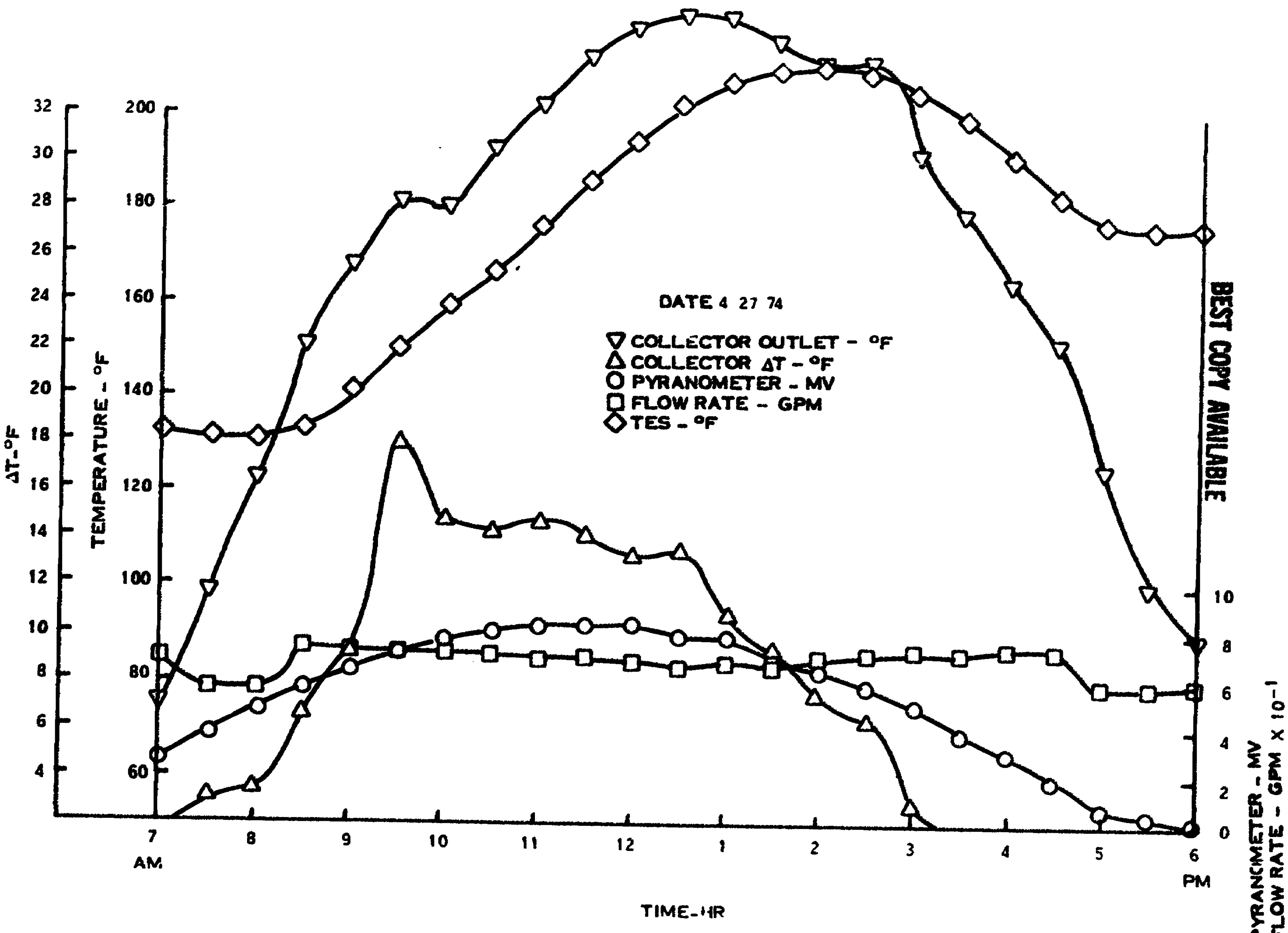

Figure 6-27. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-27-74

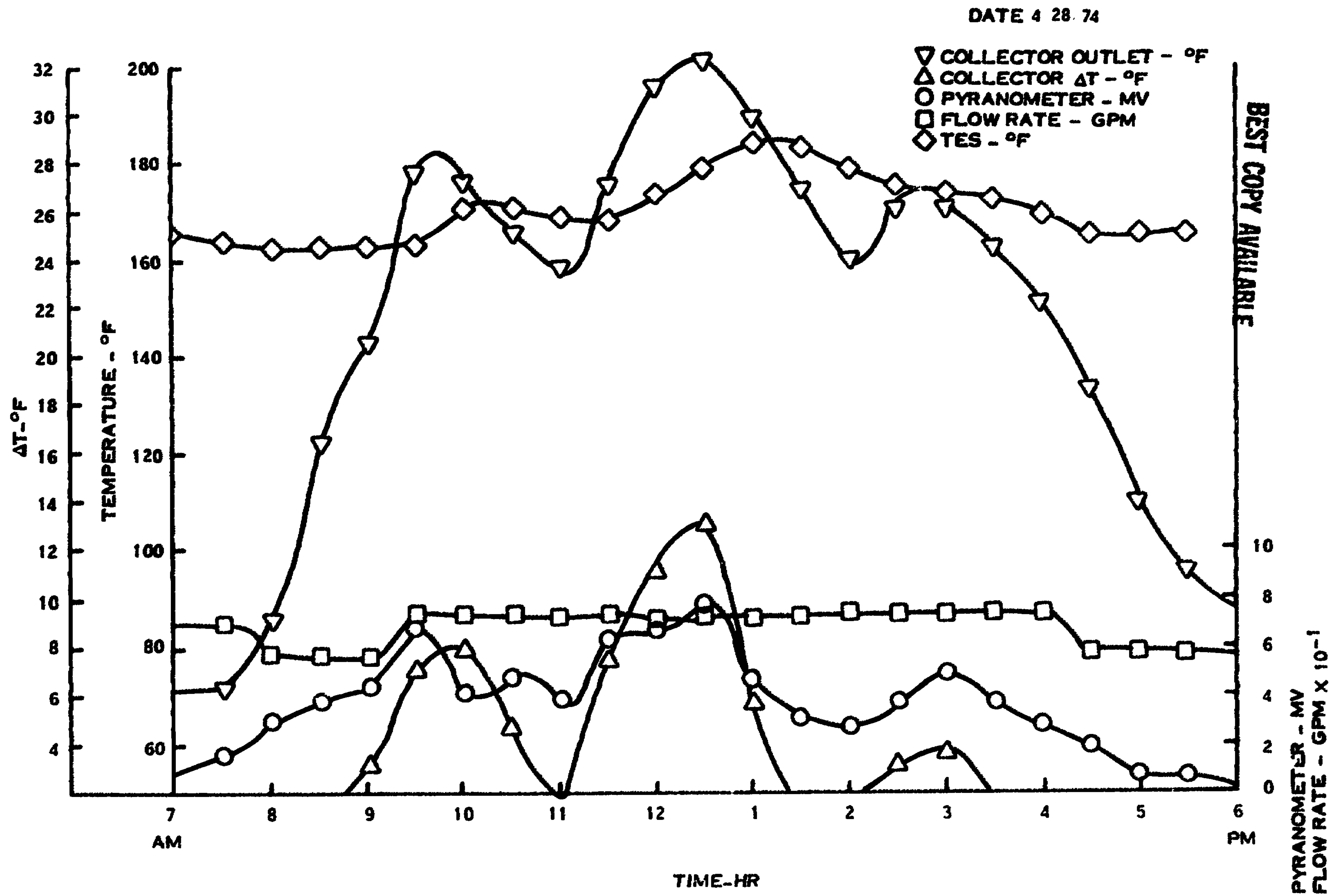

Figure 6-28. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-28-74

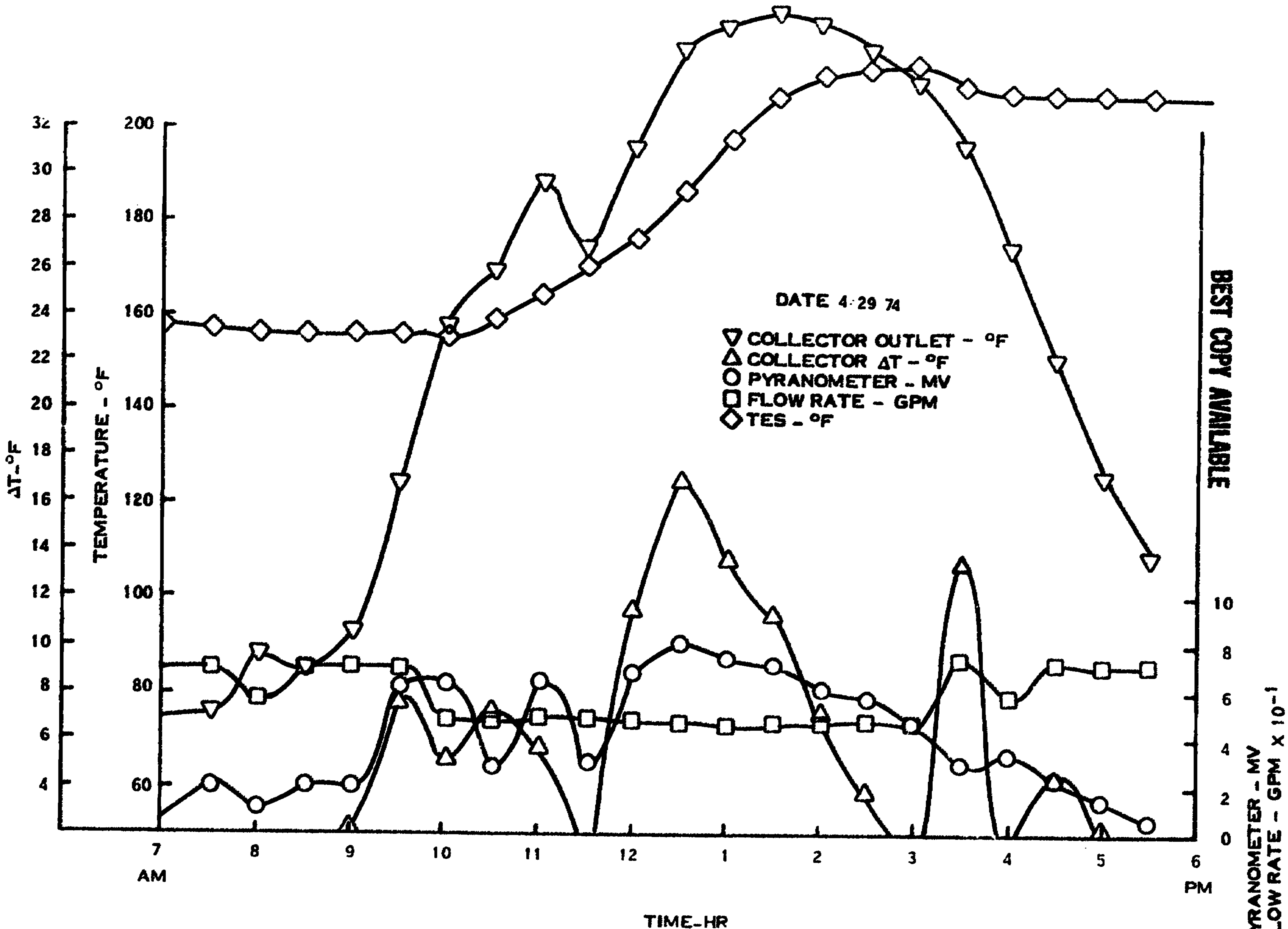

Figure 6-29. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-29-74

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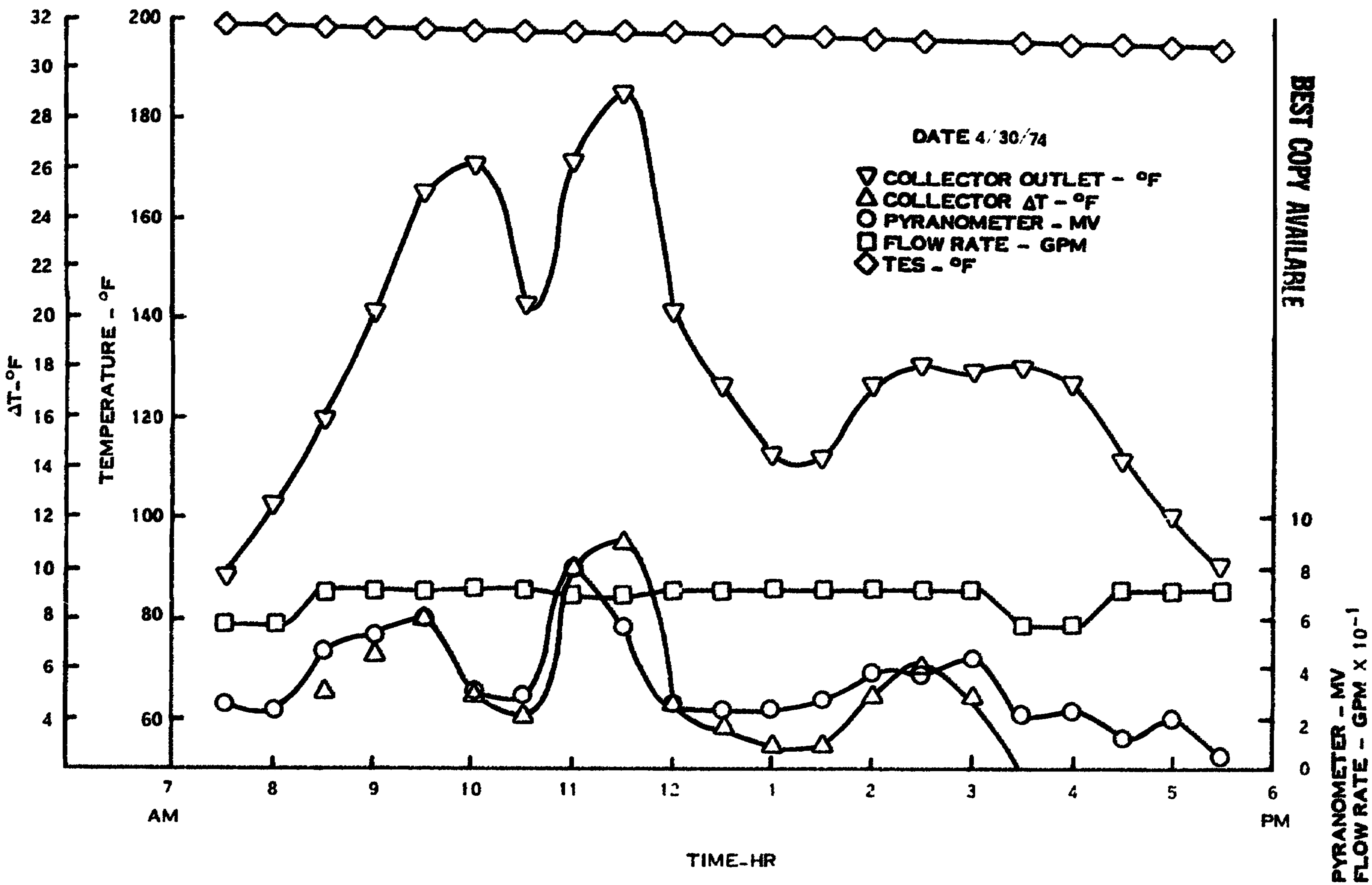

Figure 6-30. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 4-30-74

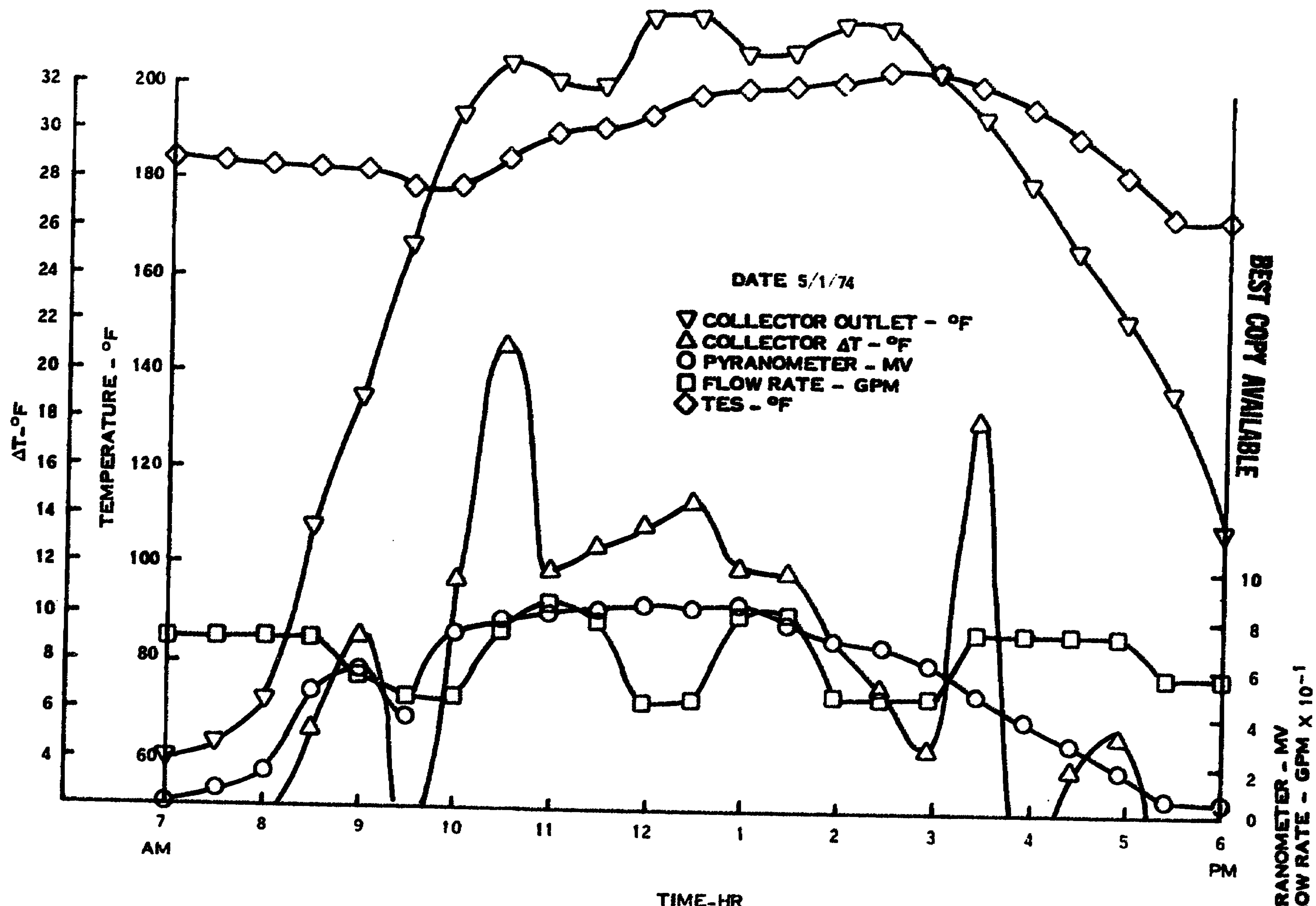

Figure 6-31. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-1-74

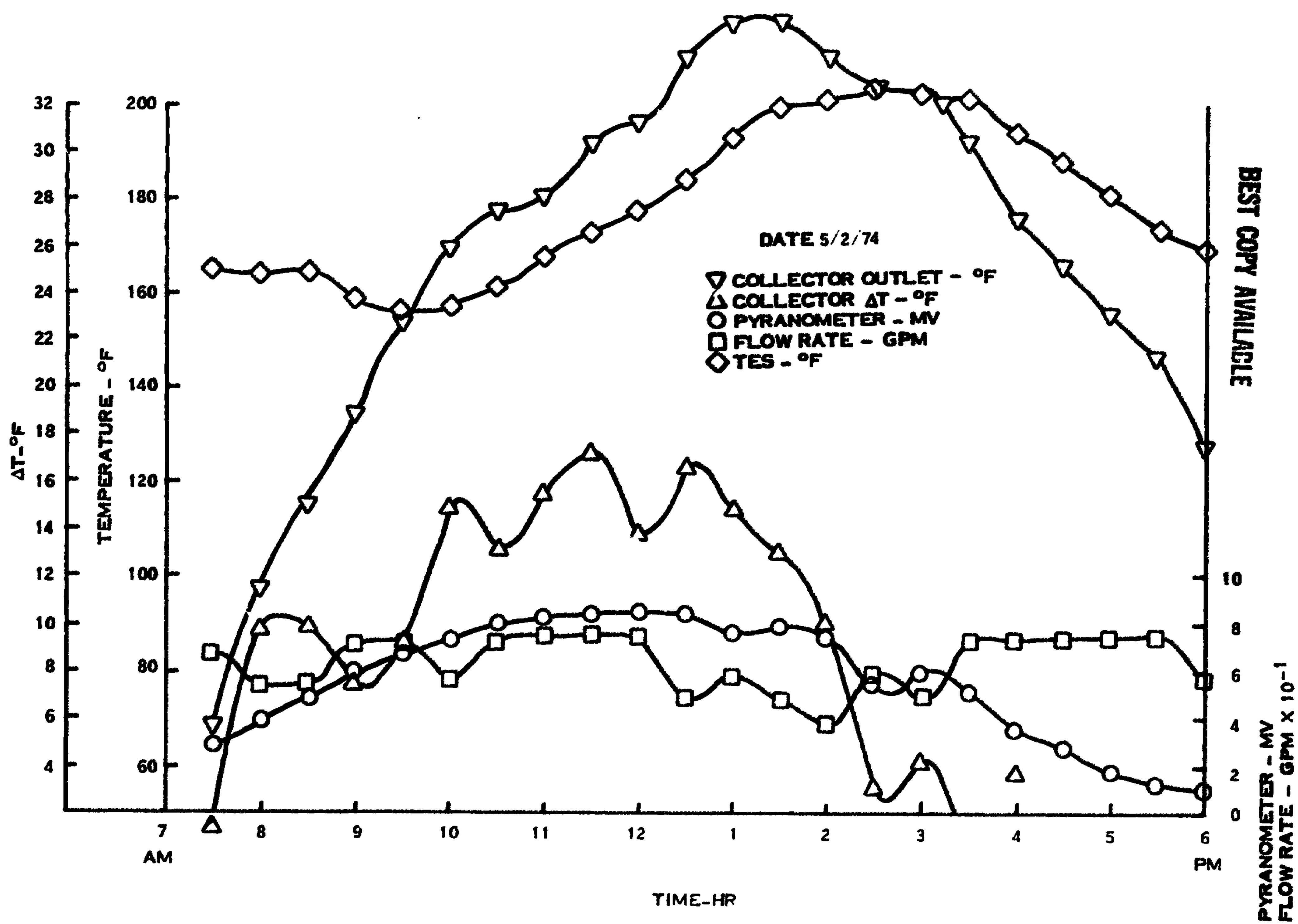

Figure 6-32. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-2-74

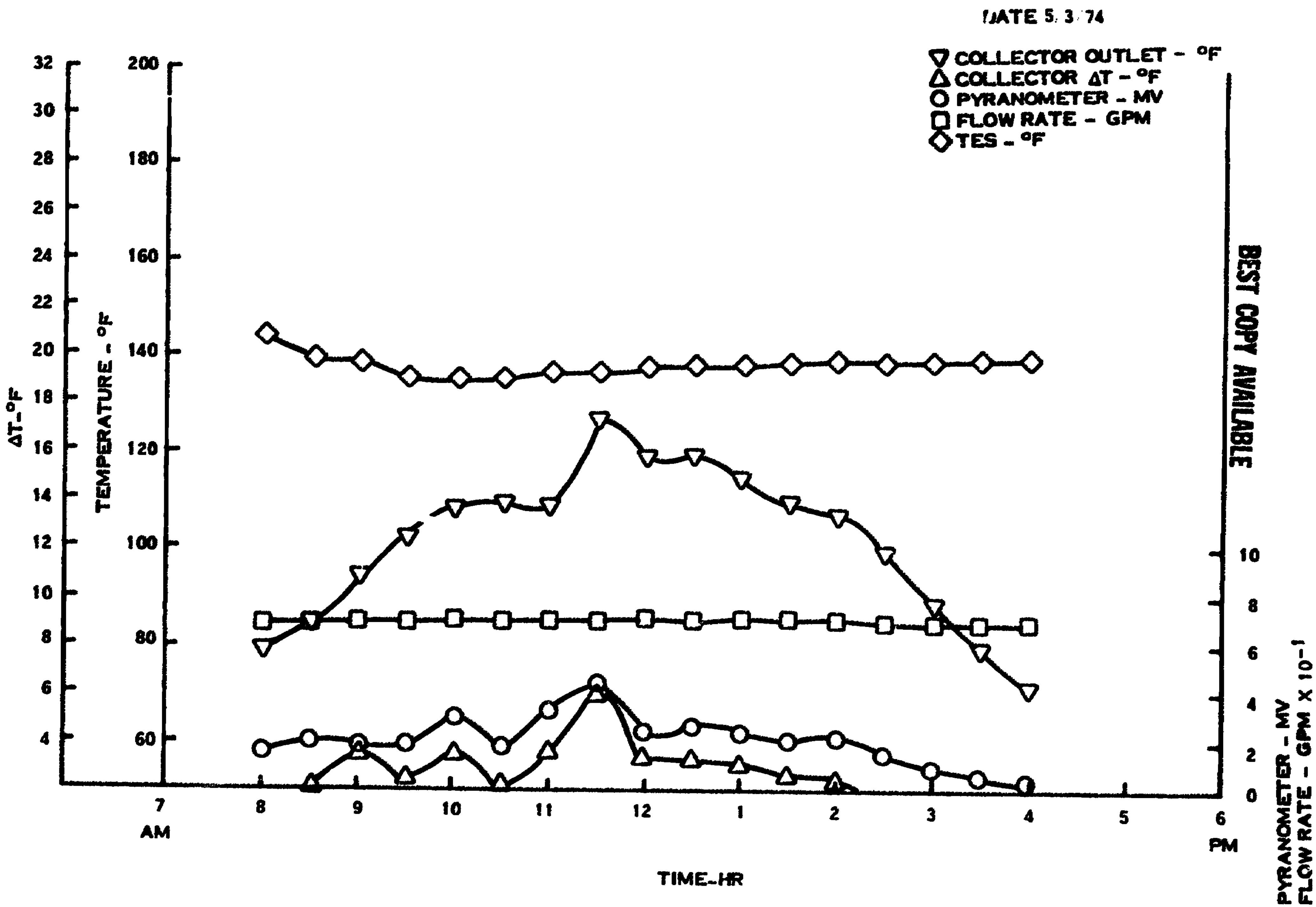

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Figure 6-33. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-3-74

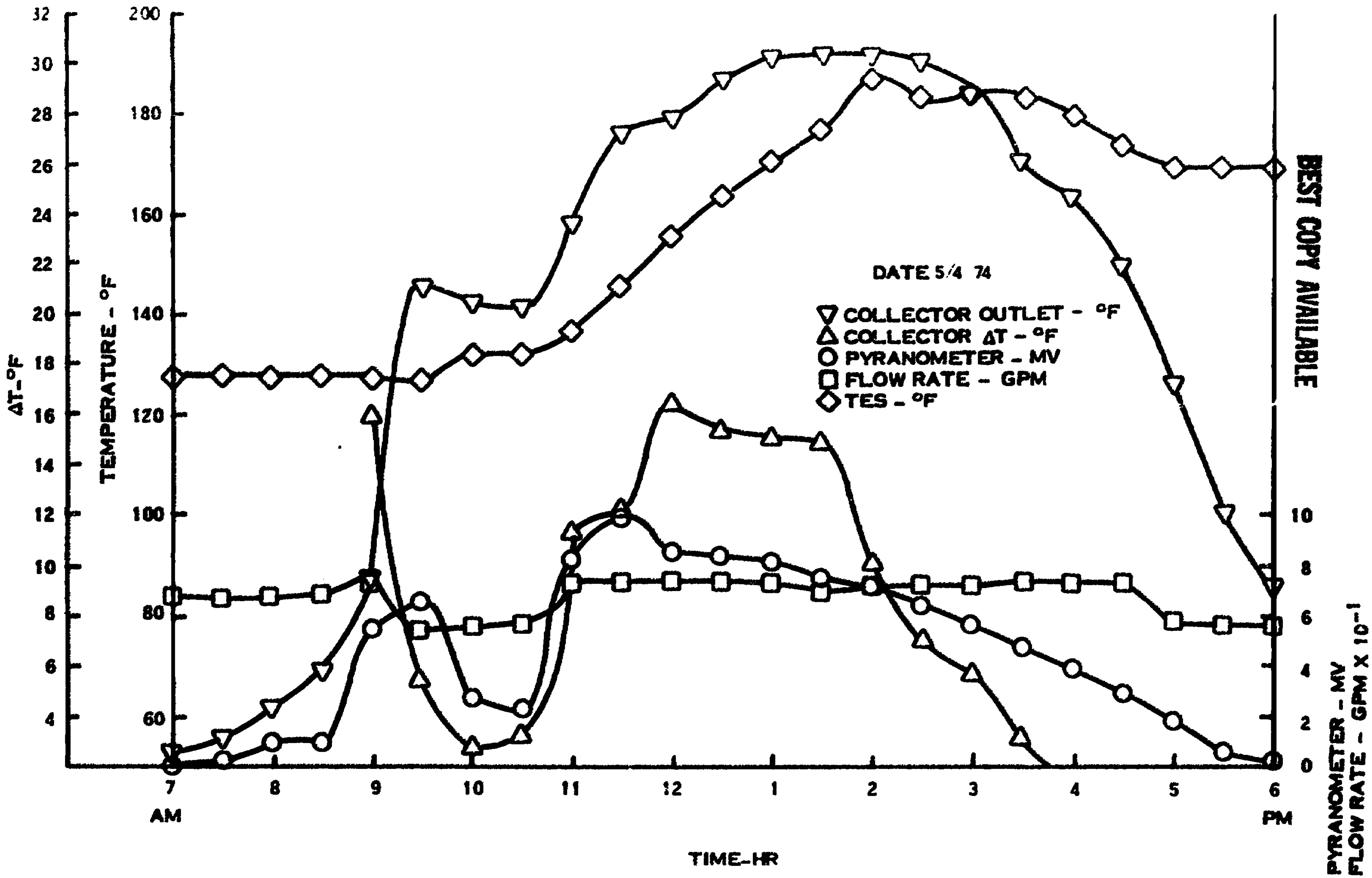

Figure 6-34. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-4-74

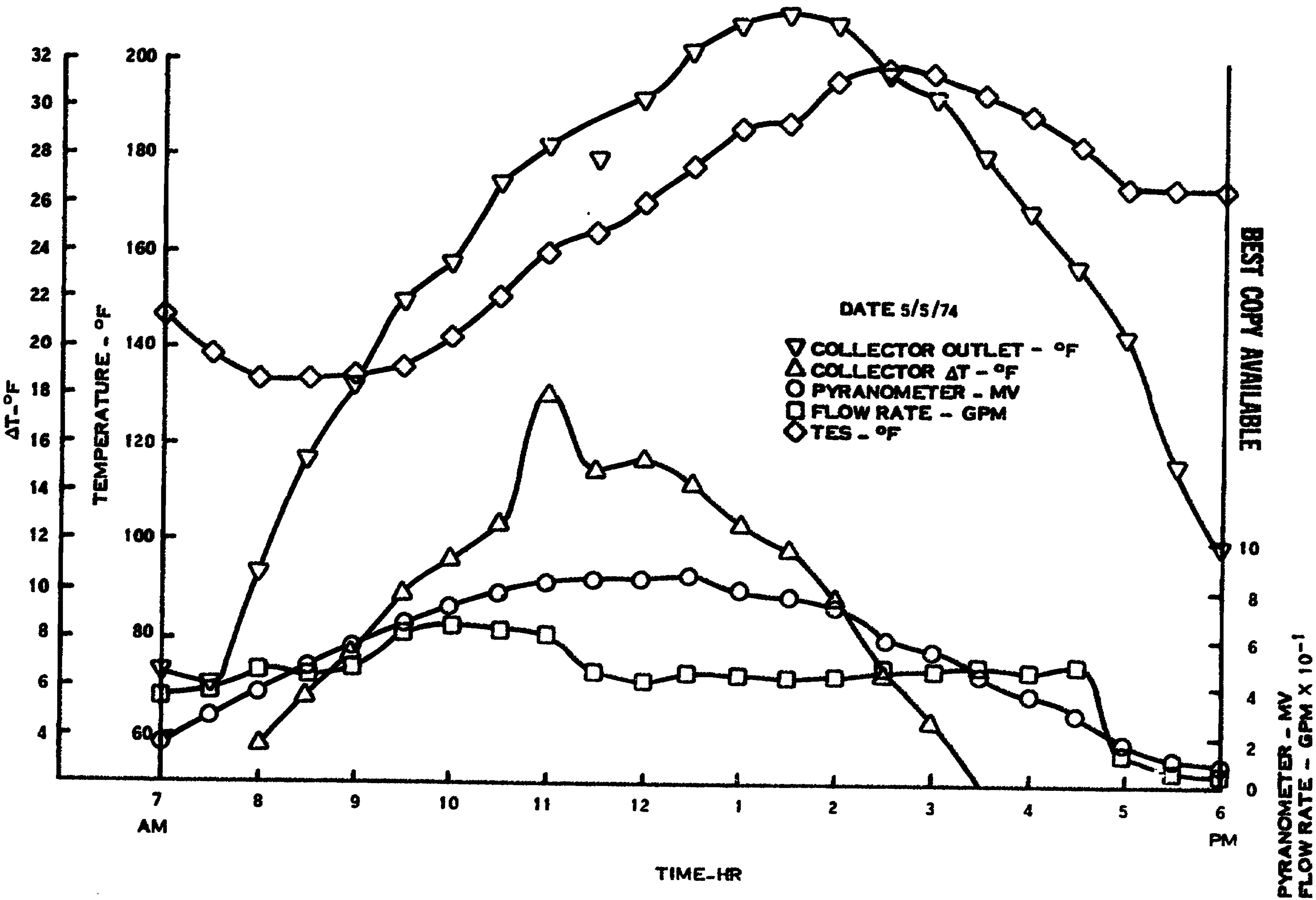

Figure 6-35. Solar Collector Loop Data Grover Cleveland School, Boston, Mass. 5-5-74

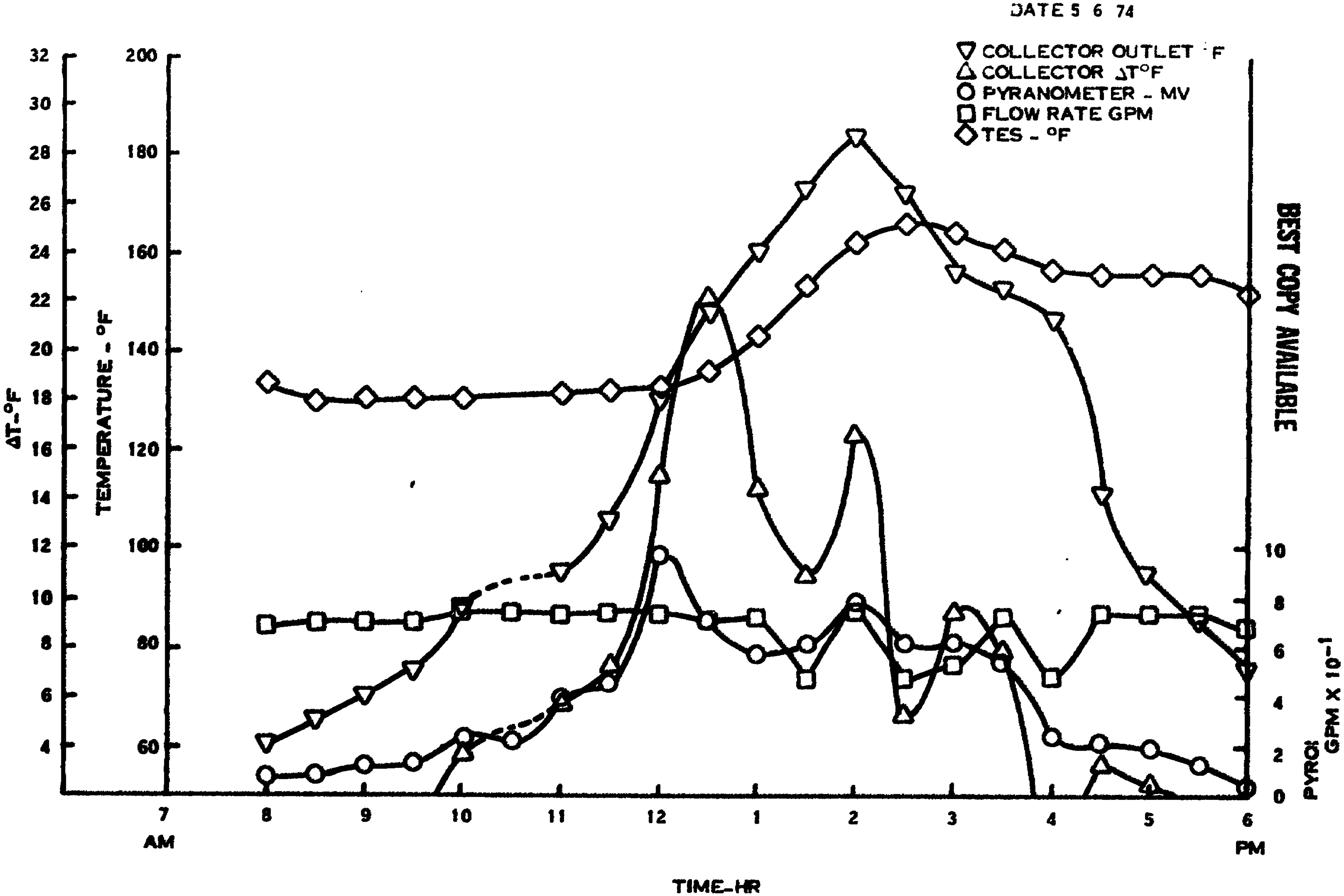

Figure 6-36. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-6-74

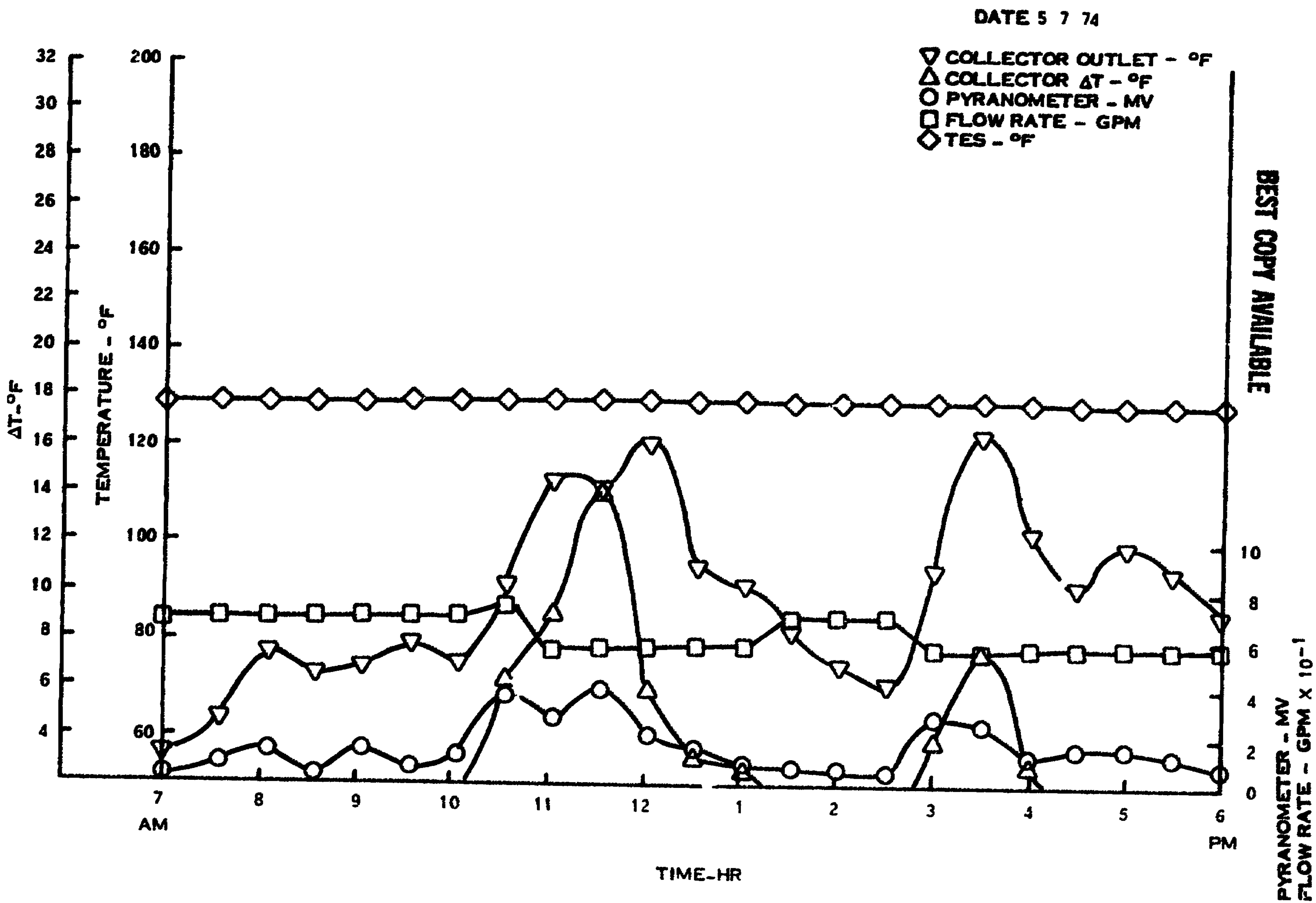

Figure 6-37. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-7-74

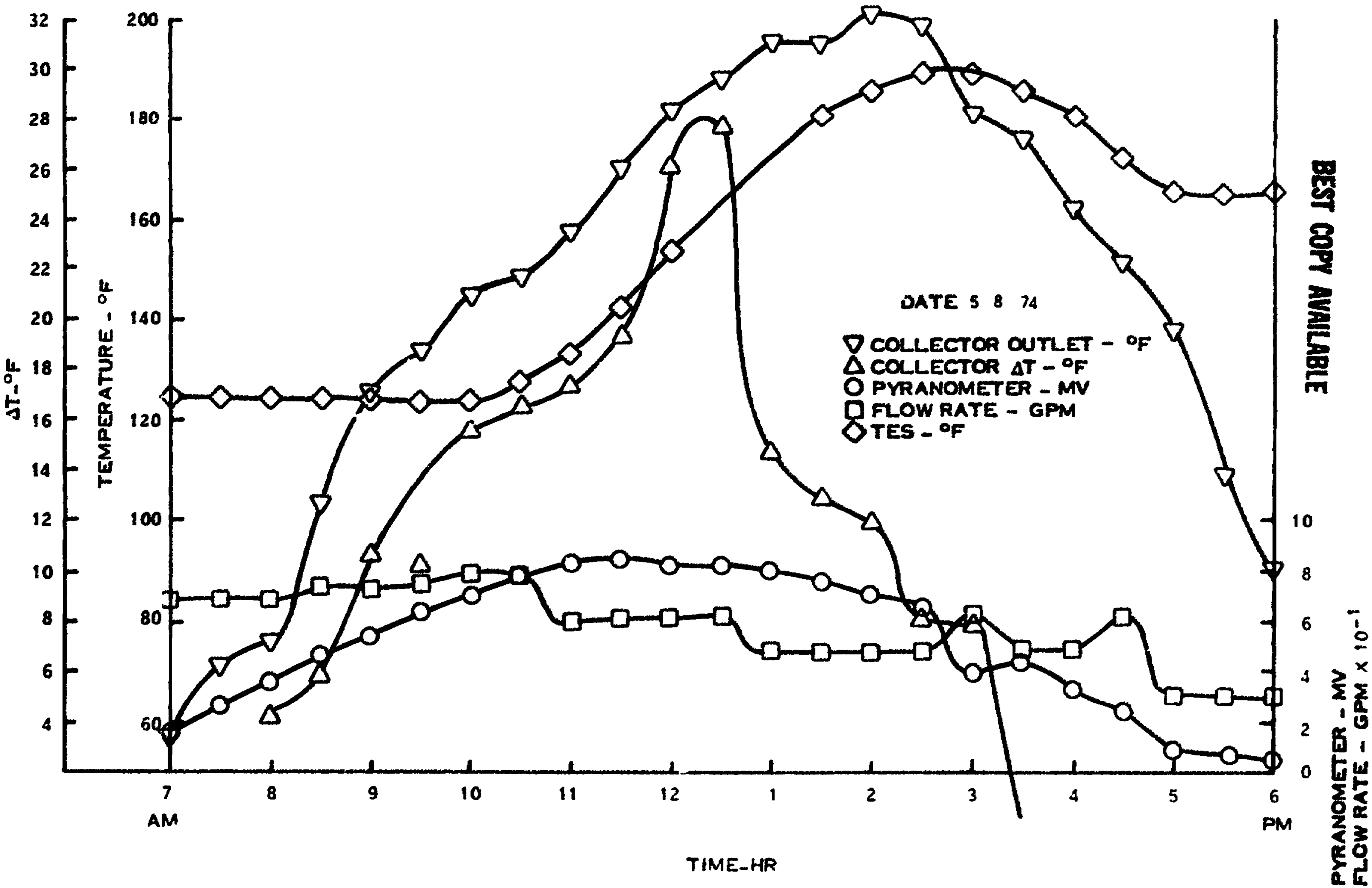

Figure 6-38. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-8-74

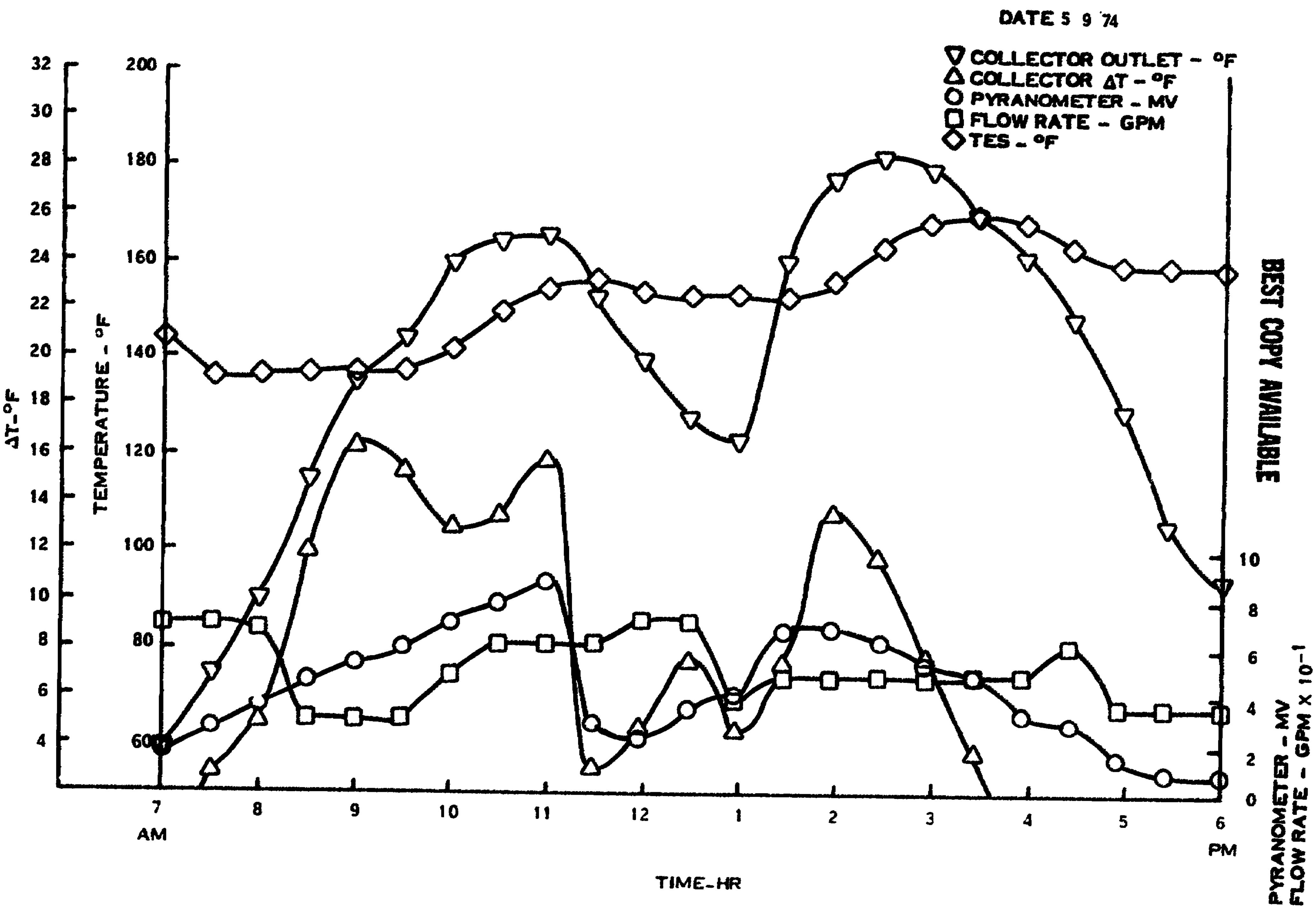

Figure 6-39. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-9-74

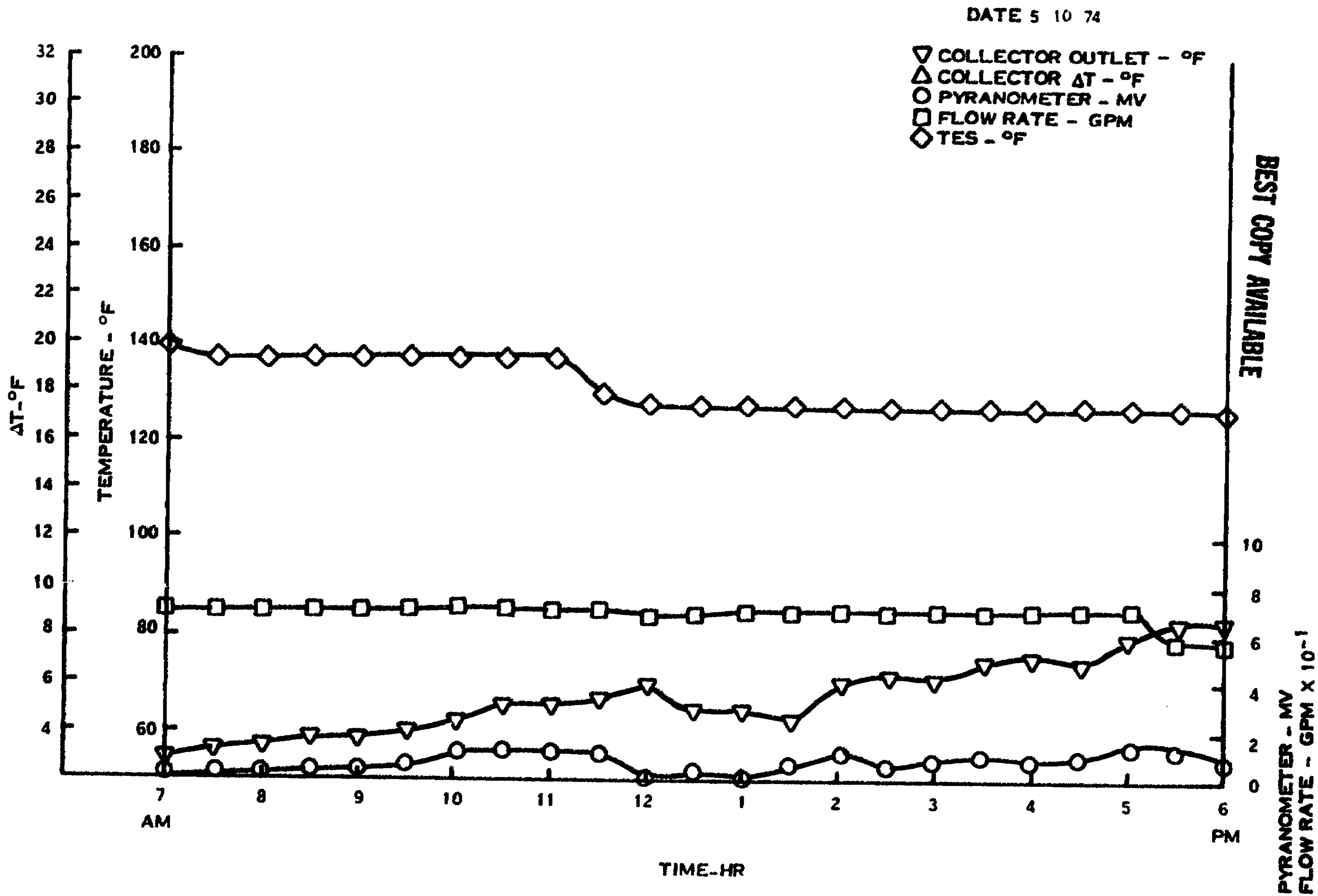

Figure 6-40. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-10-74

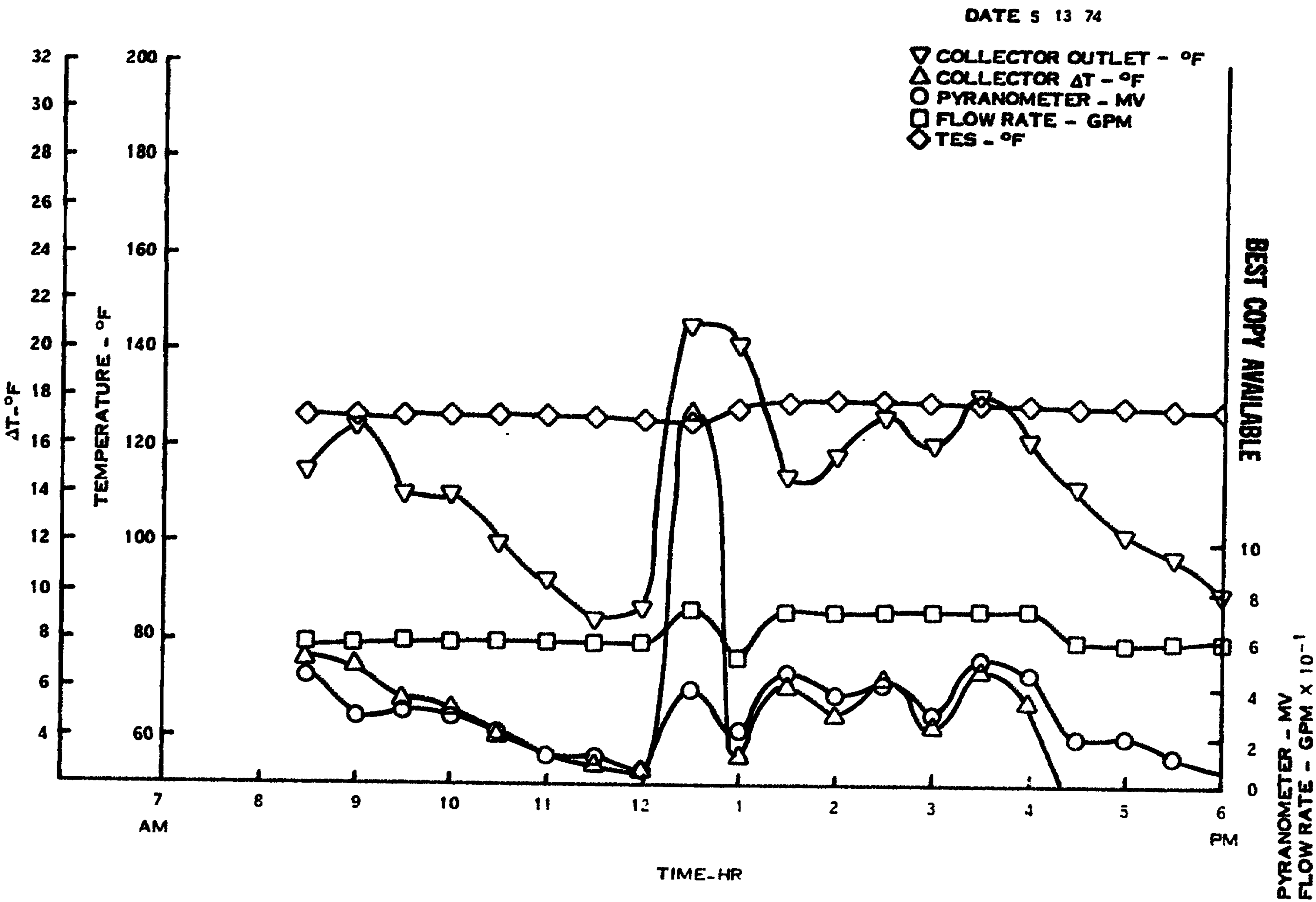

Figure 6-41. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-13-74

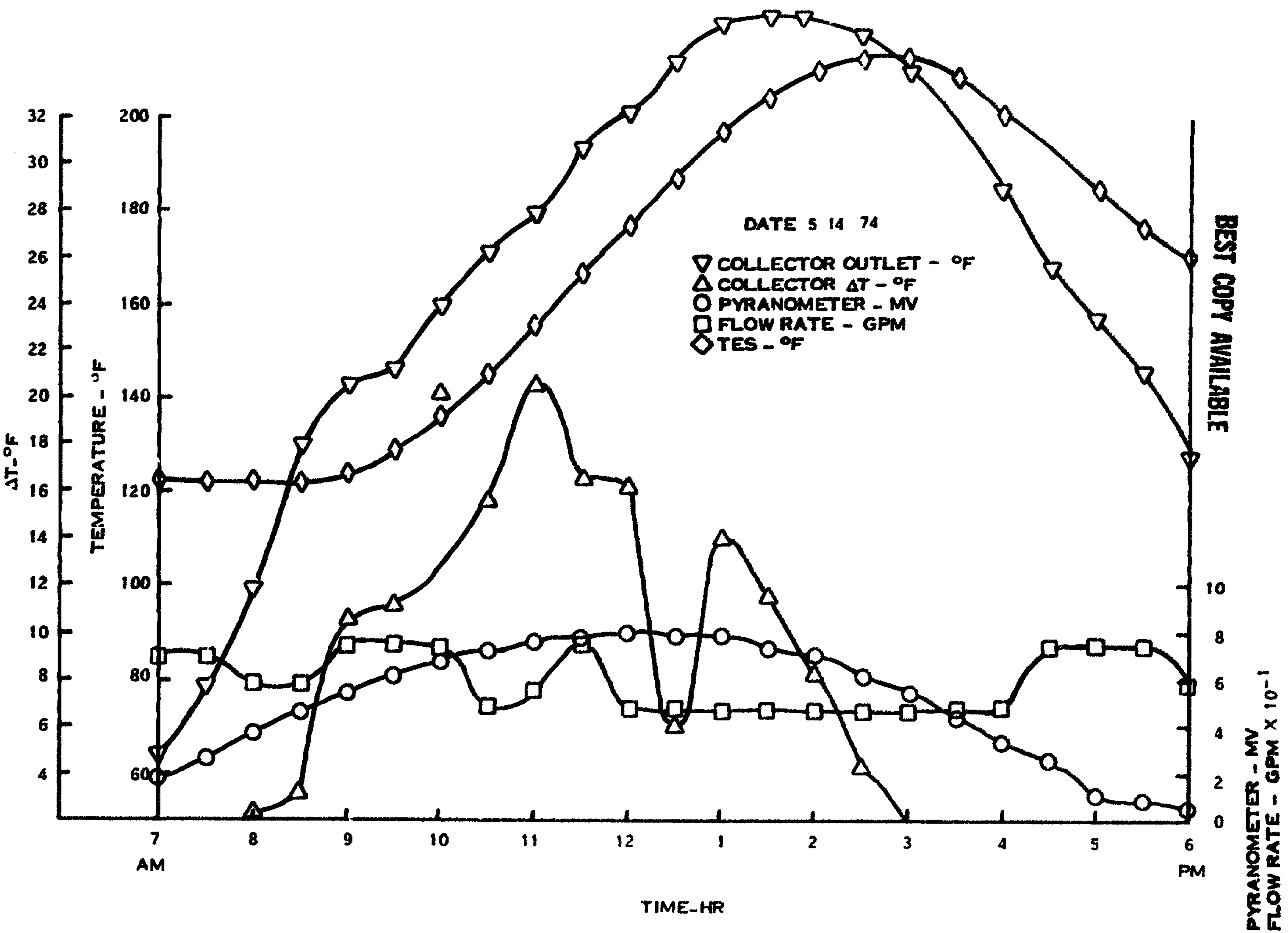

Figure 6-42. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-14-74

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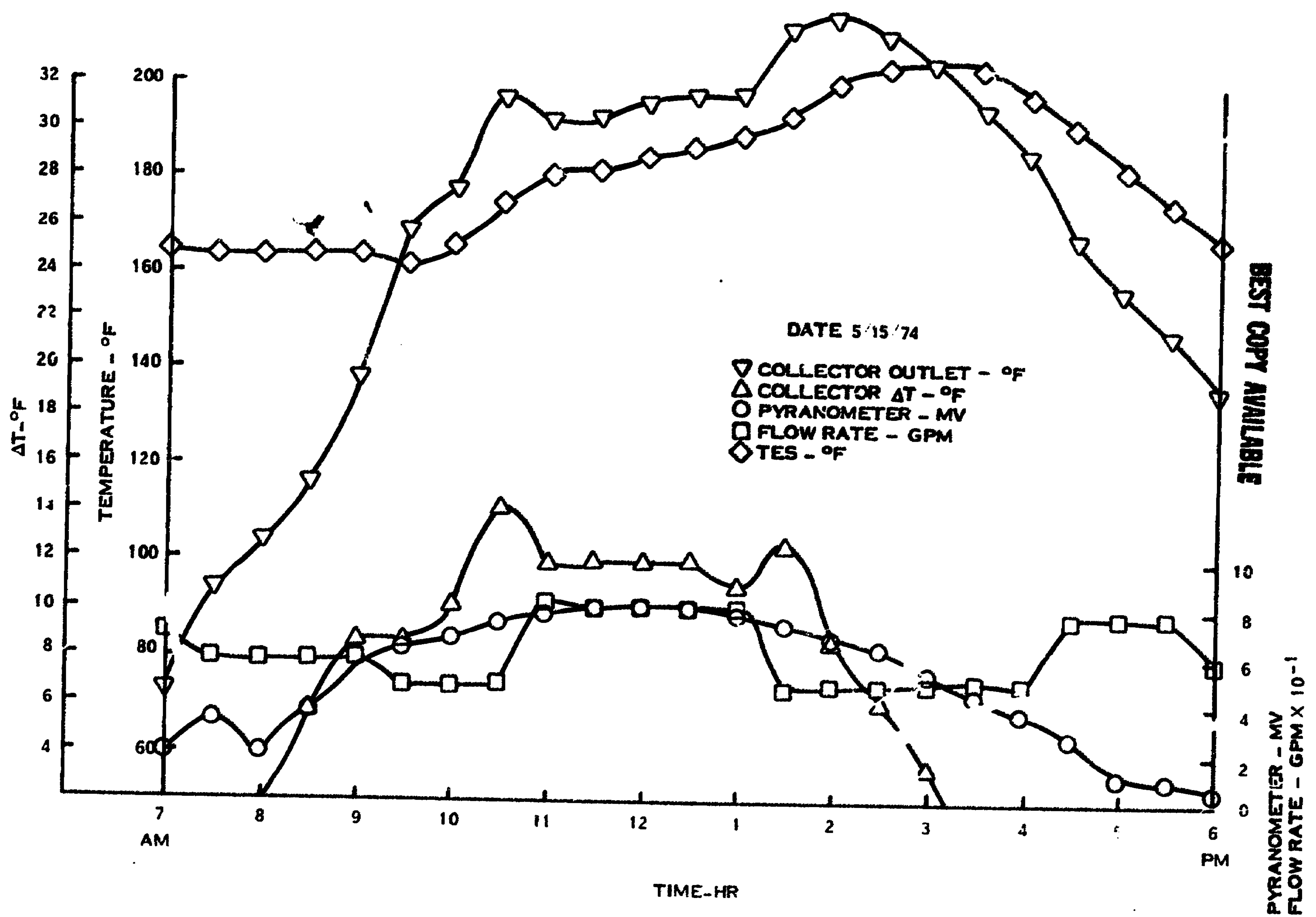

Figure 6-43. Solar Collector Loop Data Grover Cleveland School, Boston, Mass., 5-15-74

6.2.2 PERFORMANCE CALCULATIONS

The daily curves of the preceding subsection can be used to obtain integrated values of incident solar energy, heat collected, system efficiency, panel energy density, and the daily totals as given in Table 6-4. Table 6-4 shows the total heat collected by the loop through 15 May and the total heat taken by the school for that period. An analysis of April's performance defines an approximate heat balance as follows. An electronic problem prohibited the loop flow rate from being recorded by the datalogger and there were problems with the custodians not being accustomed to handling a data system; consequently, there are complete data for only 15 days in April summarized as follows:

Solar Heat Collected	29.9×10^6 BTU
Heat Losses (TES & Piping)	-1.1×10^6 BTU
Heat Used by School	-13.3×10^6 BTU
Heat Dumped	15.5×10^6 BTU

However, the net energy potentially deliverable to the school was:

Solar Heat Collected	29.9×10^6 BTU
Heat Loss TES & Piping	-1.1×10^6 BTU
Power Consumed (Pump)	-1.3×10^6 BTU
Net Energy Deliverable	27.5×10^6 BTU

Table 6-4. Grover Cleveland School, Boston, Mass., Solar Collector System Data

DATE	NOON AMBIENT ~ °F	PEAK TEMP. ~ °F	PEAK AVERAGE SOLAR ENERGY DENSITY ~ BTU/HR-FT²	TOTAL HEAT COLLECTED ~ BTU X 10⁻⁶	SYSTEM INTEGRATED η ~ %	PEAK AVERAGE PANEL ENERGY DENSITY ~ BTU/HR-FT²	HEAT DELIVERED TO SCHOOL: BTU X 10⁻⁶	HEAT DELIVERED TO SCHOOL: KW-HR
11 Apr	53	192	256.52/196.37	4.523	53	[illegible]	[illegible]	[illegible]
12 Apr*	50	-	-	-	-	-	-	-
13 Apr*	-	-	-	-	-	-	-	-
14 Apr	-	[illegible]	[illegible]	1.67	44	[illegible]	[illegible]	[illegible]
15 Apr	-	[illegible]	[illegible]/118.92	1.677	[illegible]	115.8 [illegible]	[illegible]	[illegible]
16 Apr	55	183	259.[illegible]/199.45	3.965	54	[illegible]	1.[illegible]	[illegible]
17 Apr	25	200	259.40/200.69	[illegible]	43	[illegible]	AC	AC
18 Apr F	65	204	253.57/186.90	2.673	37	[illegible].08/48.[illegible]9	[illegible]	[illegible]
19 Apr*	-	-	-	-	-	-	-	-
20 Apr	40	196	265.36/198.24	3.109	43	135.50/84.6	1.818	531
21 Apr*	-	-	-	-	-	-	-	-
22 Apr*	75	-	-	-	-	-	-	-
23 Apr	70	165	183.[illegible]/132.49	.[illegible]	29.[illegible]	55.[illegible] 37.1	AC	AC
24 Apr	50	[illegible]	1[illegible].06/92.14	.254	31.6	5[illegible].7/29.3	[illegible]	[illegible]
25 Apr	44	[illegible]	2[illegible].93/1[illegible].50	1.77[illegible]	35	8[illegible] 51.[illegible]	[illegible]	[illegible]
26 Apr	51	17[illegible]	2[illegible].21/188.7[illegible]	1.59	[illegible]	[illegible]	.55	[illegible]
27 Apr	-	218	[illegible].67/199.39	2.[illegible]	[illegible]	128.[illegible]	[illegible]	[illegible]
28 Apr	-	[illegible]	[illegible]/153.85	.[illegible]7	34	[illegible] 5.9	[illegible]	[illegible]
29 Apr	75	[illegible]	227.03/151.[illegible]	1.38	[illegible]	73.8 34.8	AC	AC
30 Apr	52	185	2[illegible].44/1[illegible].68	.925	3[illegible].5	74.3 3[illegible]	AC	AC
		APRIL HEAT COLLECTED		= 29.69	AVE. η = 4[illegible].2%	APRIL HEAT DELIVERED	= 13.[illegible]	3[illegible]
1 May	55	215	253.62/198.10	2.4[illegible]	33.5	[illegible]	AC	AC
2 May	50	218	24[illegible]/198.10	2.44	35.5	13[illegible]	.75	[illegible]
3 May	55	127	117.94/71.50	.[illegible]	32.[illegible]	37.3 23.3	.178	[illegible]
4 May	-	[illegible]	260.10/195.81	2.11	[illegible]	12[illegible]	.9[illegible]	[illegible]
5 May	-	208	250.52/2[illegible].41	1.8[illegible]	[illegible]	[illegible]	1.[illegible]	4[illegible]5
6 May	50	163	25[illegible]/153.77	2.7[illegible]	4[illegible]	15[illegible] 58.75	1.[illegible]	[illegible]
7 May	50	122	1[illegible].2[illegible]	.846	5[illegible]	[illegible] 35.[illegible]	.[illegible]	[illegible]
8 May	55	[illegible]	247.67/195.33	2.81	4[illegible].5	[illegible]	.[illegible]	[illegible]
9 May	55	[illegible]93	244.72/150.09	1.79	3[illegible].2	99.5 46.69	.45	[illegible]
10 May**	49	82	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
11 May**	-	67	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0	≈ 0
12 May*	-	-	-	-	-	-	-	-
13 May	[illegible]	[illegible]	1[illegible]	[illegible]	4[illegible]	[illegible].3	.[illegible]	[illegible]
14 May	65	[illegible]	2[illegible]/2[illegible].92	[illegible].21	34.6	[illegible]	1.[illegible]	33[illegible]
15 May	75	213	235.68/194.31	2.[illegible]	33.0	1[illegible].7 [illegible]	.13[illegible]	[illegible]

* UNUSABLE OR NON-EXISTENT DATA

** VIRTUALLY SUNLESS DAYS WHICH WERE NOT PLOTTED

F MAIN PUMP FAILED AT 5 PM

AC VIRTUALLY NO HEAT DELIVERED DUE TO USAGE OF AIR CONDITIONING

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The net energy deliverable shows the amount of heat that could be used by the school for room heating less some losses in the system and due to equipment power consumption that is charged against the system. A significant portion of this heat was not used due to the school heating load during the reporting period. Estimates of the heating load for April '74 were obtained from Boston Edison Co. at 78,336 kW hours for 30 days. These estimates are based on total degree days for April.

To compare the heat required to the heat supplied we first determine the amount of heat required for the heating units AC-6 and AC-7. Since they represent about 30 percent of the school's heated area, we ratioed that 23,500 kW hours are attributed to AC-6 and 7 over the 30 day period. Assuming half of this for the 15 days of solar heating data gives 11,750 kW hours; consequently, the net energy available to the school, 27.5×10^6 BTU (or 8057 kW hours), represented 68 percent of the required heat load. However, due to system losses only 48 percent of this energy can be identified as having been delivered to the school, the rest being dumped. (Heat exchanger Valve 1a was stuck open prior to 16 April and, therefore, the system was dumping heat and collecting simultaneously.)

Some additional system performance parameters or points are:

1. Maximum one day heat collection $\approx 4.5 \times 10^6$ BTU
2. Peak incident solar flux recorded ≈ 294 BTU/hr-ft^2
3. Thermal energy storage response $\approx$ 10-12°F/hr increase
4. Thermal energy storage heat loss rate $\approx 0.6^\circ$F/hr with 138°F temperature difference
5. Maximum intergrated one day efficiency $\approx$ 54 percent in converting solar energy to hot water
6. Total heat collected by the system to date $\approx 52 \times 10^6$ BTU
7. Average conversion efficiency to date $\approx$ 37 percent
8. Collector outlet temperature typical rise rate under full sun $\approx 35^\circ$F/hr
9. Typical rise rate of the collector inlet/outlet temperature difference under full sun $\approx 4.5^\circ$F/hr.

6.2.3 INDIVIDUAL EXPERIMENTS

A few individual experiments have been performed with the system. The system basically runs in an unattended mode and consequently "experimentation" only occurred when there was a happy coincidence of proper conditions and time in the work schedule, both occurring on a visitation day.

6.2.3.1 Pyranometer Correlation

This was a comparison of cleaned/uncleaned readings and also a comparison of the Eppley Model 8-48 pyranometer readings with those of a nearby weather station.

On May 8 after approximately 9 weeks of weathering, the glass pyranometer dome was carefully wiped with a soft cloth and denatured alcohol. Output readings immediately prior and subsequent with a 2:00 PM clear sky condition indicated a negligible change (actually lost 0.02 millivolt after cleaning). Since it had rained some in the preceding 36 hours, the test was repeated May 16 when no rain had occurred in the preceding 5 days. Again, there was a negligible change. The conclusion being that there is no need to clean the pyranometer at least in Boston with rain occurring about once a week.

The U.S. Weather Bureau at Blue Hill, Massachusetts records hourly integrated values of solar flux incident on a horizontal surface. Blue Hill is reasonably near Dorchester and May 8 was a clear, blue sky type of day which produced orderly solar flux curves and was widespread enough to expect Blue Hill to have the same insolation as Dorchester. Figure 6-44 shows a plot of the GE pyranometer data which was taken each half hour for the morning of May 8. Two values were obtained from Blue Hill for the hours ending at 10:41 and 11:41 AM, EDT, 220 and 244 BTU/ft^2 respectively, which are also shown on the curve. The GE pyranometer data was then integrated graphically and mathematically converted from the 45 degree pyranometer angle to equivalent horizontal plane values using relationships from Reference 2. The

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Reference 2 "Availability of Solar Energy for Flat-plate Heat Collectors" by Benjamin Y. H. Liu and Richard C. Jordan and Published in Low Temperature Engineering Application of Solar Energy by ASHRAE, 1967.

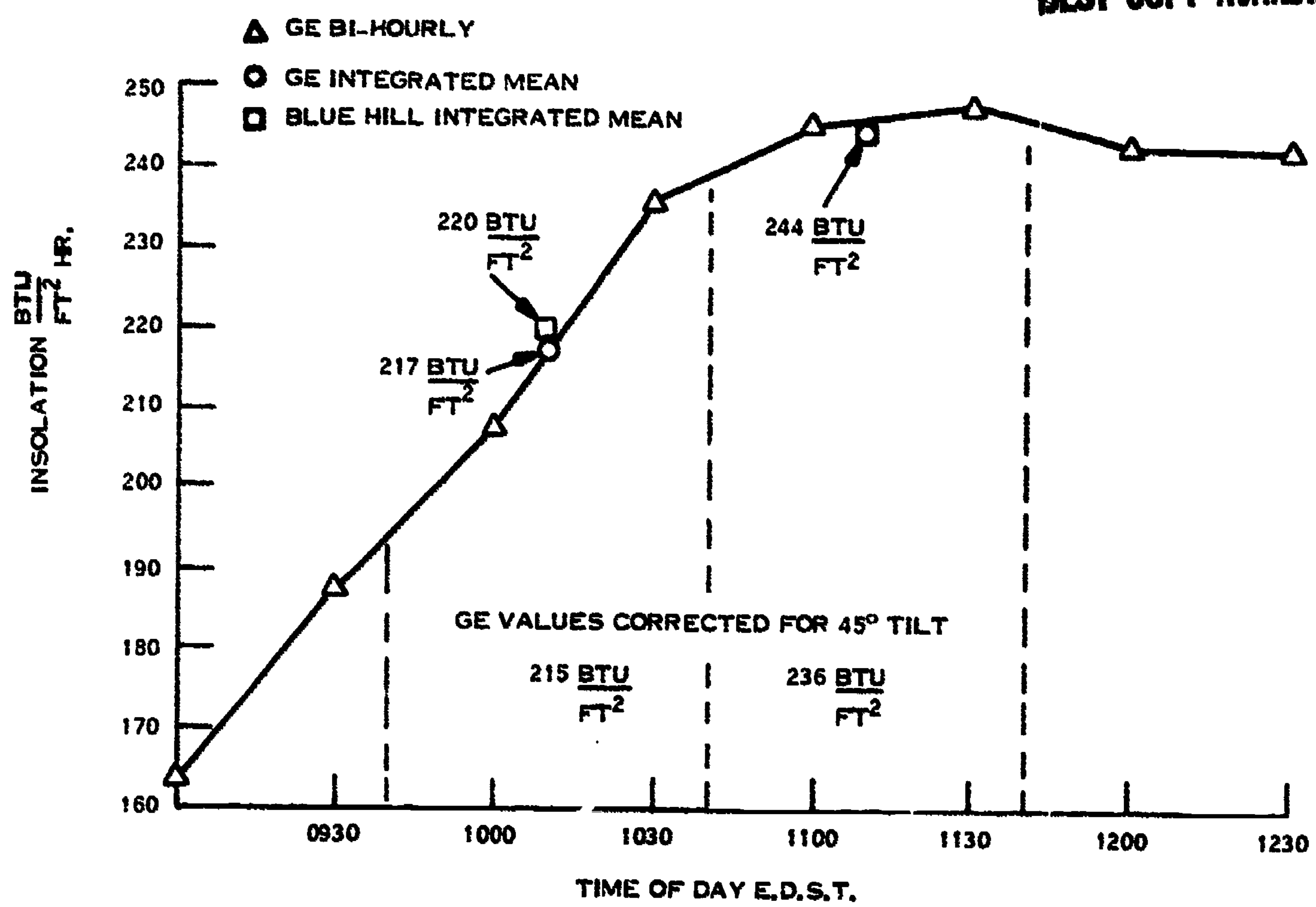

Figure 6-44. GE Pyranometer Data

comparative values are 215 with 220 BTU/ft^2, and 236 with 244 BTU/ft^2 for GE and Blue Hill, respectively Interestingly enough, the conversion from 45 degrees to horizontal only produces a few percent change for this particular time of day. The conclusion was that 29.5 BTU/hr-ft^2 MV is a reasonably accurate coefficient for our pyanometer; however, this experiment will be repeated to obtain both horizontal and tilted data simultaneously.

6.2.3.2 Collector Detail Thermal Data

There are four collectors (101, 102, 103 and 104) in the system with internal thermocouple instrumentation. All four collectors were located together; two groups in tandem to insure pairs with identical fluid flows (101/102 and 103/104) and two groups side by side (101/103 and 102/104) to provide identical exposure conditions and match with the panel flow meters originally in the system. The thermocouples in the four collectors were installed in identical locations; specifically:

a. Center of pan rear exterior surface

b. Center of outer window interior surface

c. Center of inner window interior surface

d. Absorber panel sunlit surface near left inlet nipple

e. Absorber panel sunlit surface near center

f. Absorber panel sunlit surface near left outlet nipple.

The sequence above was expected to also be in order of ascending temperature; however, the outlet temperature, f, was normally about the same or, in some instances, even a few degrees cooler than the panel center temperature, e. This was attributed primarily to the middle thermocouple being located nearly on the splice plate between the two absorber plates, more than 2 inches from a liquid passage, while the inlet/outlet thermocouples are located nearly on the liquid passage at the nipple adapter. In addition, there are more two dimensional heat flow effects near the inlet/outlet nipples. The net result is that the middle thermocouple is nearly the hottest of the six temperatures.

A comparison of the middle thermocouple, e, with the average of the inlet/outlet thermocouples, d and f, also provides an indication of what lateral temperature differentials exist within the absorber plate.

These characteristics are shown graphically in Figures 6-45 and 6-46. The transient temperature distributions in Collector 104 on May 5 are shown in Figure 6-45. This figure also points out one of the difficulties of instrumenting windows. The window thermocouples had to be emplaced prior to developing a good technique for instrumenting Lexan and, as a result, the thermocouples were taped to the "inboard" surface. In this instance, the inner window thermocouple tape/window bond is loose and the thermocouple is responding to a temperature between that of the inner window and the absorber plate. The same type problem may also be influencing the outer window values. The thermal distributions both longitudinally and through the collector thickness are shown for three different times in Figure 6-46, again for Collector 104 on May 5. Referring to the procedure described above, it can be inferred from the longitudinal differentials that the maximum lateral temperature differential on the absorber plate is a relatively modest 8 to 9°F.

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6.2.3.3 Bypass Heat Exchanger Effectiveness

This area has been rather crudely experimented with and is by no means complete. Some conclusions can be drawn however. The bypass heat exchangers will not withdraw 450,000 BTU/hr from the loop with a 100°F liquid to air temperature difference. However, they appear capable of doing so at 130-140°F. Consequently, the total effectiveness is lower than predicted with an overall coefficient of about 3300 BTU/hr-°F seeming more like actuality.

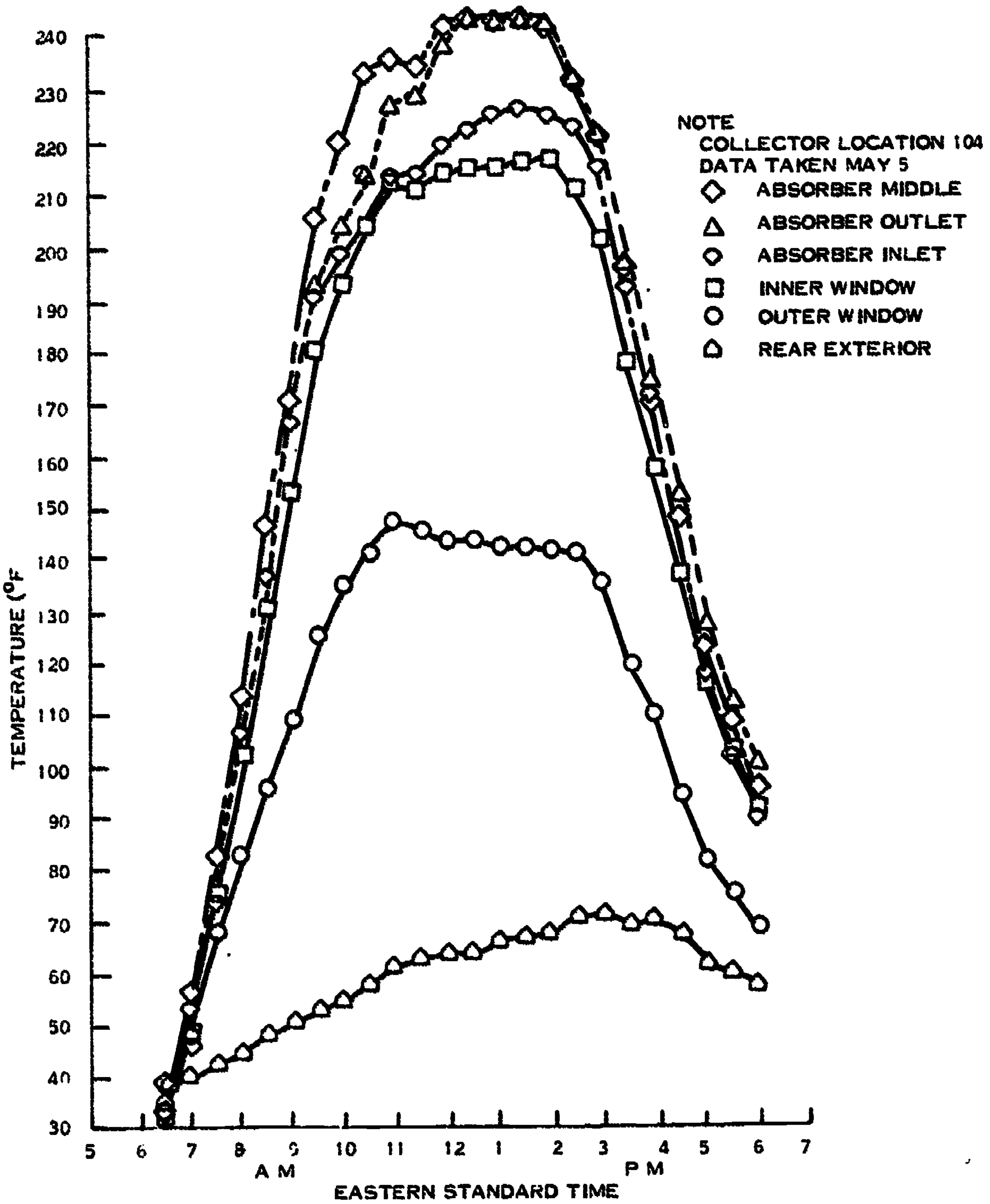

Figure 6-45. Solar Coll: ctor Temperature Transients

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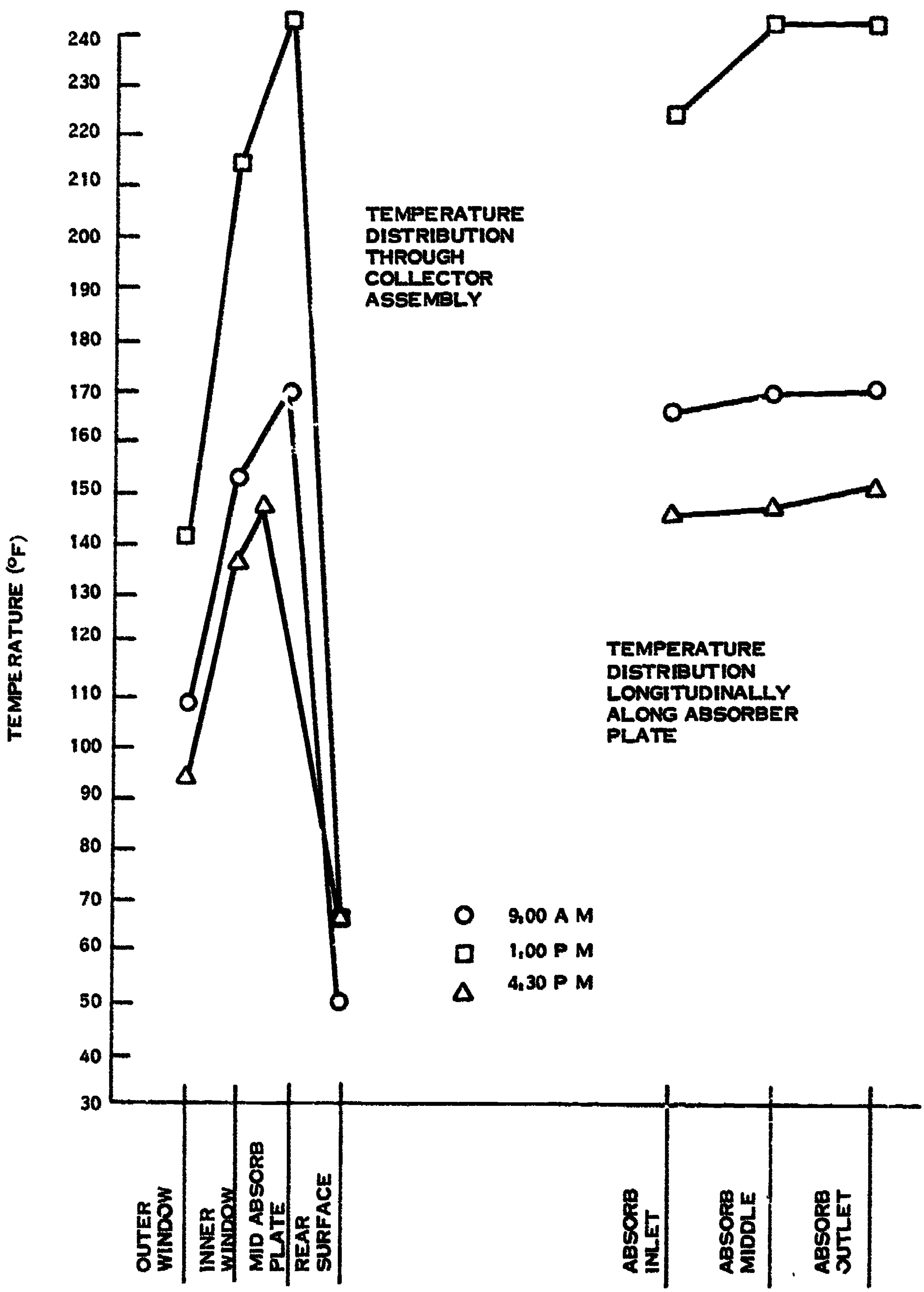

Figure 6-46. Solar Collector Temperature Distributions

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6.2.4 WINDOW CLEANING

There was significant discussion during the planning stages of the project as to how often and what type of window cleaning procedures should be employed on the collectors. Since cleaning a 4600 square foot array is a formidible 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 adherance.

Bank B collectors were cleaned after approximately two weeks exposure and 3 to 5 days without rain. Two cleaning techniques were used (detergent and pure water with a soft rag). That night it rained and the following day all collector windows appeared equally clean. 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).

6.2.5 PROBLEM AREAS EXPERIENCED

One objective of the solar heating experiment was to get a system into operation so that system problems would surface. Resolution of these problems are necessary for development of a better product for the retail market.

6.2.5.1 Condensation on Panels

Condensation formed in various panels in an apparently random pattern. Various techniques were tried to solve the condensation:

1. Lift window and dry with rag.
2. Lift window and blow dry air in collector.
3. Allow the normal heating/cooling and breathing to clear panels.
4. Increase size of breather holes.

None of these methods was found to clear up a panel permanently.

The condensation was isolated to very small leaks in the joint between the collector inlet/outlet nipples and the absorber plate. Subsequent failure analysis proved the nipples were loose. Tightening of the nipples resolved the leaks and the panels cleared of any further condensation.

6.2.5.2 Pump Motor Failure

The main pump is used to circulate the fluid through the solar collectors and heating units. The pump was installed in early March and started operating on a 12 hour day basis on March 6, 1974. On April 18 one pump motor bearing failed causing the motor to freeze and burn out. The pump motor was replaced with a new motor. The original motor was repaired by the supplier and is now kept as a spare.

6.2.5.3 Panel Flow Meters

Visual flow meters were installed on four panel outlets. Each flow meter measured the outlet fluid flow of a tandem pair of collectors. The flow meters were installed in Bank C and were placed into operation on March 11, 1974. Immediately the meter windows fogged up indicating a small internal leak. The windows were removed, fittings and seals checked, and the flow meters were dried out. The leakage rate continued to the point that the water glycol fluid was actually dripping from the flow meters. On April 19 the flow meters were removed from the system.

6.2.5.4 Collector Weld Failure

The A and D banks of collectors were brought on line on March 20. Collector serial number 138 was installed in the bottom row of Bank A. Three days after initial operation solar collector serial number 138 developed a leak and partially filled the collector. The collector was removed, returned to General Electric, Valley Forge, Pa., for failure analysis. Partial disassembly was accomplished and the leak was isolated to the nipple adapter fitting weld on the absorber plate.

Each of the 144 collectors contains 4 welds, 2 input and 2 output connectors, and only one weld has developed a leak. All collectors were leak checked in final assembly prior to shipping to Boston. Therefore, the weld must have been worked by flexing of the collector inlet tubing during thermal cycling. The fitting may have been weakened by flexing or impact during transportation or installation.

6.2.5.5 Panel-Window Separation

In a small number of panels outward bowing of the 4 foot ends of the panels has occurred after several weeks operation. The overall length of these panels, in the area fitting inside the outer window exceeded the inside length of the cover window (between the weather sealing lips). Consequently, in these cases, the outer window ultimately raised in the center of the ends since the structural strength and rigidity of the frame pans far exceeds that of the sealing lip of the window. The dimensional growth of the collector frames in question is believed to result from one or more of the following causes:

1. Variable or over-filling of the absorber assembly with urethane foam. Tighter controls on the amount of injected foam will be established and effected in the fabrication of future units.

2. Thermal instability of the urethane foam at elevated temperatures. The available foam used has a nominal upper service temperature of 200°F. In many cases this temperature has been exceeded in the installed collectors, possibly causing outward-bowing of the frame ends due to foam expansion. Future applications will utilize insulations stable at temperatures in excess of maximum absorber temperatures achievable by the particular design.

3. Assembly of outer window and frame combinations which result in clearance between the frame pan and window flange of less than the lower design limit. In future assemblies, more careful dimensional control will be exercised, commensurate with less severe schedule pressures.

6.2.6 CONTROL AND INSTRUMENTATION SYSTEM IMPROVEMENT

The basic control systems design was frozen in early February so as to allow system fabrication and delivery in time to support an early March operational date. Several improvements were incorporated after delivery to Boston.

6.2.6.1 Backup Power Supply

The control system operates on 28 volts supplied by the power supply located in the lower left side of the control and instrumentation console. The power supply is protected by circuit breakers from an overload condition. On several isolated incidents the power supply circuit breaker tripped pointing out the desirability for a backup 28 volt power supply. Two automobile batteries were purchased and the circuit was changed to use these batteries as backup power. A battery charger was installed in order to keep the batteries charged.

6.2.6.2 Low Pressure Warning Horn

The solar collector requires fluid flow on sunny days to protect the collectors from overheating. An audible warning of a failure of the main pump was desirable. A pressure switch was installed between the main pump inlet and outlet ports. A pressure differential less than three psig across the pump is used to indicate a pump failure and set off the warning horn.

6.2.6.3 Comparator to Control TES Flow

The original logic design for control of TES flow was to cause Valve No. 3 to open anytime the loop temperature rose above 145^{o}F. On a typical day the system operates in the bypass mode for warm-up, switches to heating when the loop temperature reaches 80^{o}F, and when the temperature loop exceeds 145^{o}F the TES is charged via Valve No. 3. However, as the sun sets in the afternoon, and the loop temperature decreases, the TES temperature may exceed the loop temperature while the logic calls for TES charging. In effect the solar collectors become radiators and cool the TES fluid until the loop reaches 145^{o}F.

A comparator circuit is being fabricated and will be installed in June. The circuit will require both that the loop liquid be above the Mode 3/4 transition temperature and that the loop liquid exceed the TES liquid temperature. This will conserve heat stored in the TES and make more heat available to the school. This was an oversight in the original design.

6.2.6.4 Backup Pump

The solar collectors are intended to have fluid flow at all times they are exposed to the sunlight. The system contains two pumps. The main pump which pumps all fluid through the solar collectors and the various heat loads (TES, heaters units AC-6 and AC-7, bypass coils). The TES pump's primary function is to pump the fluid around the loop between the TES tank and the solar coils in the heater units AC-6 and AC-7. An additional plumbing line and two hand isolation valves were added to the system to provide a capability, so the TES pump can be used as a backup for the main pump by operation in the manual mode. This redundancy was installed to provide the system reliability and protection of two main pumps without the added cost of another pump and the complication in the control system. The backup mode was used when the main pump bearings failed. The modified piping schematic is shown in Figure 6-47.

6.3 MAINTENANCE

The actual system maintenance activities have been related to the data system, i.e., changing recorder paper, printer ribbons, etc. The activities during GE site visitations have been principally of a surveillance nature with a considerable number of odd jobs to incorporate modifications or conduct small tests which were not done during the checkout period. Visits were originally on a once a week basis but system performance has let that stretch out to every few weeks. Checklists were made up for use by GE personnel and the school custodians and are shown in Tables 6-5 and 6-6, respectively. A more comprehensive maintenance checklist will be made up for the 1974-75 heating season operation including such items as periodic lubrication, etc. The experiment period was too short to require "annual" maintenance types of activities.

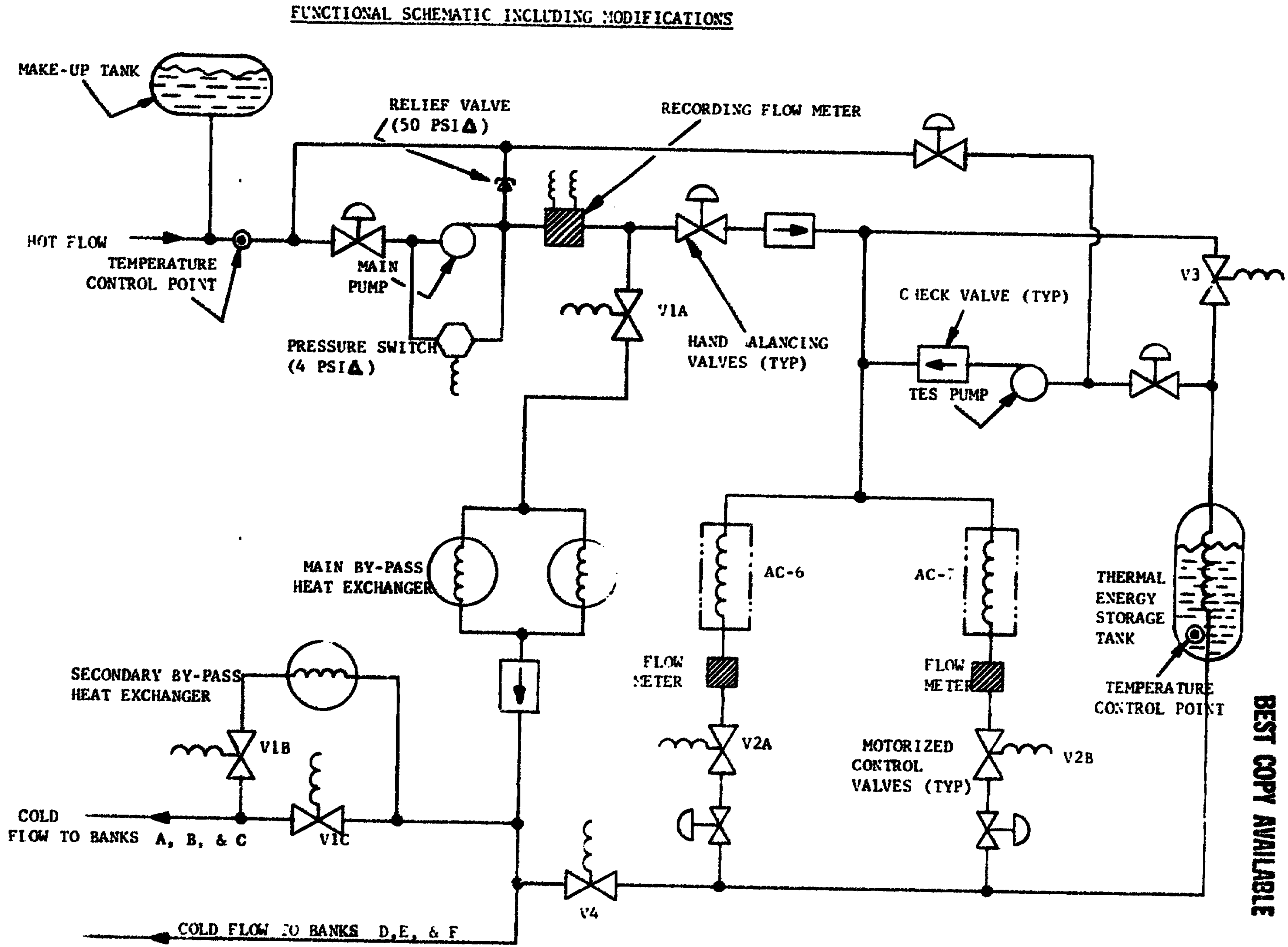

Figure 6-47. Modified Piping Schematic

Table 6-5. GE Checklist for Grover Cleveland School Solar Heating System

General

Main worry is that liquid circulation will stop while sun is shing due to:

a. Power failure (audible/visible alarm)

b. Pump failure (mechanical or NPSH)

c. Vandalism (inspection for damage/leaks)

If any audible alarm sounds, call King of Prussia immediately.

J. Notestein 8-242-5588
K. McFarland 8-242-4888
J. Ladd 8-242-6065

1. Locate log book in control room and record indicated values starting page 174 and on of log book. (Note: one day's data falls on two pages).

2. Check that system is in "automatic cycle" and "automatic" mode.

3. Check that red needles are set as follows on the three "system control" panel temperature meters:

Red Needle	Set Point	Purpose
Left on left expansion tank	80°F	Useable heat
Right on left expansion tank	145°F	Extra heat
Left on right expansion tank	0°F	Not used
Right on right expansion tank	225°F	Safety limit
Left on thermal energy storage	130°F	Useable TES heat
Right on thermal energy storage	300°F	Not used

4. Check that "Energy Flow" panel indicators agree with Condition Control Chart (attached), based on left "Expansion Tank" and "Thermal Energy Storage" meters (record temperature values).

5. Go to pump area and check:

   a. Main pump suction above 3 PSIG (record value).

   b. Main pump discharge 35 - 45 PSIG above suction and below 65 PSIG (record value)

   c. TES pump suction within 10 PSIG of main pump discharge

   d. TES pump discharge equal to suction value if pump is off and 10 - 15 PSIG above suction value if pump is on (record value).

6. Check drip bucket under main pump to see that it is catching drips and to see if level is up to groove (approximately 6" below top of bucket). If liquid is up to groove, empty bucket into roof drain, replace, and record action in log book column provided.

7. Open both lower valves to TES tank sight glass. Air/liquid level should be 1 - 8" from top of glass (record value). Close lower valves to isolate TES tank (Note: Upper sight glass valve should always be open and hose bib on top of TES tank should always be closed).

8. Open top and bottom valve to Make-Up tank sight glass. Liquid level should be 1 - 6" from bottom (record value). Close both valves.

9. Walk around loop and check:

   a. Six panel group flow meters between tape marks indicated (between 0.8 and 1.2 GPM/panel pair with 1.0 GPM as nominal).

   b. AC-6 Jamesbury valve is WIDE OPEN and flow through AC-6 flow meter is 2.5 - 3.0 times that through AC-7 flowmeter (record values).

   c. Leaks - most likely as green drips from bottom of panel or bottom header.

   d. Visual flow meters on back of panel group C are showing similar and midrange poppet positions with no large bubbles in flow stream.

   e. Record panels showing more than 5% condensation by panel number on left log book page (south row is 100 series, middle row, 200 series, north row, 300 series; bottom panel is odd - top is even; and bottom west is origin; i.e., 101, 201, 301).

10. Record any narrative anomalies with date, time and name in log book starting at page 250. Call King of Prussia if any values are out of range or anything looks wrong prior to taking any corrective action.

Table 6-6. School Head Custodians Checklist for GE Solar Heating System

Philosophy:

Follow checklist, note any discrepancies, record in log book, and call GE, King of Prussia, Pa. before taking corrective action. Principal concern is to keep water circulating when sun is shining.

General:

If audible alarm sounds, telephone GE IMMEDIATELY.

John Notestein	1-(215)-962-5588
Keith McFarland	1-(215)-962-4889
John Ladd	1-(215)-962-6065

1. Locate log book in control room.
2. Check that panel is in "Automatic Cycle" and "Automatic" mode.
3. Check that panel flow meter is reading value which is both steady and between 55-80 GPM.
4. Check that paper tape from data logger is piling up neatly.
5. Check that "Energy Flow" panel indicators look like they should based on Condition Control Chart (attached).
6. Walk around loop (omit after sunset) and check that:
   a. Main pump suction pressure is above 3 PSIG
   b. No signs of leakage (most likely green drips off lowest edge of panel or bottom header). Dripping from main pump is normal - do not empty catch bucket - it is our measuring cup.
7. Telephone GE if something doesn't look right (using GE phone 1-215-962-5588) and record any abnormalities in log book starting at page 100 (with date, time, and name of entrant).
8. As early as possible in the morning (prior to 7:30 a.m.) push "feed" button on data logger to run out some blank paper and write time and date on paper.
9. Between noon and 1:00 p.m. read reporting values, enter in log book (page 3 and on), and telephone values back to GE using GE phone line:
   a. Solar flux from most recent value of channel 1 on data logger.
   b. Ambient temperature from right most panel temperature meter.
   c. Weather condition by eyeball: sky is clear, 30% cloudy, or 60% cloudy, total overcast; weather is sunny, light, dark, rain, or snow.
   d. Wind direction/ velocity from weather station meters.
   e. Thermal energy storage tank temperature from labled meter fourth from right.
   f. Collector inlet temperature from meter third from right. (each division is 5°F).
   g. Collector outlet temperature from meter second from right. (each division is 5°F).
   h. Flow rate from panel flow meter.
   i. System status is "Automatic" or "Manual" and "No Problem" or "Problems".
   j. Initial log book to know who took readings.
10. At about the same time each night shortly after sunset (8 or 9:00 p.m.) push "Feed" button on data logger, write time and date on all paper tapes (6 recorders plus data logger), tear off data logger tape and place in envelopes for GE.

SECTION 7

SOCIETAL AND ENVIRONMENTAL INTERACTIONS

New technologies and products require public acceptance prior to becoming a profitable venture. One of the prime objectives of the Solar Heating experiments sponsored by The National Science Foundation was to determine acceptance within the general public.

The average citizen has treated solar energy as something to read about or see on television. The Dorchester residents, in general, have not acted positively or negatively over the installation and operation of the Nation's first solar heating system in a public school. Most visitors, however, are technically-oriented personnel and/or have a definite interest in this new development.

7.1 REACTION OF CONSTRUCTION PEOPLE

In late January a team of General Electric engineers visited Boston to finalize some of the design concepts, and select a general contractor. The Public Facilities Department of the City of Boston made all necessary arrangements for access to the school and provided a conference room for a meeting with prospective general contractors.

Two prospective general contractors were asked to present their capabilities and interest in performing the work. They were selected from the many potential contractors based on recommendations of the architect-engineering subcontractor and various other contacts familiar with the Greater Boston Area.

The Vappi Company was selected because of their expressed interest in working in the Solar Energy field and apparent ability to aid us in obtaining the necessary construction materials. Vappi was asked to select subcontractors so that we might brief them and determine their suitability. During these briefings, it became apparent that a key to completion on time was a harmonious work force. Subcontractors were selected based on their willingness to accept a Time and Material (T&M) contract of an undefined magnitude, a history of good labor relations, expertise in their field and materials on hand or ability to rapidly obtain the necessary materials.

There appeared to be a general disbelief that a solar heating system would work in Boston, and no one could build a system of the magnitude described within six weeks. Once the subcontractors were selected, a member of the design team was assigned to work with each subcontractor to assist him in selecting parts, materials, and processes, and to insure that each work element and each piece of material was available when needed.

Construction began on the roof of the Grover Cleveland School on February 13. The first hole was cut into the roof at approximately 1:30 PM. The welder started removing the cap from the column at approximately 2:30 PM. Immediately after the cutting process started, the fire alarm went off. The fire watch in the classroom immediately below the work ascertained that the construction had not caused a fire. After an inspection by the Fire Department, school resumed (conclusion: a student triggered false alarm). However, a fireman from the city fire department was then assigned to the construction site during the remaining cutting and welding processes.

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 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 work 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.

Certificates of participation, a typical example of which is shown in Figure 7-1, were given to all workers and companies who participated in the impossible task of designing, fabricating and installing the solar heating system in the Grover Cleveland School in Boston.

7.2 INTERACTION WITH SCHOOL

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.

SOLAR HEATING EXPERIMENT

JOHN NOTESTEIN

is awarded this

Certificate of Participation

in recognition of his involvement in the Solar Heating Experiment at the Grover Cleveland School, Dorchester, Massachusetts, from January 14 to May 15, 1974.

L.L. Farnham
General Manager
General Electric Company
Space Systems

D.J. Fink
Vice President
General Electric Comapny
and General Manager
Space Division

Figure 7-1. Certificate of Participation

They were 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.

7.3 INTERFACE WITH THE PUPILS

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 7-2. Mr. A. Furnace, a tired old man, is retiring as the new solar heat is being applied.

7.4 VANDALISM

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 kids threw rocks at the collectors. This did occur on numerous occasions and Figure 7-3 shows the number of rocks and one baseball that were thrown to the top of the three story building over one weekend. No damage to the system has occurred from items thrown; however, loss of one school window per week was typical. Further design considerations were to minimize the exposed copper that attracts some scrap metal collectors. All copper is covered with insulation. Usage of glass sight glasses and flow meters were minimized or valved to lessen the possibility for breakage and subsequent system drain.

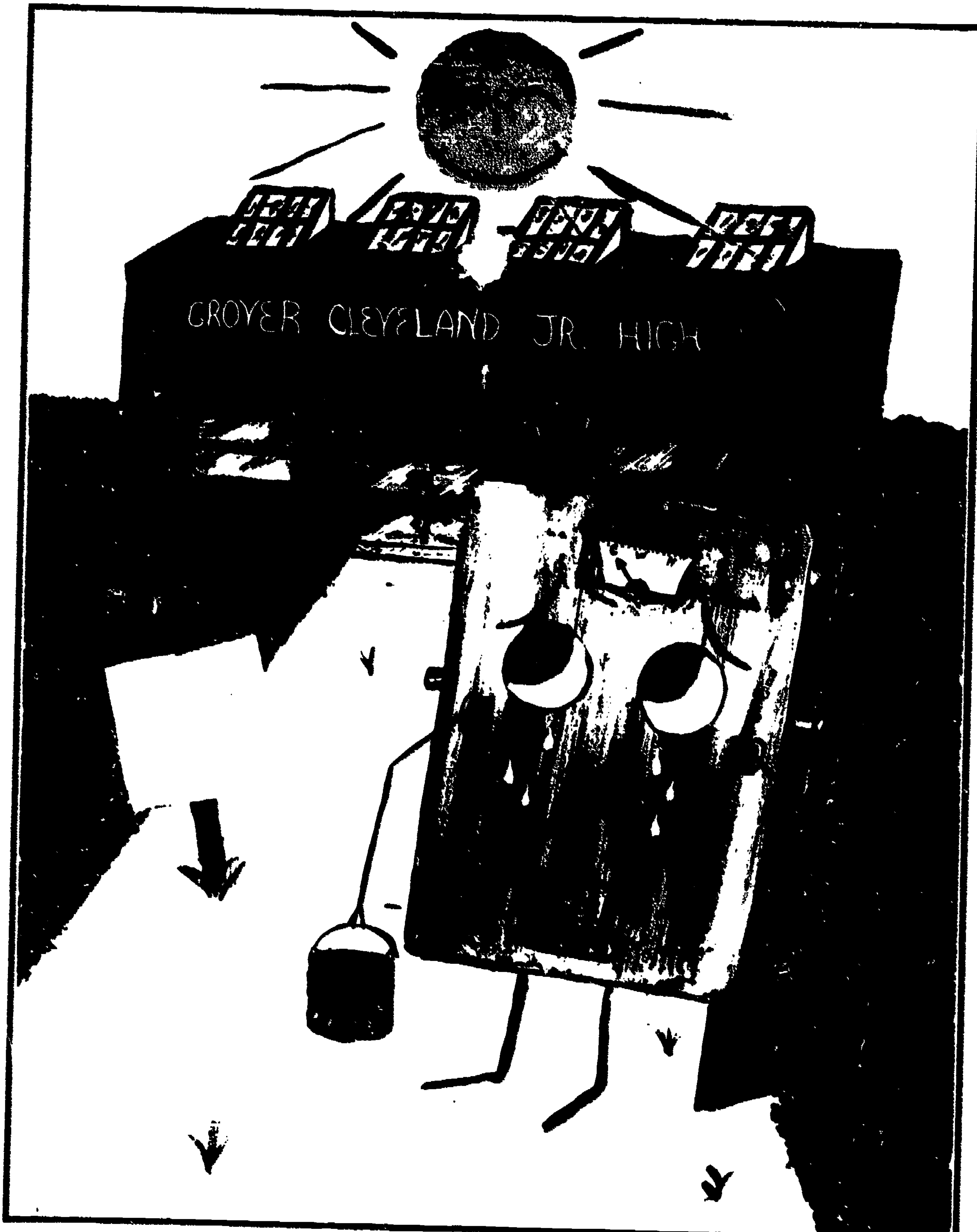

Figure 7-2. Winning Poster

Figure 7-3. Rocks and a Baseball Found on the Roof after a Weekend

The roof and control room are kept locked at all times when not under the surveillance of an authorized worker. Additional brick/mortar work was completed on the back side of the school so as to not tempt the neighborhood children to climb up for an inspection.

In addition to the thrown missiles typified by Figure 7-3, the only other act of vandalism between February 13, when construction started, and May 15, end of the initial operational period, was when someone gained access to the control room while the engineer was out on the roof making a visual inspection. All switches were operated changing the state of every valve and pump. One switch was disloged from the panel. The switch was re-installed and the system was returned to normal operation by the engineer before any damage occurred.

7.5 COMMUNITY INTERACTION

The Dorchester Community is located south of Boston. The area is composed of primarily Irish with some blacks and Puerto Ricans. The community is a blue collar community. Most of the housing and business establishments are housed in old buildings. The original section of the Grover Cleveland School was built approximately 50 years ago; it is being renovated and will return to active service in the Fall of 1974. Across Charles Street from the school is the Fields Corner MBTA Station.

Figure 7-4 shows the school in January 1974 from the MBTA Station north entrance way. The roof line is broken with the sky lights. Figure 7-5 shows the school in May 1974. Note that the roof line has been smoothed out in the center section of the building by the solar collectors.

Figure 7-6 is a view of the school taken from three blocks south on Dorchester Avenue. The school roof line blends into the surroundings and is noticeable only if one specifically knows what to look for (center of picture). The solar collector installation is not visible on the ground level from either the east or west ends because of the roof lines of the buildings.

The northern exposure is primarily hidden from all but a few homes by the small hill behind the school. The solar collectors cast no shadows on buildings nor block the view from any of the homes in the local neighborhood.

The homes north of the school and immediately adjacent to the school reportedly have complained about the noise from the existing air conditioners on the school. If the collector form casts shadows or blocks views of any local residents, these family residents would be affected. In the four months since installation no local residents have registered a complaint with the school, city or any other public officials against the Solar Heating System installation.

7.6 VISITOR INTERACTION

Visitors from all parts of the country have telephoned, visited and asked questions. This includes college professors, power company executives, architects, college students, competitors and a very few blue coll.. workers from Dorchester.

The visitor traffic was and still is composed primarily of technically oriented personnel. The average 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 after contract award and again in early March when the system went operational.

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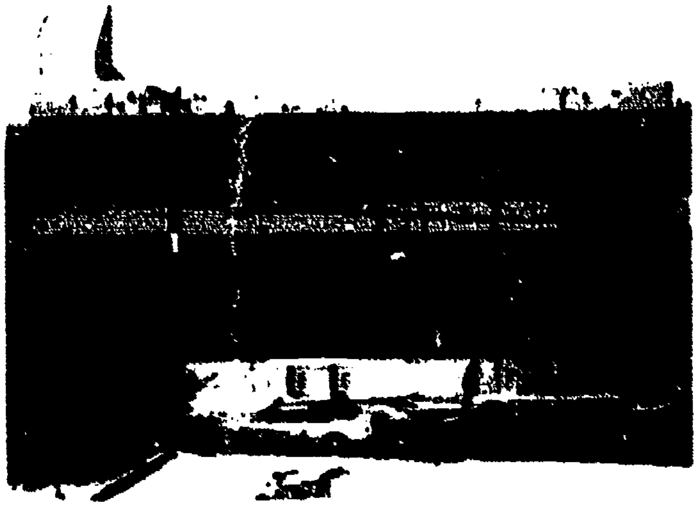

Figure 7-4. Grover Cleveland School in January 1974

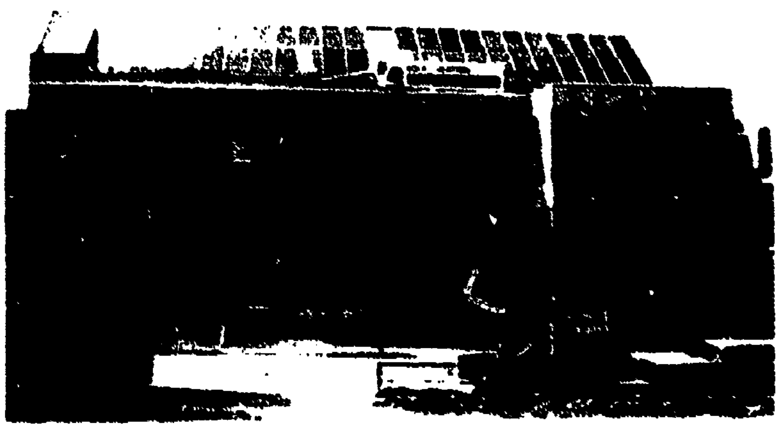

Figure 7-5. Grover Cleveland School in May 1974

Figure 7-6. Grover Cleveland School from Three Blocks South

SECTION 8

CONCLUSIONS

This section is a summary of the major conclusions reached in performing this experiment during the January - May 15, 1974 time period.

- Solar heating is effective and feasible in the northeastern United States.
- Over a full season the solar system is expected to provide over 2/3 of the heating requirements of the middle third of the school (the portion served by the solar heating system).
- Institutional personnel (schools, governments, utilities, etc.) are highly interested in solar energy applications. They took the initiative to understand the system and actively participated in helping others to understand its operation and benefits.
- The technically aware public shows considerable interest in solar energy applications as evidenced by the number and types of visitors to the school.
- This solar system was compatible with local residences and businesses. No objections to shadowing, aesthetics or even the inconveniences of the construction were evident.
- The construction workers were skeptical initially but became quite proud of working on the project when it became apparent that solar heating worked.
- Even large, roof mounted planar arrays are not particularly noticeable from a distance of a few city blocks (Figure 7-6).
- It is possible to utilize a solar array as a fascia to enhance a building's roof line (Figures 7-4 and 7-5).
- Resistance to vandalism is a major design consideration. These Lexan window solar collectors withstood frequent impacts from thrown rocks and baseballs (Figure 7-3). There has been no damage to date and, for comparison, the school averages one broken window per week.
- Electronic integrators should be utilized for important data which varies randomly, i.e., solar flux.