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SIMS PROTOTYPE SYSTEM 4 - PERFORMANCE TEST REPORT

Prepared by

IBM Federal Systems Division
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16. ABSTRACT

This document presents the results obtained during testing of a self-contained, preassembled air type solar system, designed for installation remote from the dwelling, to provide space heating and hot water. Data analysis is included which documents the system performance and verifies the suitability of SIMS Prototype System 4 for field installation.

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1.0 INTRODUCTION

The solar system tested is a space and domestic duct water heating system intended for a small single-family dwelling. The prototype system was designed by IBM under Contract NAS8-32036 with NASA Marshall Space Flight Center. The system is an air-type , stand-alone, prepackaged, transportable module which utilizes the following major components:

(1) Twelve Solaron Corporation Series 2001 air type solar collector

(2) Prefabricated modular pebble bed, thermal storage unit

(3) Grainger Inc. Model 7C 808 air blower

(4) Grainger Inc. Model 2C986 air blower with 5K900 motor

(5) Two Ruskin Model CD454PB/MP1161 dampers

(6) Two American Warming Model SHB-D-1217 back-draft dampers with cohrelastic blades

(7) Two American Warming Model DAA-P-8150 balancing dampers

(8) Jackson Manufacturing Model UCO 5225 hot water tank for system preheat tank

(9) Halstead Mitchell Model SW2-18-18-8 air-to-air liquid heat exchanger

(10) Elmswood Thermostat Model 3100 (Part of absolute temperature control system)
(Two Solar Controls Model 77-177 (ΔT controller) were also tested as a control comparison.)

The components are configured into the collector, energy storage energy transport and control subsystems which make up the System 4 configuration. Section 4.0 describes subsystem operation and presents summarized test results. A system schematic diagram of System 4 is shown in Figure 1.0-1. All testing, data collection and data processing to support this evaluation were performed by the Solar Energy Systems Division of Wyle Laboratories, within the MSFC Solar Heating and Cooling Test Facility. Appendix A contains the detailed test procedure with representative test data.

The major objectives of the system test were as follows:

- To verify that individual marketable components perform within the system to meet overall system requirements.
- To verify design concepts and to insure that the system will operate satisfactorily before field installation.
- To provide a performance data base for future comparison with the performance observed during the National Solar Data Network Evaluation when the system is installed at the field test site.

System 4 performance at the test site was evaluated from test data and used by IBM to predict performance at the proposed field site. This performance was then compared with performance predicted from vendor data during the design effort.

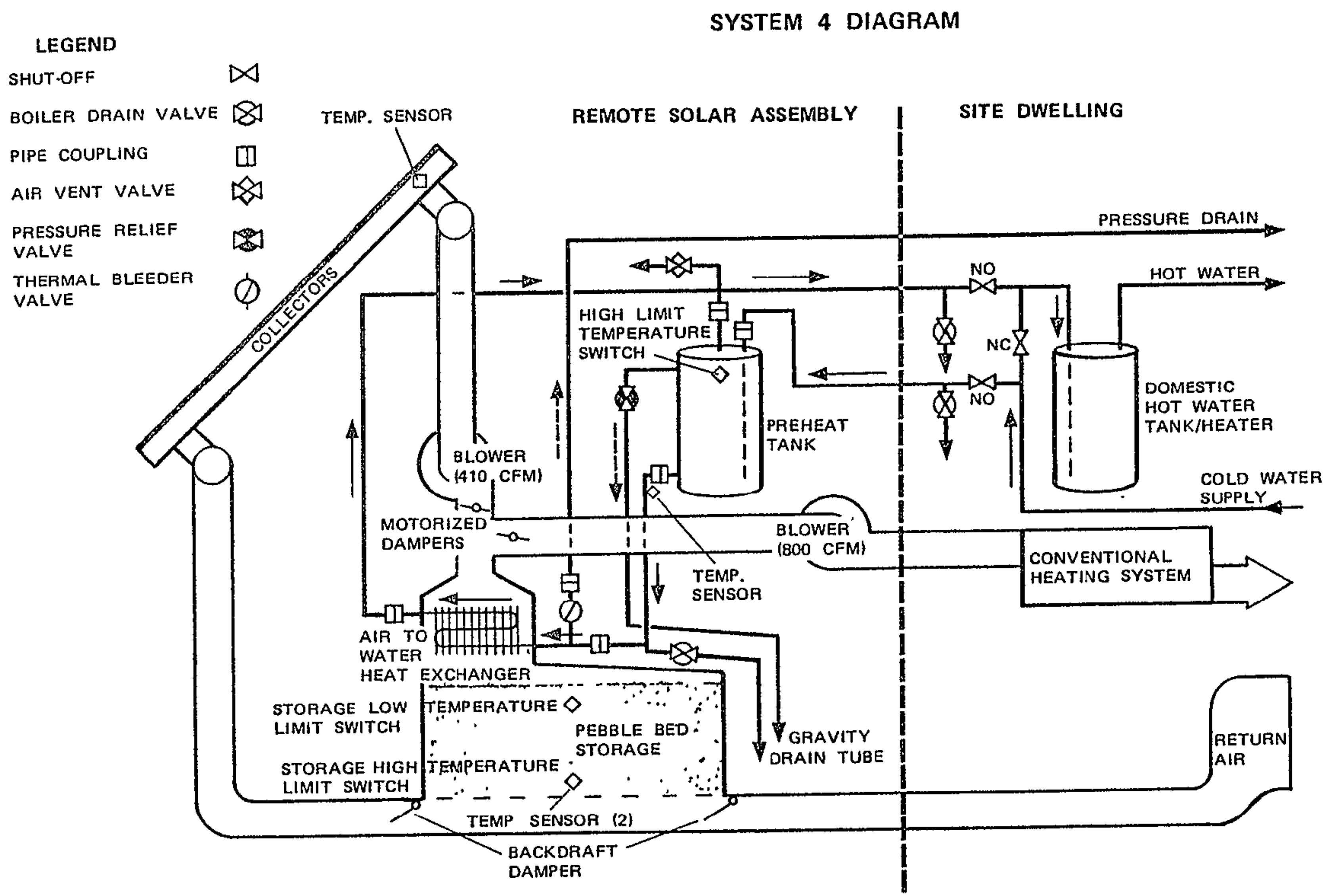

Figure 1.0-1, System 4 Schematic Diagram

2.0 SIGNIFICANT RESULTS

The performance testing of SIMS Prototype System 4, in the MSFC Solar Heating and Cooling Test Facility, resulted in the following conclusions:

- System operation was obtained without significant problems.
- The original control system limited the capacity of the system, but otherwise performance was satisfactory.
- The performance of the system, based on test data projected to Clinton, Mississippi site, will provide 48.2% of the 59.63 MMBTU total annual space heating and hot water load.
- The thermosphon domestic hot water system can supply the daily hot water demands.
- SIMS Prototype System 4 has proven suitable for field installation.

The test data was analyzed and compared with design system performance prediction. The results of these analyses are discussed in later sections.

3.0 TEST DESCRIPTION

The first tests performed on System 4 were operational functional tests. These tests were conducted to evaluate the performance of each functional component, as it performs within the system, prior to beginning the overall system performance evaluation. All component problems were corrected or adjustments made before continuing with the testing.

System performance testing was conducted with dedicated test runs to evaluate three principal areas of system performance as follows:

- DHW Heating
- Pebble Storage Charge and Discharge
- Space Heating

Domestic hot water heating test runs were started with pebble bed storage temperatures uniformily at 70^{o}F or elevated to approximately 100^{o}F. In addition, the water load was applied in either of two schedules as follows:

Schedule 1:

Time	Draw
At start of test (Generally 8:30 AM)	52 gallons
10:00 AM	10 gallons
12:00 Noon	10 gallons
2:00 PM	10 gallons
3:00 PM	10 gallons

Schedule 2:

Time	Draw
At start of test (Generally 8:30 AM)	52 gallons
10:00 AM	10 gallons
12:00 Noon	10 gallons
2:00 PM	20 gallons
3:30 PM	20 gallons

Pebble bed charge and discharge runs were performed by first preconditioning storage with uniform temperature air heated by the simulator. Then the load loop blower was run continuously to discharge air to the ambient until storage was depleted. During the test run, the return air temperature was maintained at or near 70^{o}F by the simulator.

Space heating tests were run by intermittently operating the load blower twenty minutes "on" and ten minutes "off". The test was run during good solar days starting either with depleted storage or saturated storage.

Appendix A contains the detailed test procedure of the above testing.

The absolute temperature control initially planned for System 4 was replaced with two differential temperature controllers after the initial testing was conducted. Testing on the differential control system was primarily concerned with collector blower turn-on and shut-off. The system was allowed to operate in a automatic mode with occasional DHW loads applied to eliminate system shut down by the preheat tank high-limit switch. Data was continuously collected to evaluate the temperature differential at turn-on and turn-off as insolation conditions and rock storage temperature varied.

4.0 SUBSYSTEM TEST

The collector, energy storage, domestic hot water, energy transport and control subsystems were all evaluated by the system tests. The following paragraphs describe the test experience and performance measurements.

4.1 COLLECTOR SUBSYSTEM

The basic collector module is 3 feet wide by 6.5 feet long by 7 1/4 inches thick. The absorber is 24 gage steel, with PPG "Duracron 600" surface finish. The unit housing is 24 gage steel with two 1/8 inch thick low iron safety glass covers. Twelve collectors are manifolded together in a series parallel air flow configuration.

The performance that can be expected from a collector can be evaluated from its efficiency curve. The solid line in Figure 4.1-1 represents the efficiency curve defined by the vendor. The alternate short, then long dashed line, represents the curve obtained from previous MSFC solar simulator testing. The short dashed line represents System 4 collector array efficiency as determined from test results. Efficiency was calculated by using data during periods of relatively constant insolation during solar noon. The curve was generated from data listed in Table 4.1-1 using linear regression techniques to obtain the best curve fit of the data points. The data points are all at values of $\frac{T_{IN} - T_{amb}}{I} < .2$ because of the limited data available where insolation rates are low and $\left(T_{in} - T_{amb}\right)$ values are high. This was the result of testing only in one season of the year where both ambient temperatures and insolation rates were relatively high.

The difference between the vendor's efficiency curve and the solar simulator efficiency curve is caused by (1) the difference in air flow, (2) the difference in collector boundary insulation conditions and (3) the difference in area used in the calculations. The vendor tested with an air flow of 4 cfm per square foot of effective collector area, with two collectors in series in an

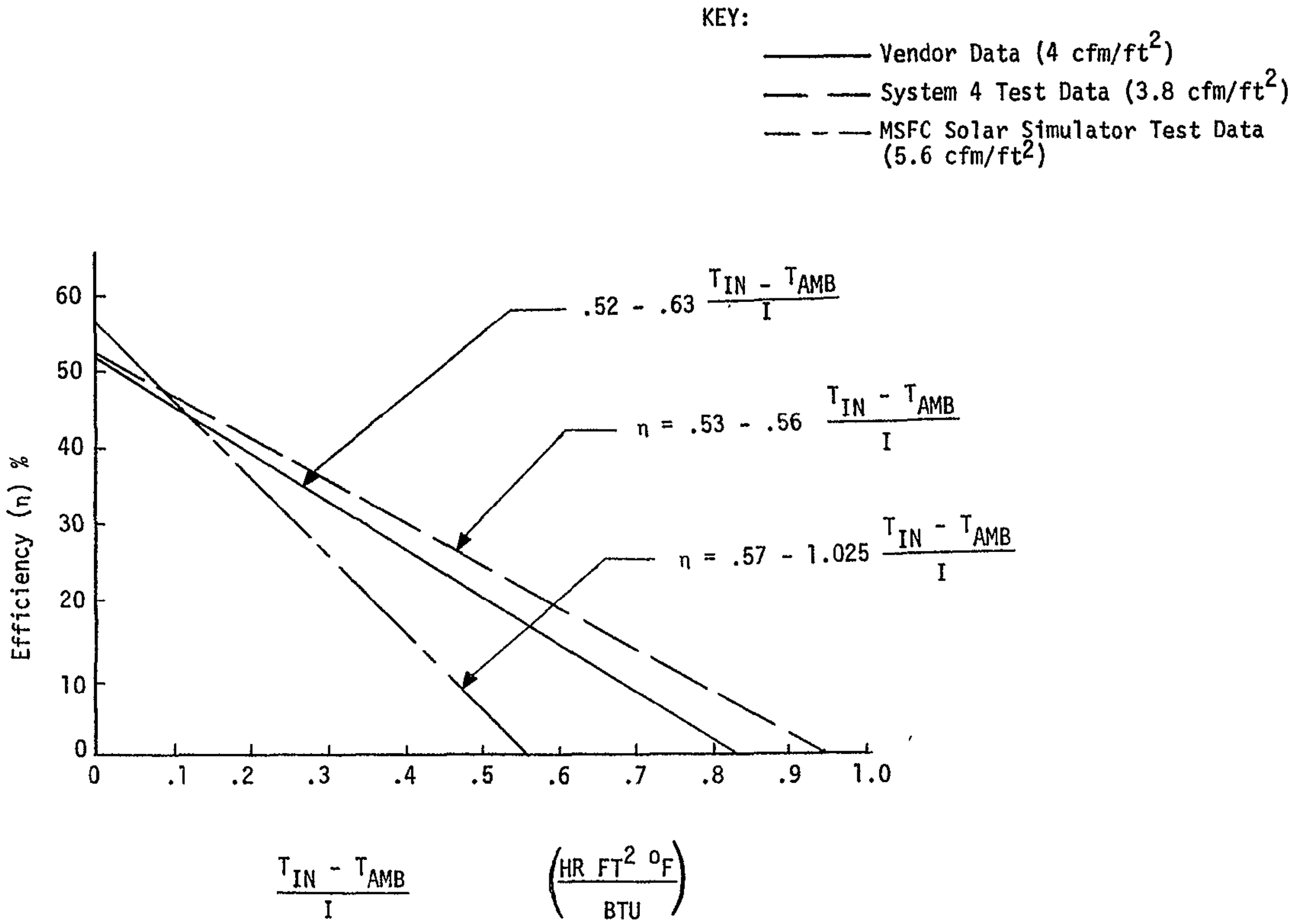

Figure 4.1-1 Collector Efficiency

Table 4.1-1 System 4 Thermal Performance Test Data

Data	4/17	4/19	4/24	4/27	5/2	5/5	5/9	5/10	5/11	5/11	5/19	5/19	5/23	5/25	6/13	6/14	6/15	7/15	7/26	7/26
Time (Hrs from Start)	3.0	3.75	3.5	4.0	3.25	4.25	3.25	4.5	3.75	7.25	3.75	4.0	4.0	4.25	3.25	4.75	6.0	1.0	4.5	5.75
Ambient (^oF)	80	60	80	68	65	65	78	77	78	80	60	85	87	90	82	80	86	90	90	93
T_{in} (^oF)	105	68	71	79	75	73	73	84	91	104	68	123	115	121	138	98	106	105	113	151
T_{out} (^oF)	165	94	156	151	145	117	155	157	161	145	94	189	173	177	196	172	167	171	178	201
Air Flow (SCFM)	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	440	440
I (Btu/Hr Ft^2)	315	100	320	310	295	215	296	295	290	200	100	285	280	120	273	277	265	275	305	290
Q_U (Btu/Hr Ft^2)	125	54	177	150	146	92	171	156	146	85	54	149	121	117	120	155	128	137	153	117
$(T_{in}-T_{AMB})/I$	.08	.08	-.03	.04	.034	.037	.017	.017	.045	.12	.08	.133	.098	.11	.20	.06	.07	.055	.074	.20
Efficiency (n)%	40	54	55	48	49	43	58	53	50	43	54	48	43	41	44	56	48	50	50	40

insulated array and used the effective area of the absorber in the calculations; whereas, the solar simulator test was conducted with an air flow of 5.6 cfm per square foot, with a single uninsulated collector and the gross collector area was used in the calculations.

The vendor's efficiency curve and the System 4 array efficiency curve were both obtained from an insulated array configuration. The effective area of the collector was also used in the efficiency calculations for both collectors. It is therefore understandable that the curves are in close agreement. The somewhat better efficiency of the System 4 array is probably the result of the higher back side and perimeter insulation values that were used in System 4.

Figure 4.1-2 is a plot of five continuous collector absorber temperature measurements versus time for a typical solar day. The figure shows how the temperature varies throughout the absorber at any instant in time. The figure also shows how the absorber temperatures are affected by the collector blower and by introducing domestic hot water load.

The loss coefficient of the collector was evaluated in a non-solar condition by operating the system in the collector-to-storage mode during a late afternoon thunderstorm condition. The system was operated by manual controls. The results of the test are shown in Figure 4.1-3. A loss coefficient (U_L) of 0.76 Btu/Hr ft^2 ^{o}F was calculated from data taken at approximately 6:43 P.M. This value agrees favorably with the value of 0.78 Btu/Hr ft^2 ^{o}F obtained from the System 4 array efficiency curve plotted in Figure 4.1-1.

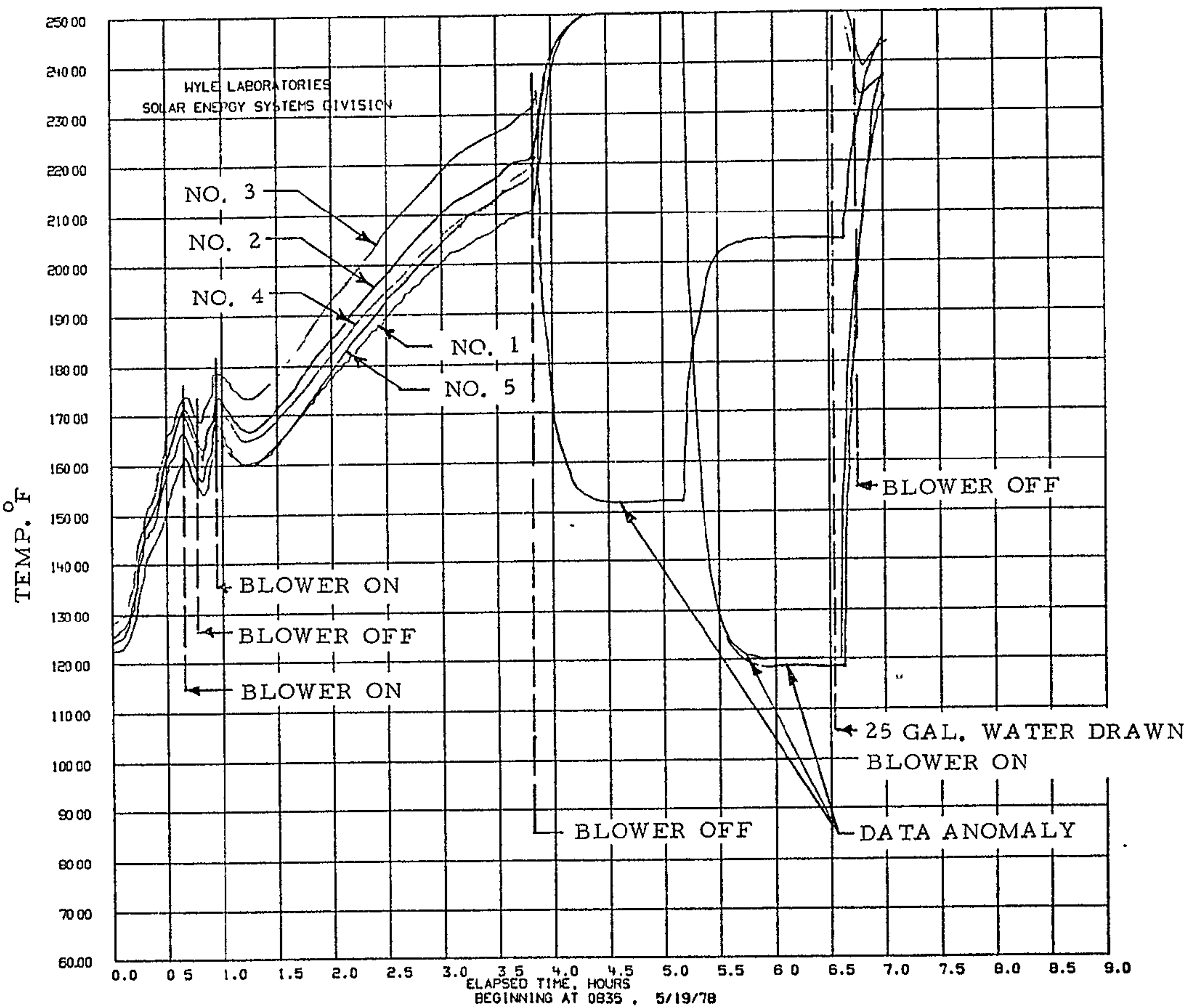

Figure 4.1-2 Typical Absorber Temperature Dispersion

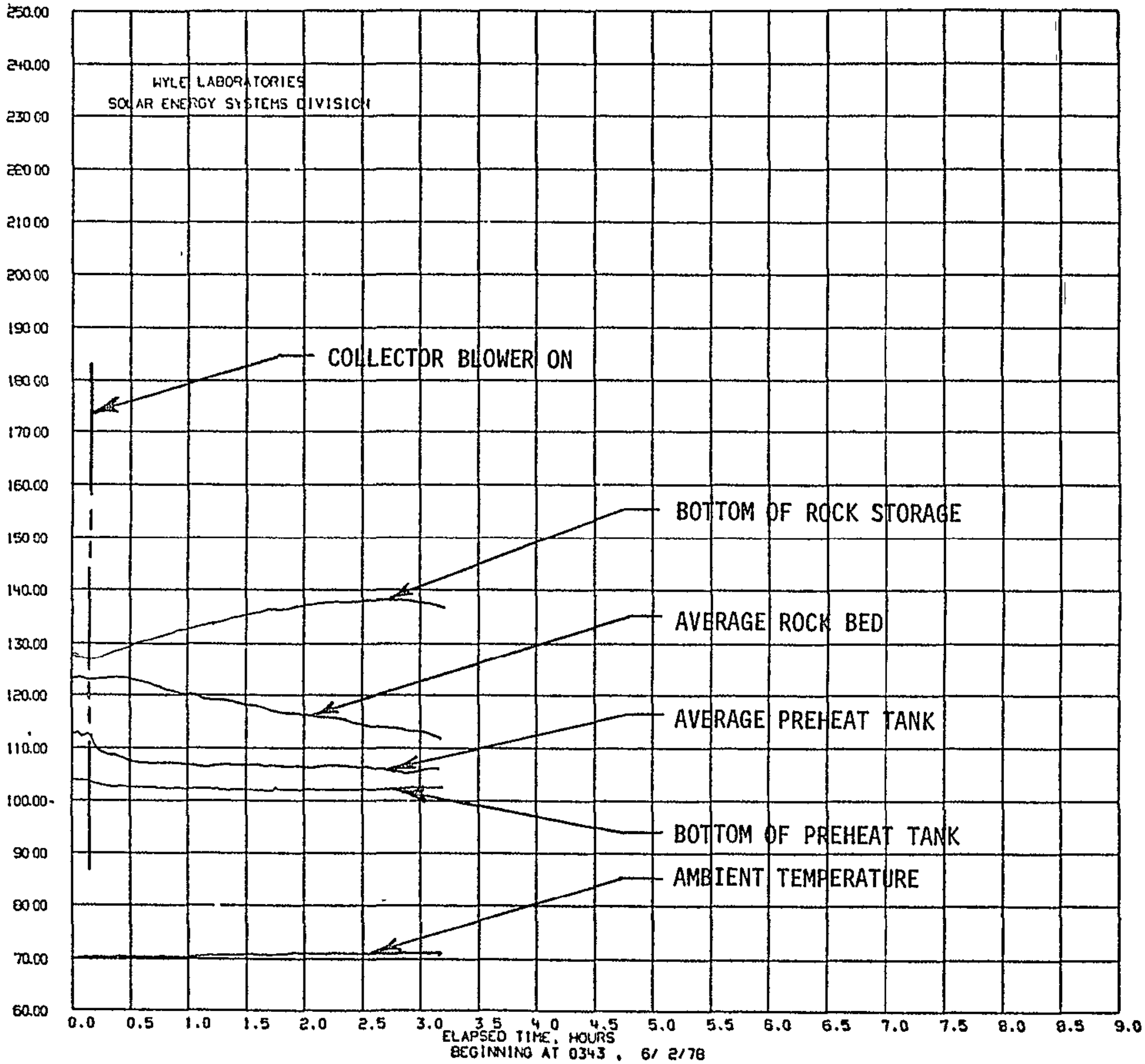

Figure 4.1-3 System 4 Performance in a Summer Mode Operation

4.2 ENERGY STORAGE SUBSYSTEM

The energy storage subsystem consists of a bed of pebbles contained in a modular designed rectangular shaped thermally insulated enclosure. The enclosure is 117.5" long by 70" wide by 52 3/4" high and contains approximately 116 cubic feet of pebbles.

The results of the discharge tests show that 80,000 to 90,000 BTU were pumped from storage in roughly 3 hours. The amount of heat in storage was slightly less than the saturated storage condition and is roughly the amount of heat that can be collected in one good solar day of collection plus supply hot water load of 120 gallons/day. Ninety thousand (90,000) BTU is sufficient to supply space heat to the site at design load (556 BTU/Hr^{O}F x (70-20^{O}F) = 27,800 BTU/Hr) for 3 1/4 hours.

A change in the control system from an absolute collector temperature control to a differential control was made to the system after the discharge tests were completed. The absolute temperature control limited the bottom of storage to 110^{O}F. The differential control system controls the energy collection based on the temperature difference between the collector and bottom of storage. This permits the temperature at the bottom of storage to rise considerably above 110^{O}F, and therefore the thermal capacity of storage is increased.

System 4 testing performed with the differential temperature control system in the summer mode of operation resulted in much higher pebble storage temperatures. The highest storage temperatures were noted on June 13. Temperatures at the top, middle and bottom of the pebble bed were 165, 152 and 142^{O}F. At that time, approximately 180,000 Btu were available in storage to supply heat to a load at 70^{O}F. Storage of this much heat would not be possible in the winter when heat is generally being supplied to the load throughout the day and night.

Figure 4.2-1 is a plot of three continuous storage temperature measurements versus time for a summer solar day. The measurements correspond to a typical measurement at the top, middle and bottom of the pebble bed. The figure shows how typical storage temperatures at the three locations are affected by the collector blower throughout the solar day.

The loss coefficient of the rock storage bed was obtained by first (1) calculating the heat loss from the decrease in bulk rock temperature, (2) determining the temperature difference between the average inside and average outside temperatures, and (3) observing the time interval over which the heat loss was measured. Having these three parameters, the loss coefficient was determine by dividing the heat loss (1) by the temperature difference, (2) and by the time interval (3). An average loss coefficient was found to be 18.2 Btu/Hr^{O}F.

The air pressure differential across storage was .01" H_2O at 400 cfm and .015" at 800 cfm.

Twenty-seven temperature measurements were located in the pebble bed storage to evaluate thermal characteristics. Nine measurements were installed in each of three horizontal planes located 4, 15 and 26 inches from the top of storage as shown in Figure 3 of Appendix A. Figures 4.2-2, 4.2-3 and 4.2-4 show how the temperature varies with time at the bottom, middle and top layers respectively. Temperature measurements in each plane after the collector blower is turned on for approximately one hour help to identify channeling or short circuiting of air flow. Maximum temperature variations of approximately 10^{O}F can be noted. Five degrees of this variation is attributed to temperature inaccuracies and anomalies. The remaining temperature variation, 5^{O}F, is considered insignificant and therefore no detrimental channeling or short circuiting exists.

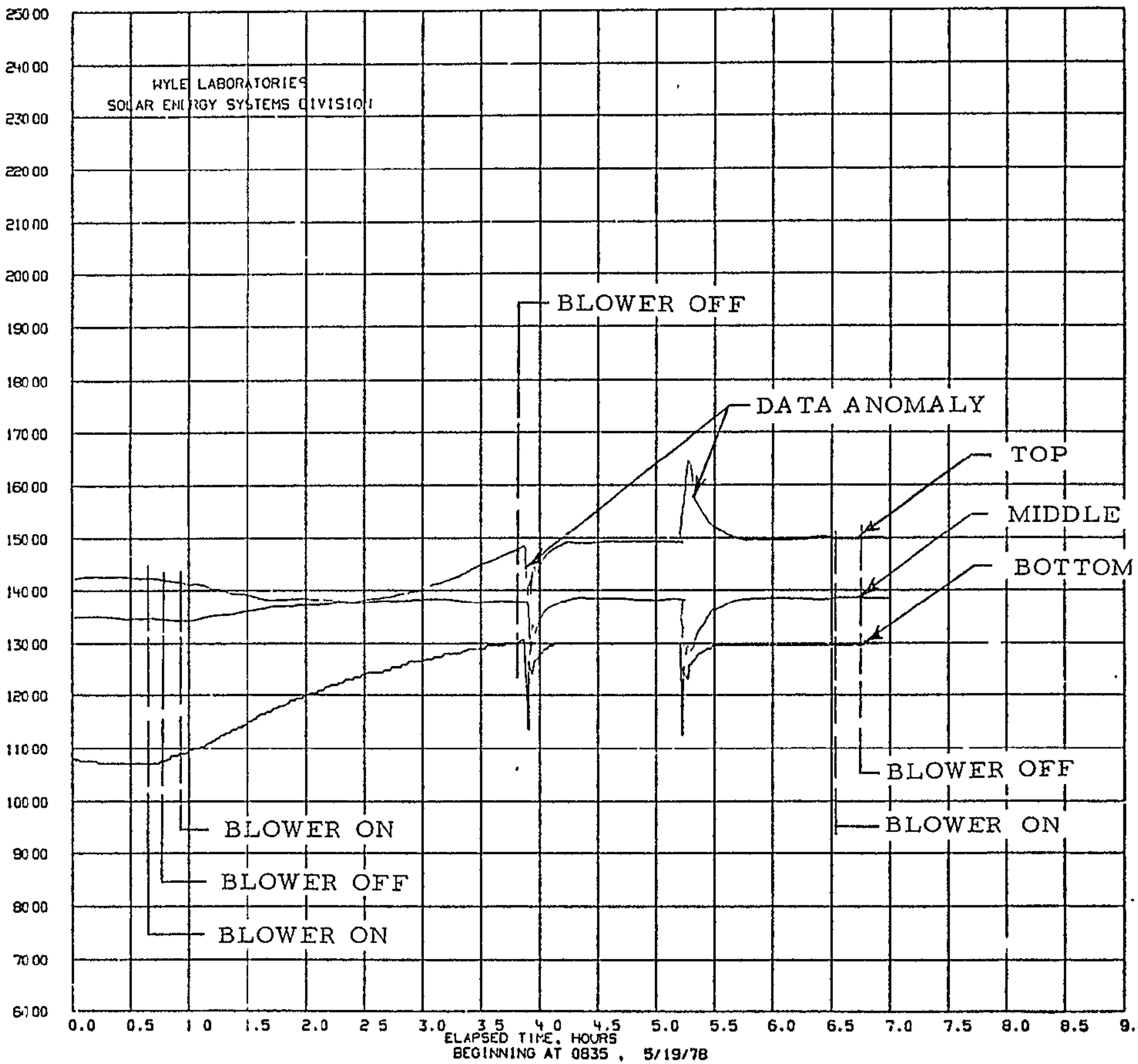

Figure 4.2-1 Pebble Storage Stratification

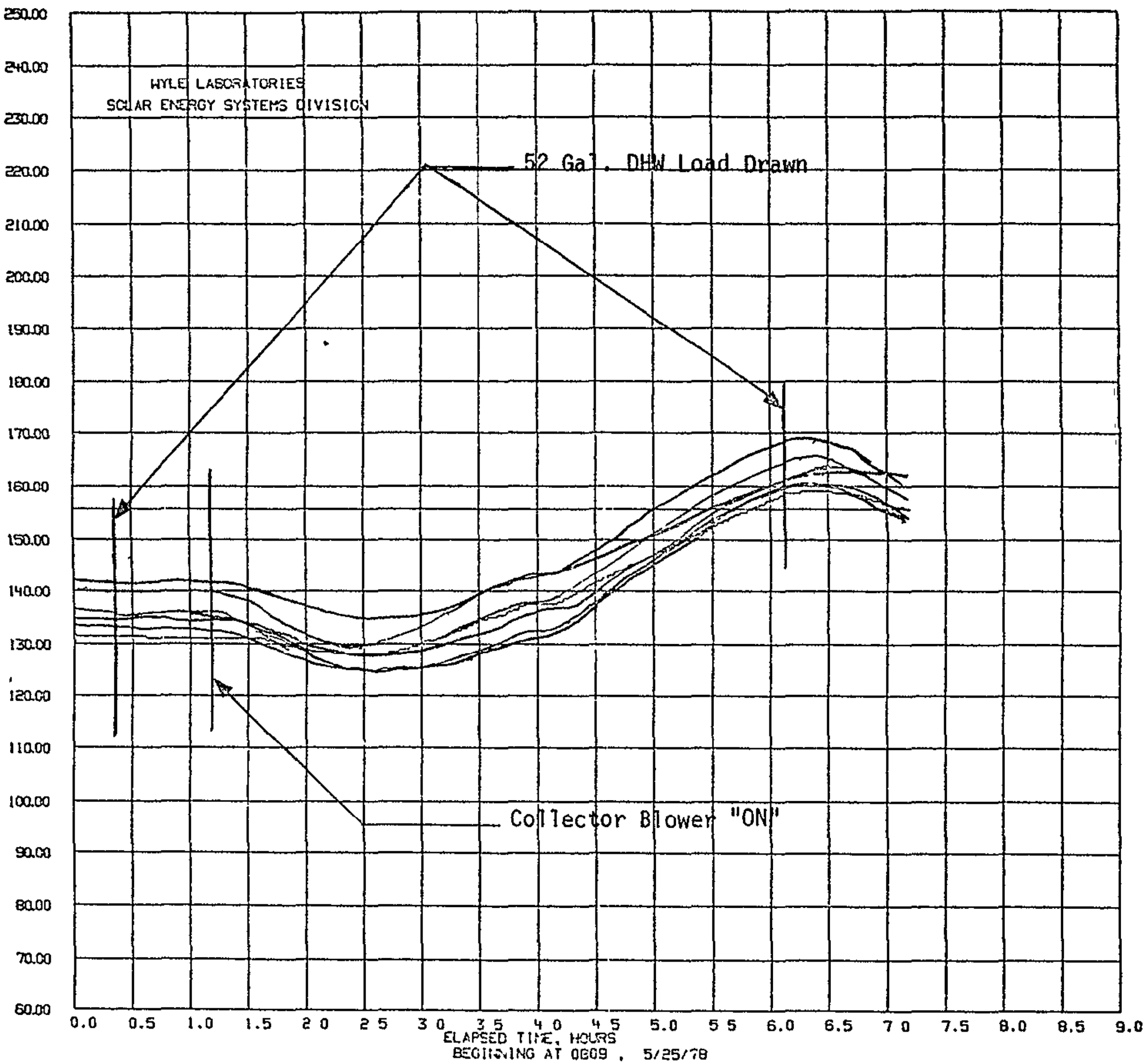

Figure 4.2-2 Pebble Bed Bottom Layer Temp. Measurement (^{o}F)

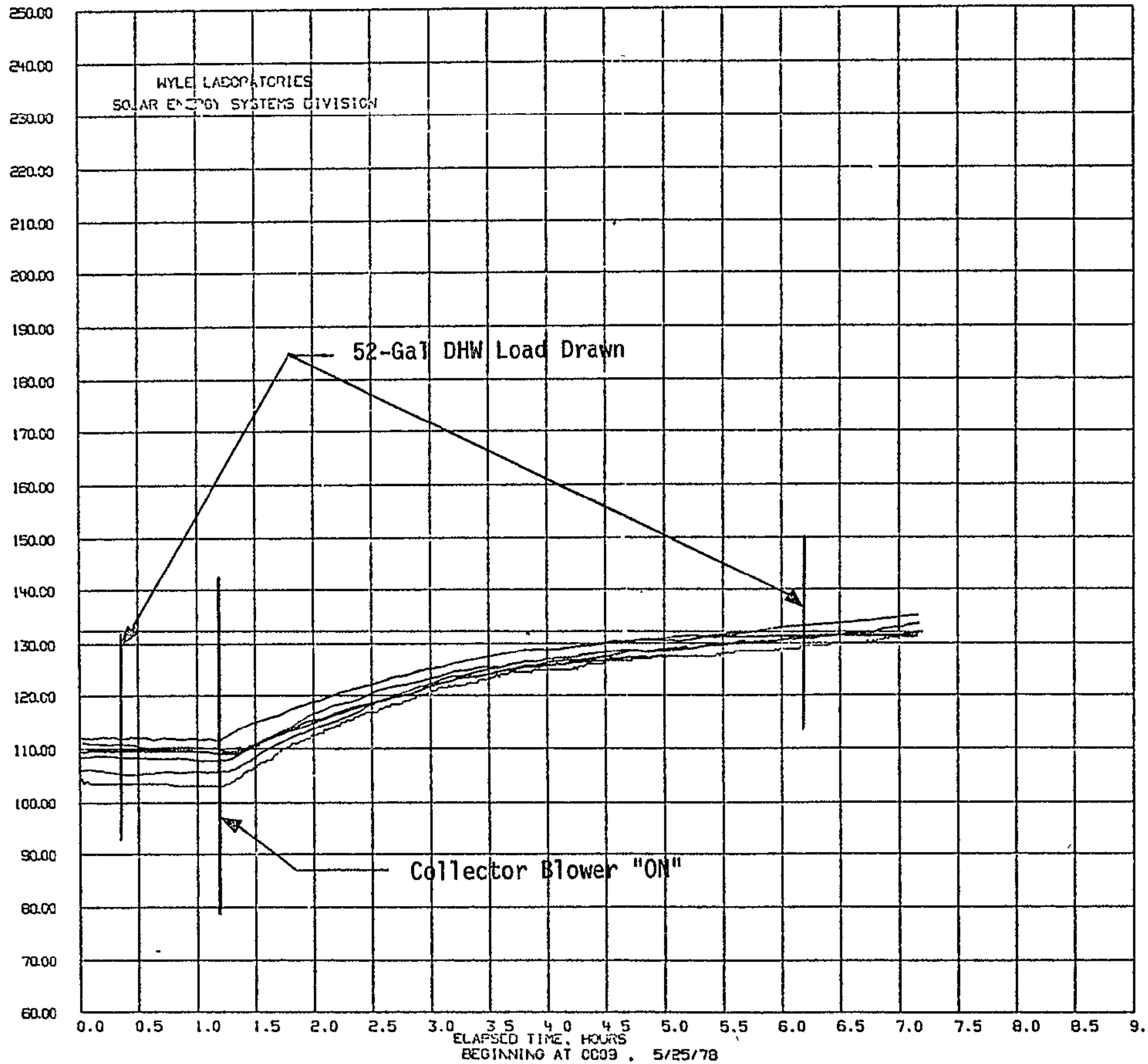

Figure 4.2-3 Pebble Bed Middle Layer Measurements (^{o}F)

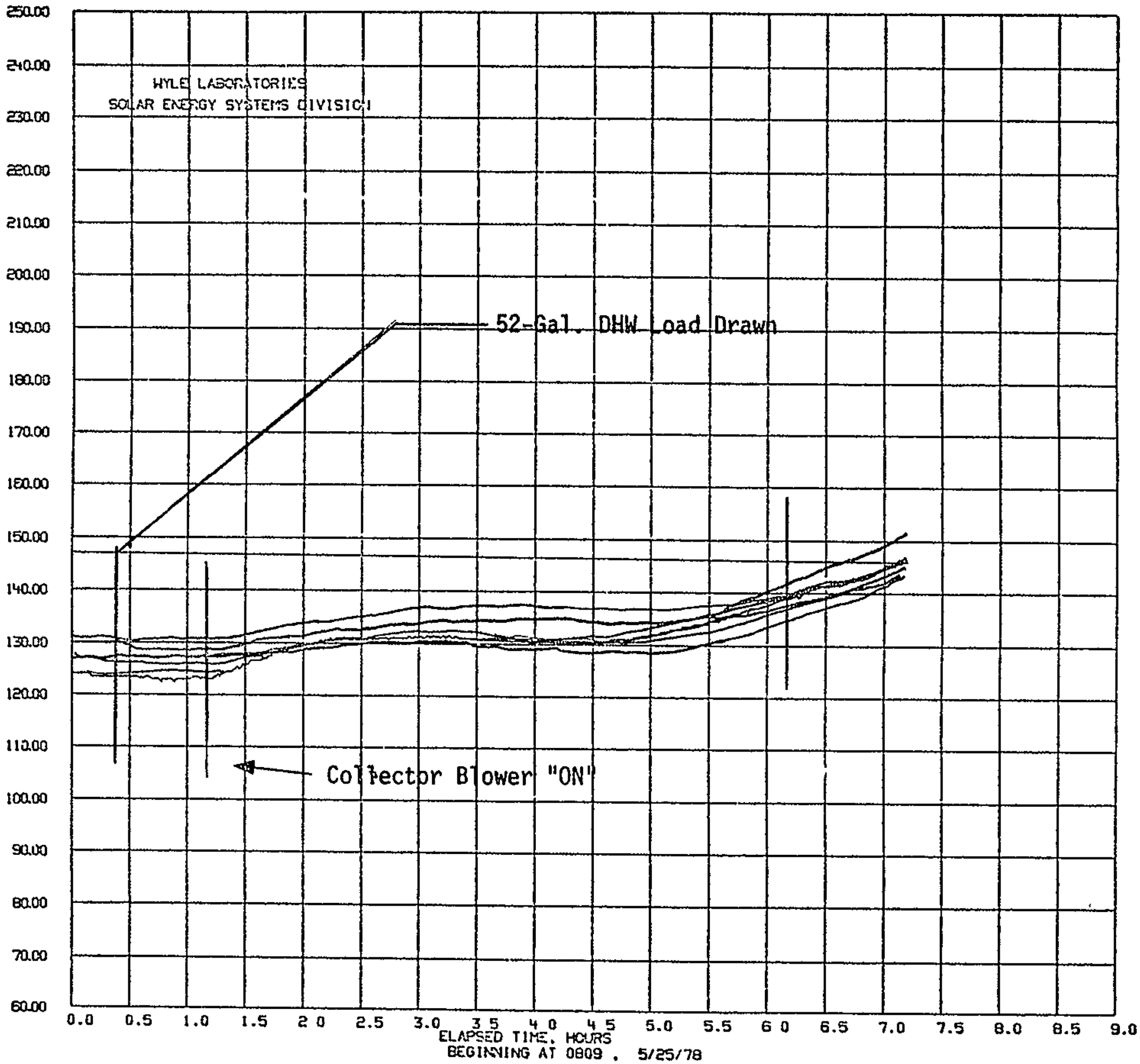

Figure 4.2-4 Pebble Bed Top Layer Temp. Measurements (^{O}F)

4.3 ENERGY TRANSPORT SUBSYSTEM

The energy transport subsystem is a two blower system with control dampers, balancing dampers, back draft dampers and interconnecting duct work. The two blowers are identical but are driven at different speeds to obtain approximately 400 cfm in the collector loop and 800 cfm in the load loop. The initial collector blower motor was 1/4 Hp, 1725 RPM, 115 VAC while the load blower was 1/2 Hp, 1725 RPM, 115 VAC.

Both motors operated near rated full load as follows:

Item	Air Flow	ΔP	Speed	Amps	Volts	PF
Collector	390 Scfm	0.68 "H_2O	921 RPM	5.4	120	.46(1)
Load	810 Scfm	1.6 "H_2O	1471 RPM	8.0	120	.60(1)
Damper	-	-	-	0.2	120	-

The power consumption for an 8-hour day operating continuously would be 8,600 and 15,000 BTU respectively.

The collector blower operated slightly above rated load to obtain 390 cfm, such that on a day with a very high ambient the motor thermal overload switch opened, thereby temporarily disabling the blower. Since the motor size was barely adequate for the 12 collector array and since it would be desirable to have the motor also be suitable for the 16 collector array unit, the 1/4 Hp motor was replaced with a 1/2 Hp, 1725 RPM, 115 VAC motor.

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(1) Power factor was calculated on the total power for the blower motor and its damper motor.

The load blower operated at the motor rated load to obtain 800 cfm. No problem was encountered during the testing; however, since the air flow to load requirement in the field may exceed 800 cfm, the 1/2 Hp motor was replaced with a 3/4 Hp, 3450 RPM, 115 VAC motor.

The pressure drop thru the collector loop and load loop where higher than expected. This was caused by the sharp duct turns and the many duct to component adapters. Also, elaborate high performance ducting with features such as turning vanes were not employed in order to minimize cost.

A large portion of the back pressure in the load loop is the pressure drop across a test instrumentation nozzle in the load duct. This nozzle will not be in the duct when the system is installed in the field. Load duct losses will vary considerably depending on the site. The new 3/4 Hp load blower motor is expected, however, to provide sufficient power for almost any application.

4.4 DOMESTIC HOT WATER SUBSYSTEM

The domestic hot water subsystem consists of an air to water, fin tube heat exchanger and a 52-gallon preheat tank interconnected with one inch copper tubing. Water circulates from the heat exchanger to the preheat tank by thermosyphon action whenever the air passing over the heat exchanger is hotter than the water in the heat exchanger.

Figure 4.4-1 is a plot of the air temperature vs. time for the air inlet and outlet from the air-to-water heat exchanger. The air temperature difference from inlet to outlet is readily determined from the plot. Since the air mass flow is constant when the collector blower is on, the heat transferred from the air to water is therefore directly related to the temperature difference. The maximum heat transfer rate occurred at 11:35 AM and was calculated to be 13,000 Btu/Hr.

Figure 4.4-2 is a plot of the water temperature vs. time for the water inlet and outlet of the air-to-water heat exchanger. The water temperature difference is readily determined from the plot. No water flow measurements were made in the thermosyphon loop because of the resistance to flow which would be caused by inserting a sensor in the loop. Assuming that all heat rejected from the air is transferred to the water, the water flow rate can be determined from the water temperature difference. A water flow rate of 0.52 gallons per minute was calculated based on the 13,000 Btu/Hr. heat transfer rate and the water temperature difference from inlet to outlet at 11:35 AM.

The effectiveness of the heat exchanger varies widely as expected. The effectiveness at the 13,000 Btu/Hr heat transfer rate on May 19, 1978 at 11:35 AM was 0.40.

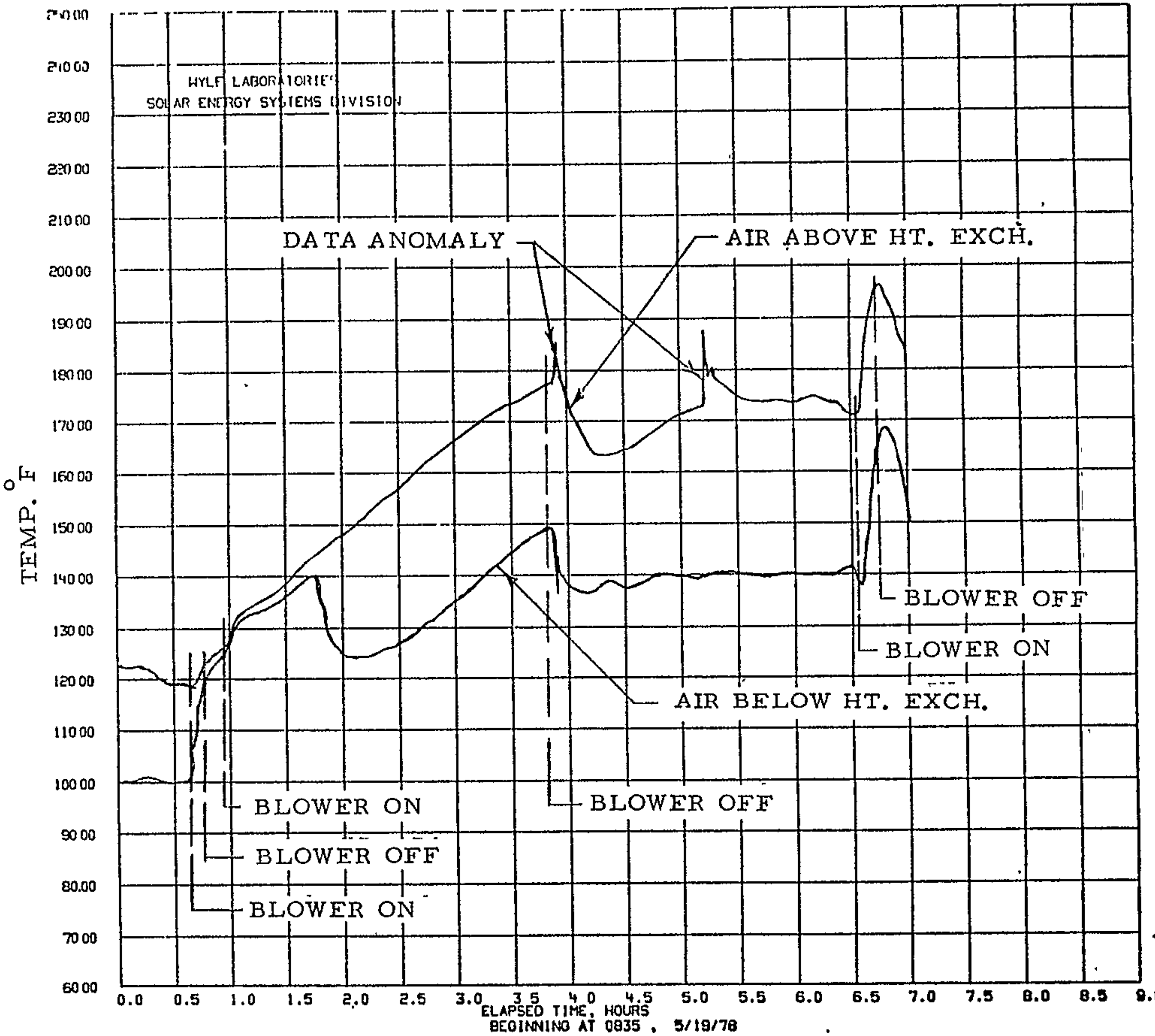

Figure 4.4-1 Air Temperature Difference across Heat Exchanger

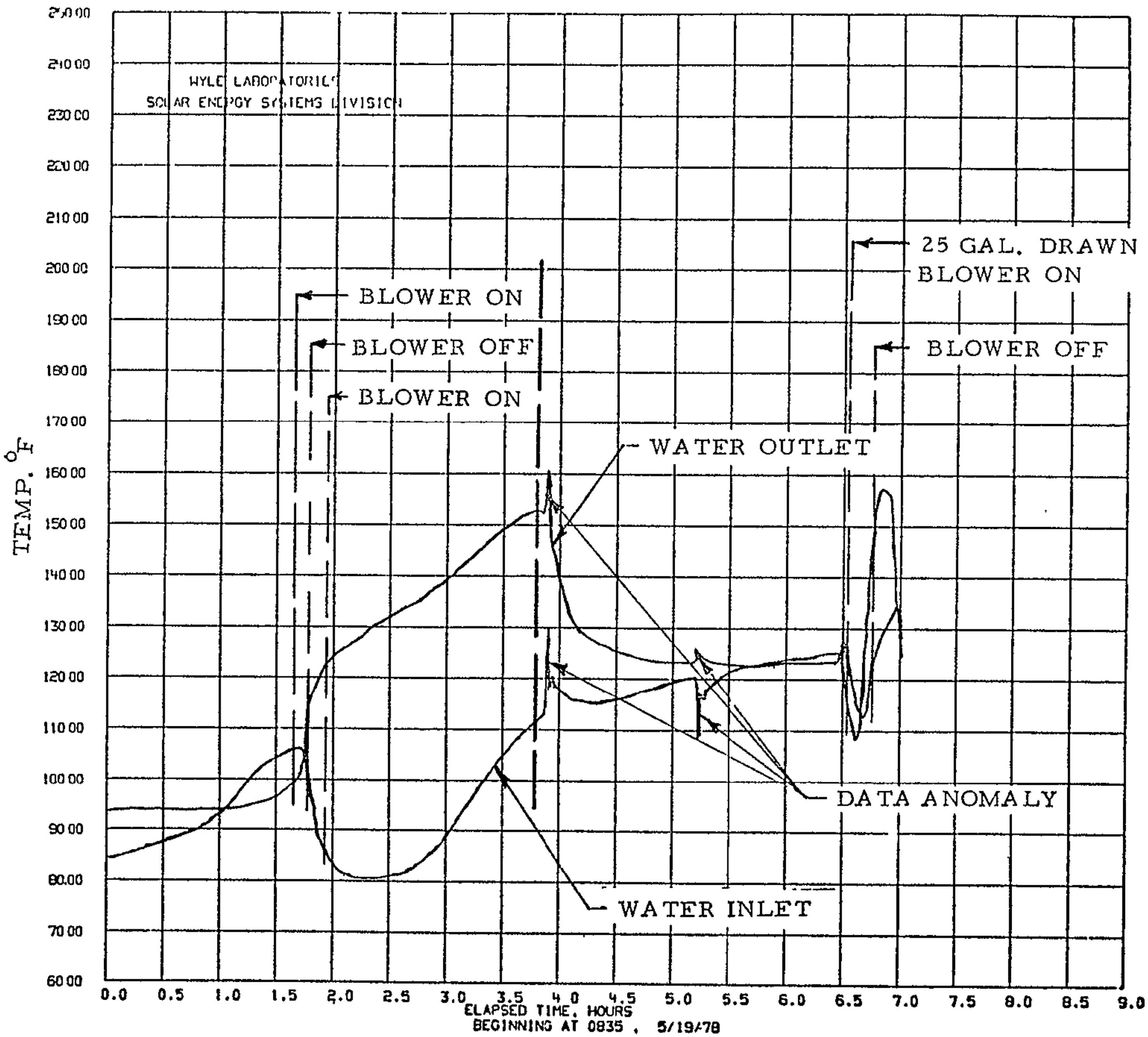

Figure 4.4-2 Water Temperature Difference across Heat Exchanger

The capability of the domestic hot water heating system to carry the hot water load is mainly dependent on the air temperature that can be delivered to the heat exchanger. This is affected not only by solar insolation but also by pebble bed storage temperature. The design daily hot water load based on 130 gal/day utilization is 79,200 Btu for the proposed field site near Jackson, Mississippi. Based on the above system condition with 13,000 Btu/Hr rate, the design daily hot water load could be met with a 6-hour per day system operation. It is expected that during the summer months, rock storage will be saturated at high temperature most of the time and during days of fair insolation 100% of the domestic hot water load can be met. During days with no solar insolation, some domestic water heating will still be accomplished by operating the collector blower to circulate the hot air from storage to the heat exchanger.

Water temperature stratification will occur in the pre-heat tank. Figure 4.4-3 shows the temperature versus time of five temperature measurements located from top to bottom in the preheat tank. Maximum temperature stratification varied throughout a solar day from about 35 to 45^{O}F.

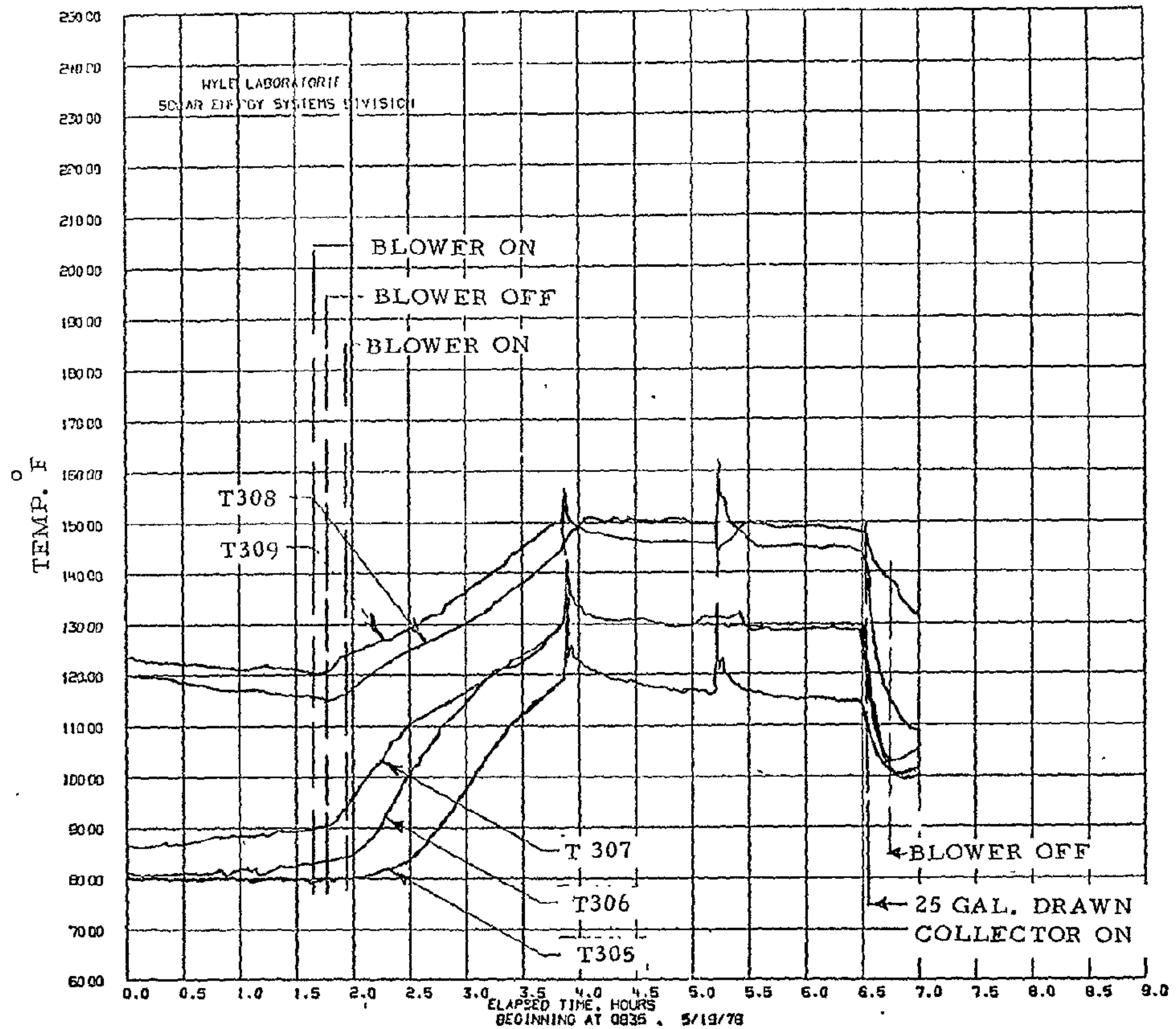

Figure 4.4-3 Stratification DHW Tank

4.5 CONTROL SUBSYSTEM

The control subsystem provides the means to control the collector blower, collector loop damper, load blower, load loop damper and auxiliary heating unit. The control system consisted of many components arranged and described as shown in Figure 4.5-1. The control system operated satisfactorily throughout the testing; however, with this system the bottom of storage is limited to 110°F, because the blower motor operation is terminated when this temperature occurs.

The collector thermo-switch measurement consistently showed cycling during days of high insolation. This cycling should be reflected by the absorber temperature; however, no absorber temperature perturbation can be detected. Also, no unusual collector blower cycling was observed by test personnel during the testing. It was therefore concluded that the switch operated properly and that the thermo-switch data was erroneous.

The initial control system was designed to initiate and terminate the collector loop blower at 123°F and 109°F respectively. Table 4.5-1 tabulates initiation and termination conditions for many of the test runs. Termination conditions were difficult to evaluate because the system was manually closed down at the end of the work day before condition for automatic termination had occurred.

The System 4 site has an anticipated high hot water load (130 gallons/day). During the summer, the system has the capacity of obtaining nearly 100% solar operation of the DHW system; however, this would be precluded by the absolute control system. During the summer, storage would quickly saturate and shut down the collector blower thereby nearly eliminating heat transfer to the preheat tank. The collector blower would then operate for only a short time each day to replenish heat loss from storage until the bottom of storage reached 110°F. This short period of operation would not be long enough to carry the DHW load. Therefore, even though the preheat tank was cold and abundant solar radiation was available, no energy would be collected. System 4 control was therefore changed to a system as shown in Figure 4.5-2.

Figure 4.5.1

SYSTEM 4 ELECTRICAL SCHEMATIC WITH ABSOLUTE TEMPERATURE CONTROL

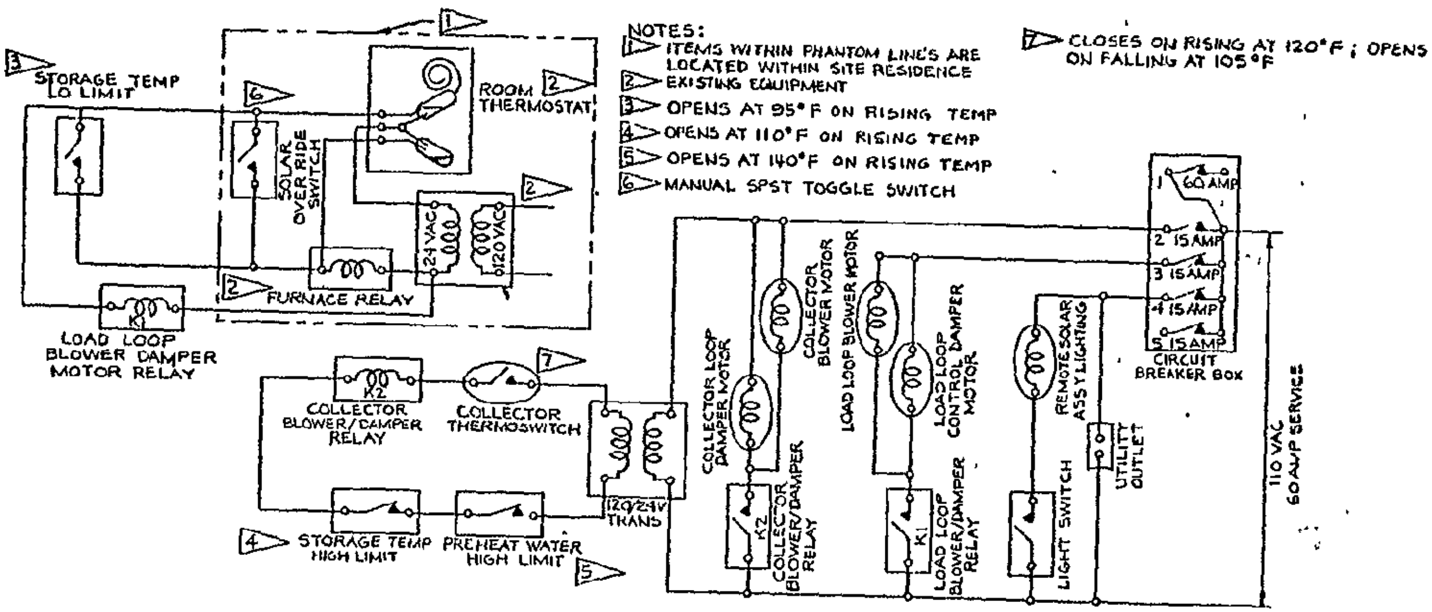

TABLE 4.5-1 INITIAL SYSTEM 4 CONTROL SYSTEM SWITCHING STATES

Date	Insolation	Absorber	T_{in}	T_{out}	ΔT	$T_{ambient}$
Initiation						
4-13-78	200 Btu/Hr Ft^2	191	65	123	58	62
4-24-78	150	184	67	123	56	70
5-2-78	155	149	65	123	58	58
5-10-78	130	129	65	123	58	65
5-11-78	130	136	66	123	57	58
Termination						
4-24-78	110	113	92	105	13	80
5-5-78	100	128	75	105	30	65
5-5-78	120	127	83	105	22	65

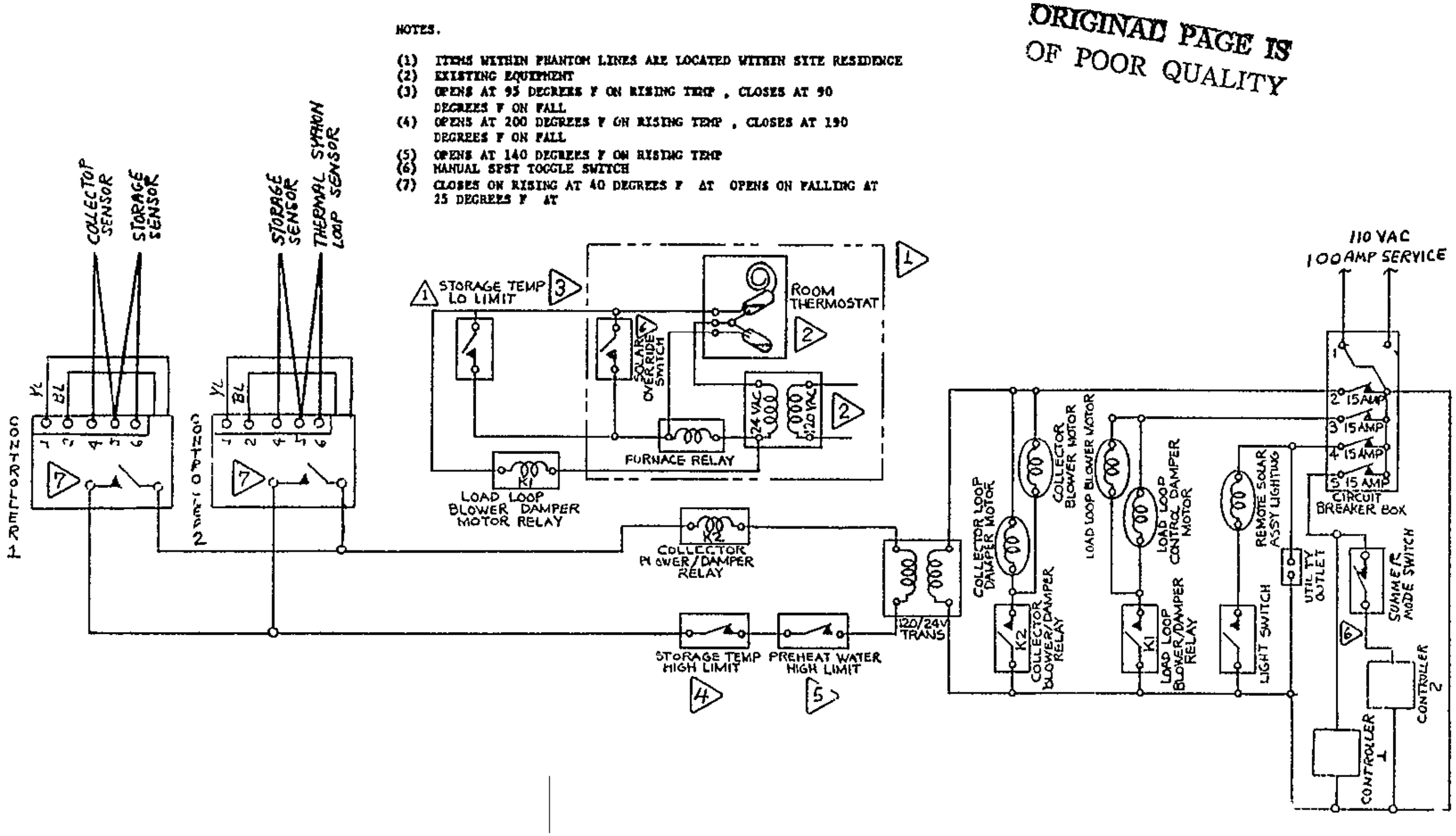

Figure 4.5-2 System 4 Electrical Schematic with Differential Temperature Control

The two differential controllers are used to control the collector loop blower. The relay in either controller can energize the collector loop blower when either the collector is 40°F greater than rock storage or rock storage is 40°F greater than the preheat tank. The temperature difference between the controller sensor pair that initiated blower turn-on must decrease to 25°F to terminate blower operation. The decision logic for system control is shown in Figures 4.5-3 through 4.5.-5.

The collector temperature sensor is located on an internal collector air duct near the outlet from the collector array. There was no temperature measurement near the collector sensor during the test. To monitor the performance of the Controller No. 1, the temperature of the collector sensor is assumed to be 40°F higher than the bottom of storage temperature. Figure 4.5-6 and 4.5-7 are plots of insolation rate, collector absorber temperature, collector outlet air temperature, bottom of storage, collector inlet air temperature and blower power vs. time. The control sensor temperatures at blower on and off condition were calculated as described above and were plotted with an χ. A dotted line was then drawn between the χs. The dynamics of the system are such that the collector sensor temperature is not always predictable; however, generally the collector sensor temperature lies somewhere between the collector absorber and collector outlet air temperatures.

The 40°F temperature differential setting of Controller No. 1 appears to be optimum. Although absorber temperatures seem unreasonably high when the collector loop blower is started, reducing the temperature differential so that collector loop air circulation could start at lower absorber temperature would result in excessive blower on-off cycling. This argument is based on the fact that there presently is a small amount of cycling which can be seen in Figure 4.5-7.

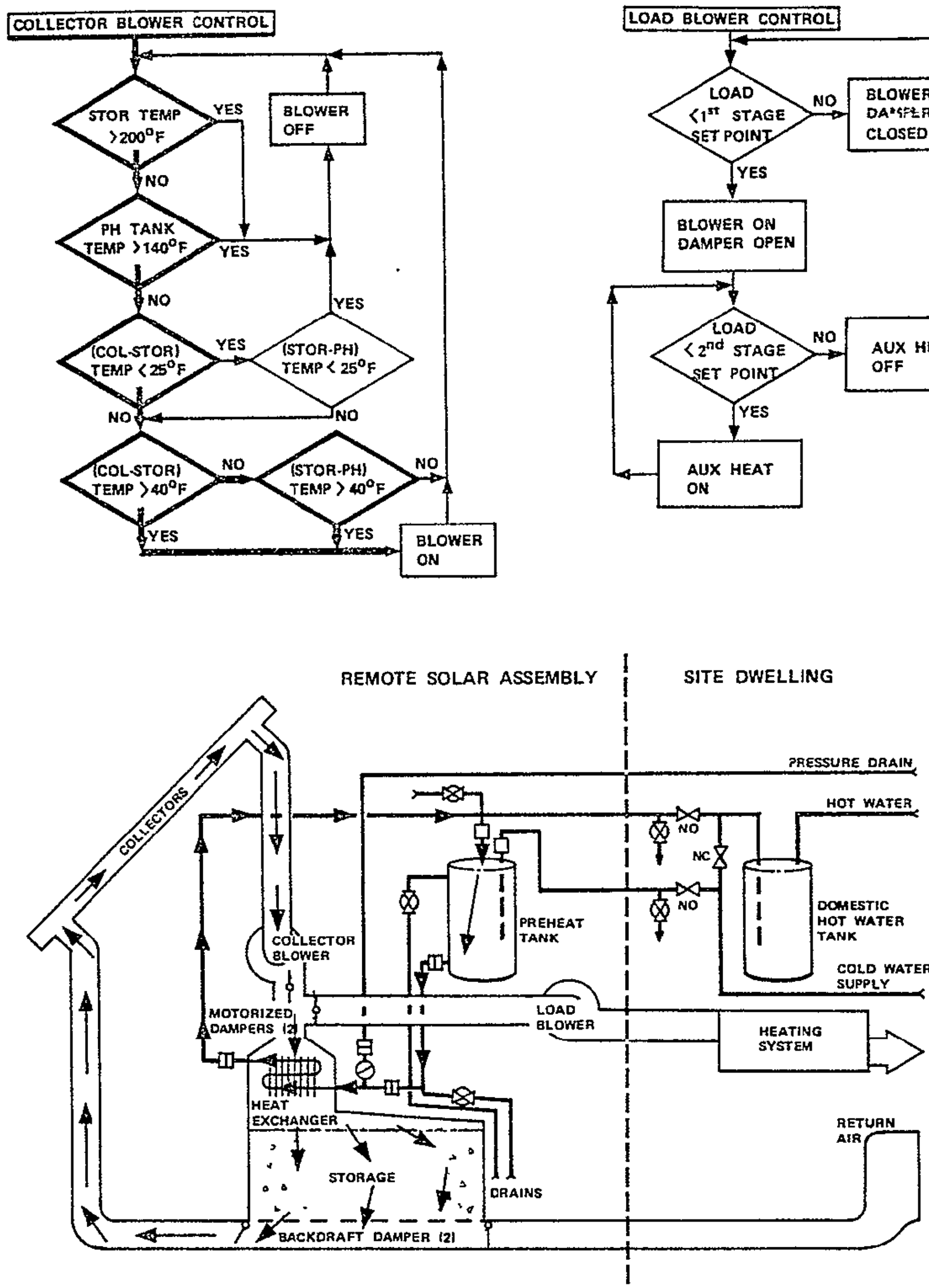

Figure 4.5-3 Collector-to-Storage Mode

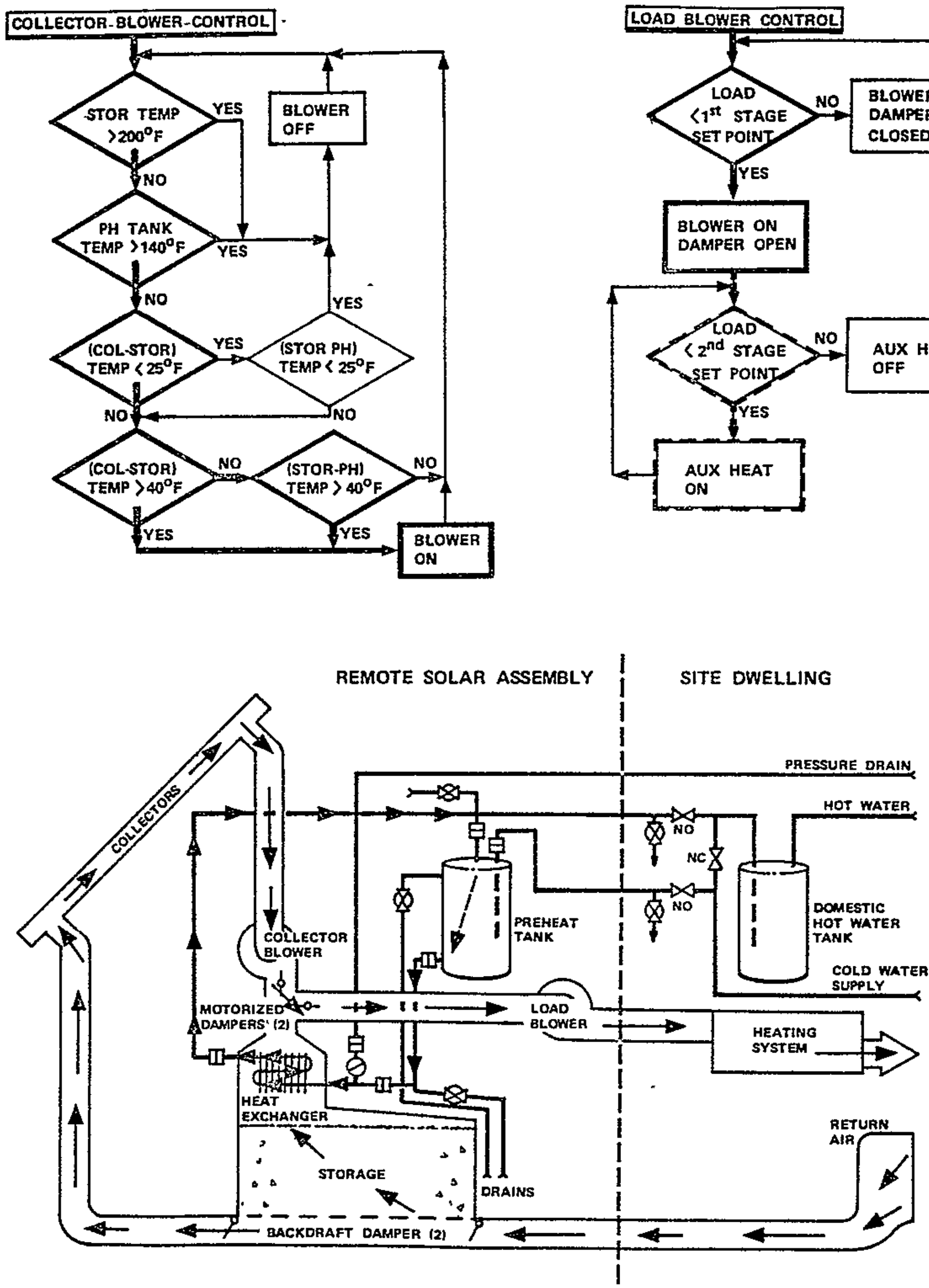

Figure 4.5-4 Collector-to-Load Mode (with or without aux. heat)

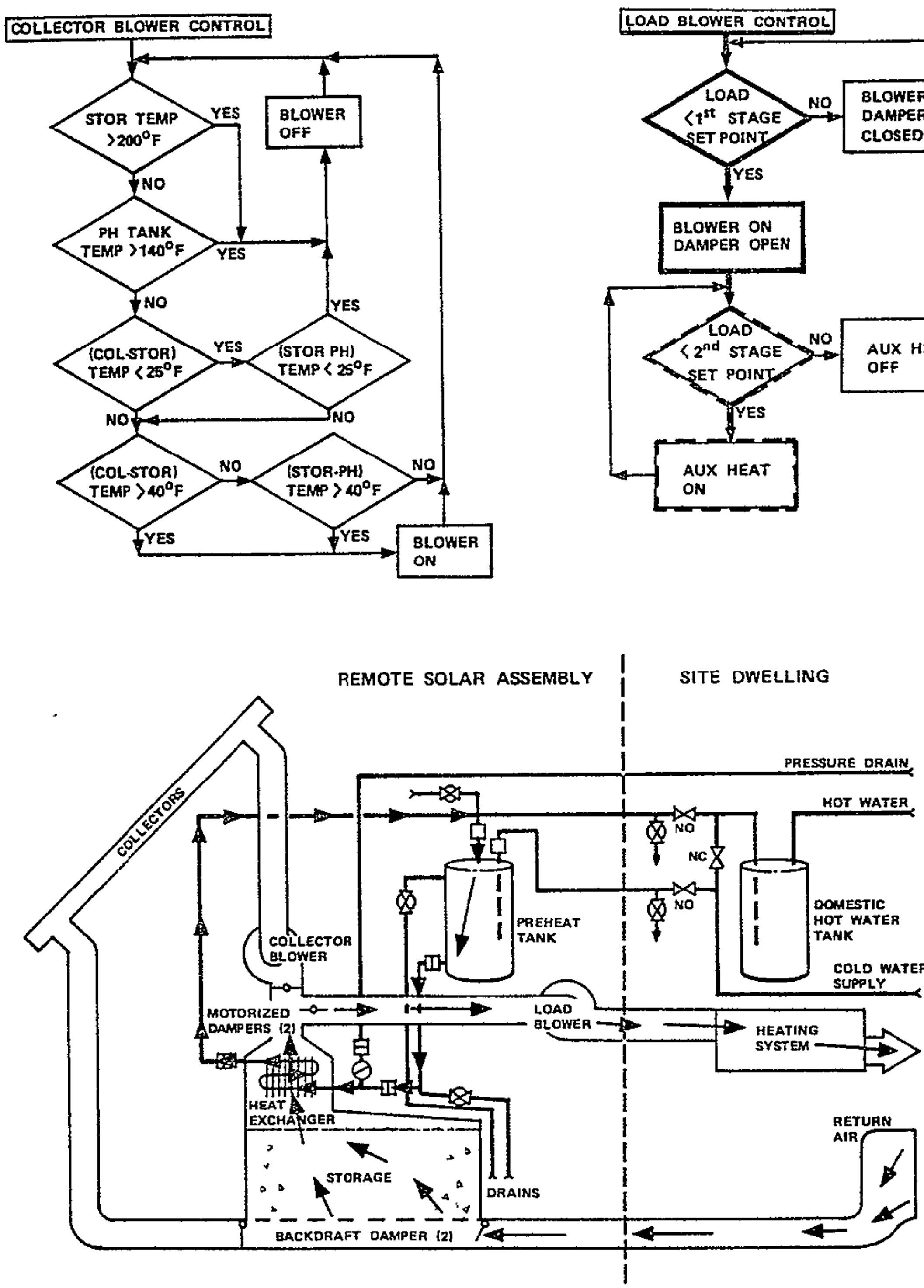

Figure 4.5-5 Storage-to-Load Mode (with or without aux. heat)

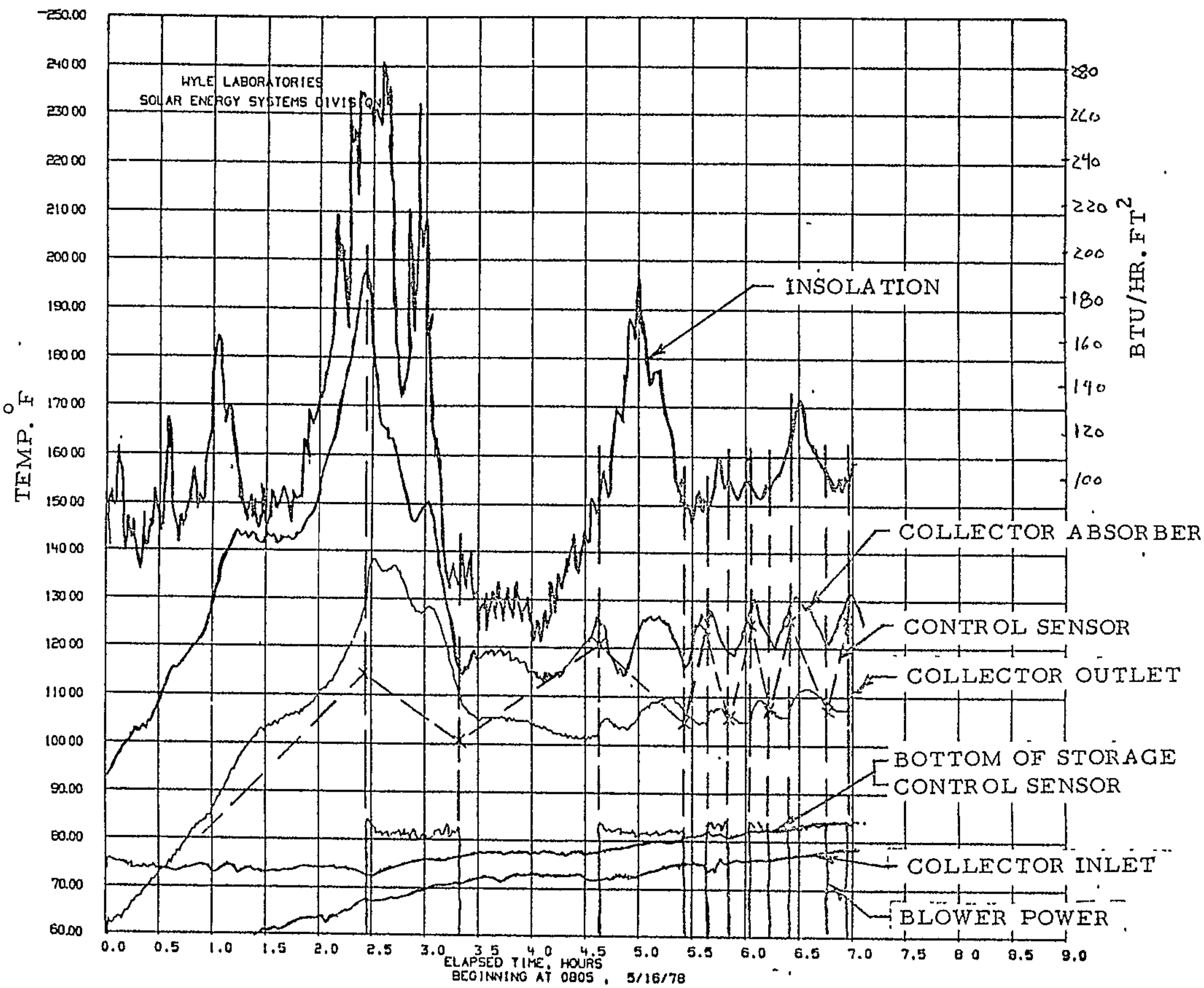

Figure 4.5-6 System 4 Controller No. 1 Evaluation (Poor Solar Day)

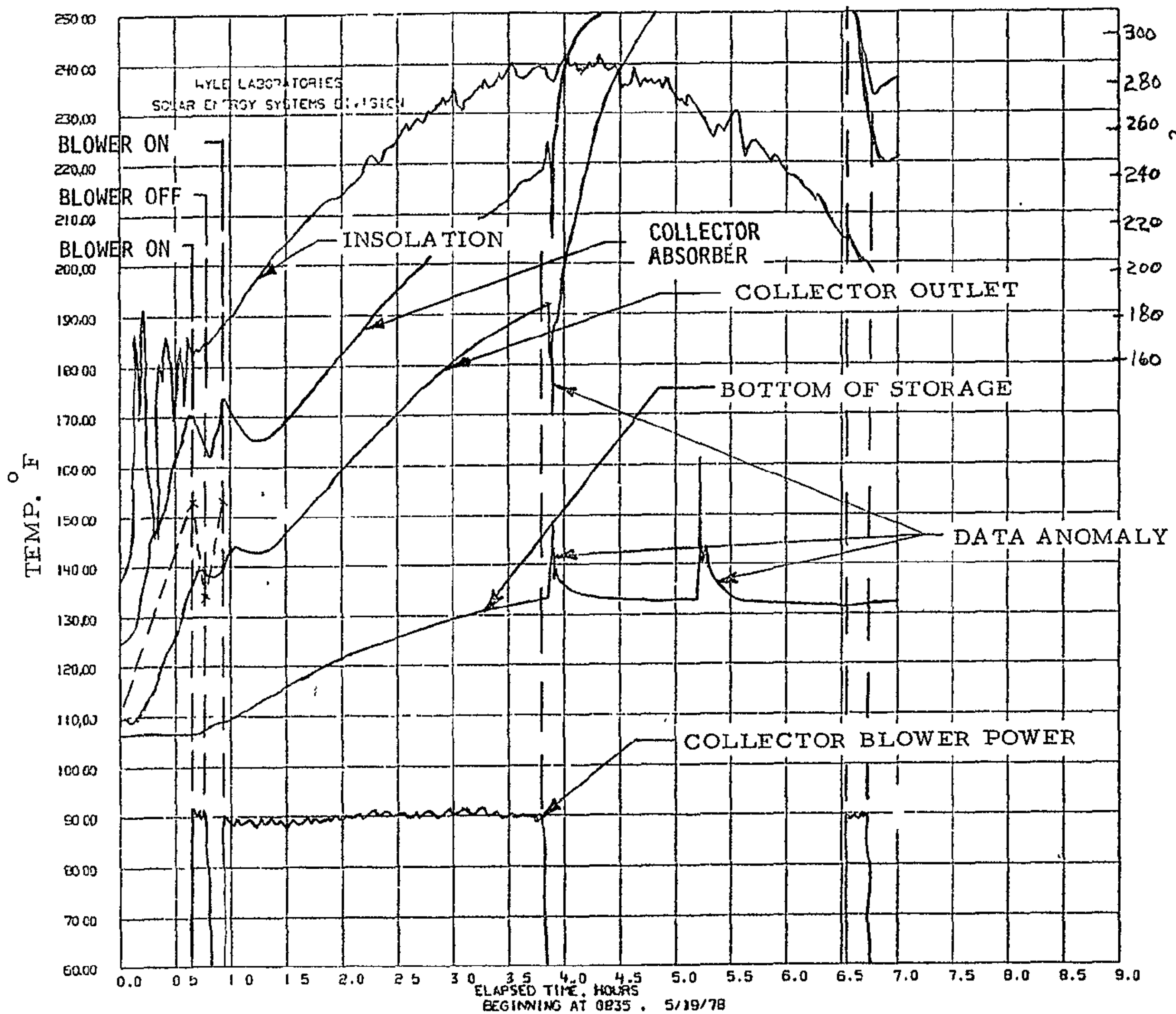

Figure 4.5-7 System 4 Controller No. 1 Evaluation (Good Solar Day)

The performance of System 4 Controller No. 2 can be evaluated in a plot of the temperatures versus time for (1) the bottom of preheat tank and (2) the bottom of rock storage as shown in Figure 4.5-8. The collector blower was turned on by Controller No. 2 at approximately 8:14 A.M. (0.4 hours after start of test). The temperature differential between the two sensors was caused by drawing water from the preheat tank which quickly lowered the temperature to 78^{o}F. At the time of collector blower turn-on, a temperature difference of only 28^{o}F is indicated in the data plot between the two measurements. The reason that the water temperature did not quickly drop to 78^{o}F is that a computer data smoothing technique does not permit the temperature measurements to respond instantly. None of the tests were run long enough to reduce the temperature differential to 25^{o}F and thereby show the performance with automatic shut-down.

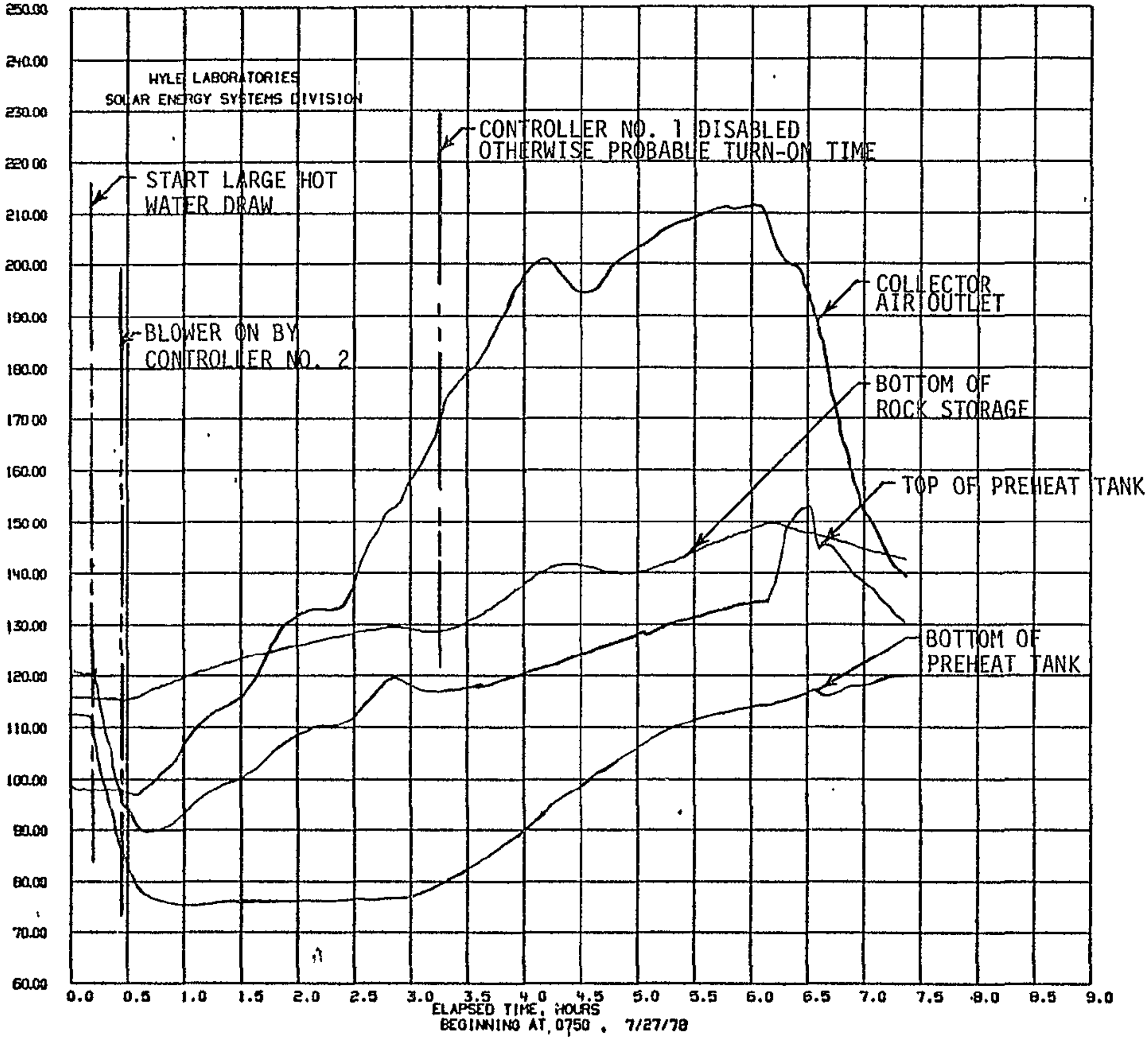

Figure 4.5-8. System 4 Controller No. 2 Evaluation

5.0 SYSTEM MEASUREMENTS

The detailed test description including test procedures and representative test data is contained in Appendix A. To help present the test data so that temperature measurements could be quickly reviewed, thermal maps were prepared.

Figures 5.0-1 through 5.0-3 are thermal maps for each of the three operating modes: (1) Collector to Load, (2) Collector to Storage and (3) Storage to Load, respectively. The date and slice time at which data was taken are noted for each map.

The Collector to Load mode test was started with a heat depleted storage bed and preheat tank. The load blower was cycled 20 minutes on and 10 minutes off, which is a high head load. As a result, no heat was stored in either pebble storage or preheat tank, which is confirmed by the low temperatures in storage and preheat tank as shown on the thermal map. No explanation can be given for the temperature distribution in the preheat tank, except there generally appears to be some reverse syphon action as collector loop temperatures begin to build up above the 70^{0} system return air temperatures.

The Collector to Storage mode was started with considerable heat in pebble storage. Temperatures throughout the collector loop are therefore quite high.

The Storage to Load mode test was conducted with the preheat tank drained of water so that all heat stored in the pebble bed would be transferred to load. Also, the pebble bed was only partially charged when the test began; therefore, storage temperatures are rather low.

4/27/78 @ 12.00
AMBIENT AIR TEMP 68°

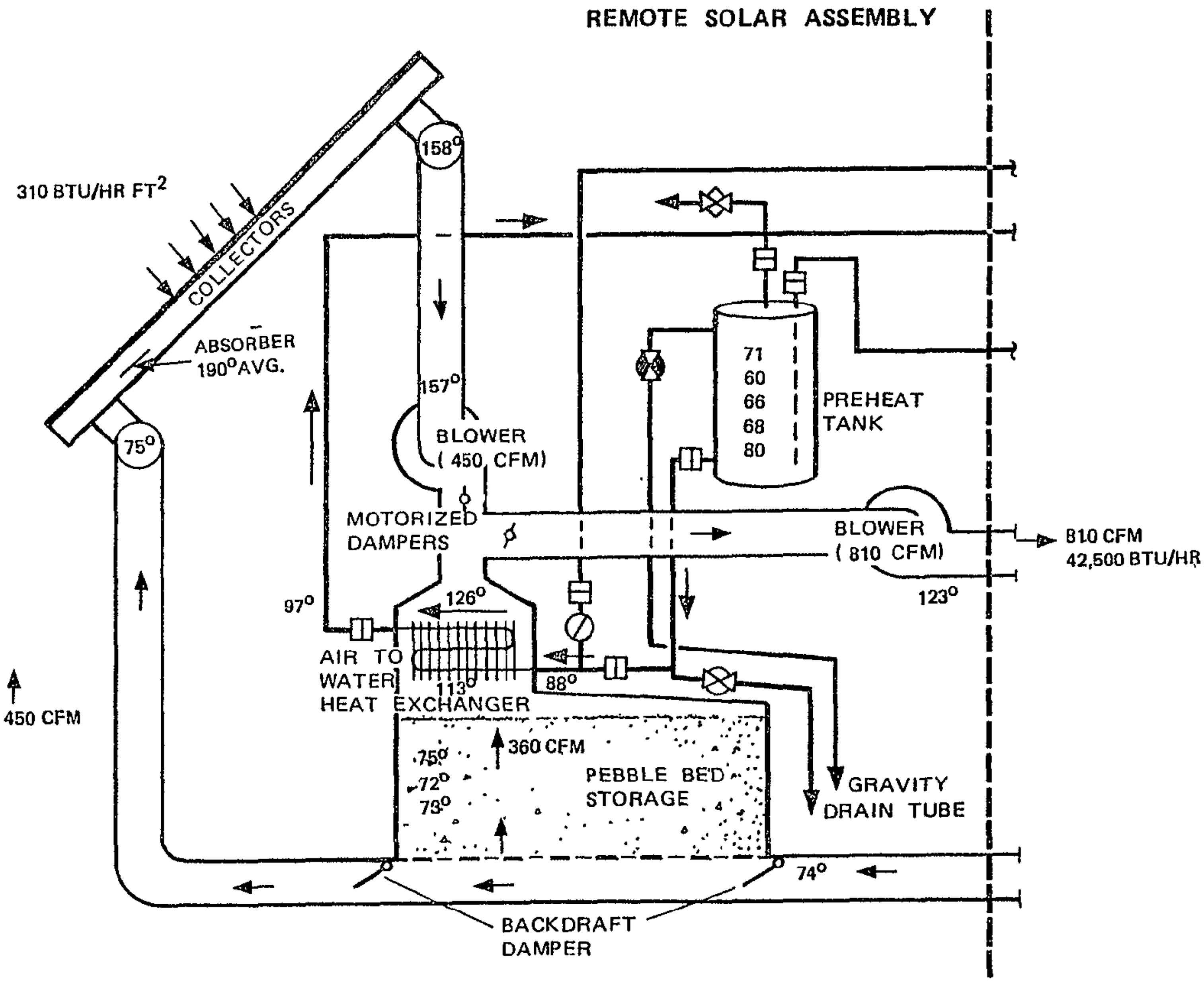

FIGURE 5.0-1 SYSTEM THERMAL OPERATING MAP (COLLECTOR TO LOAD MODE)

5/19/78 @ 12:18
AMBIENT TEMP 85°

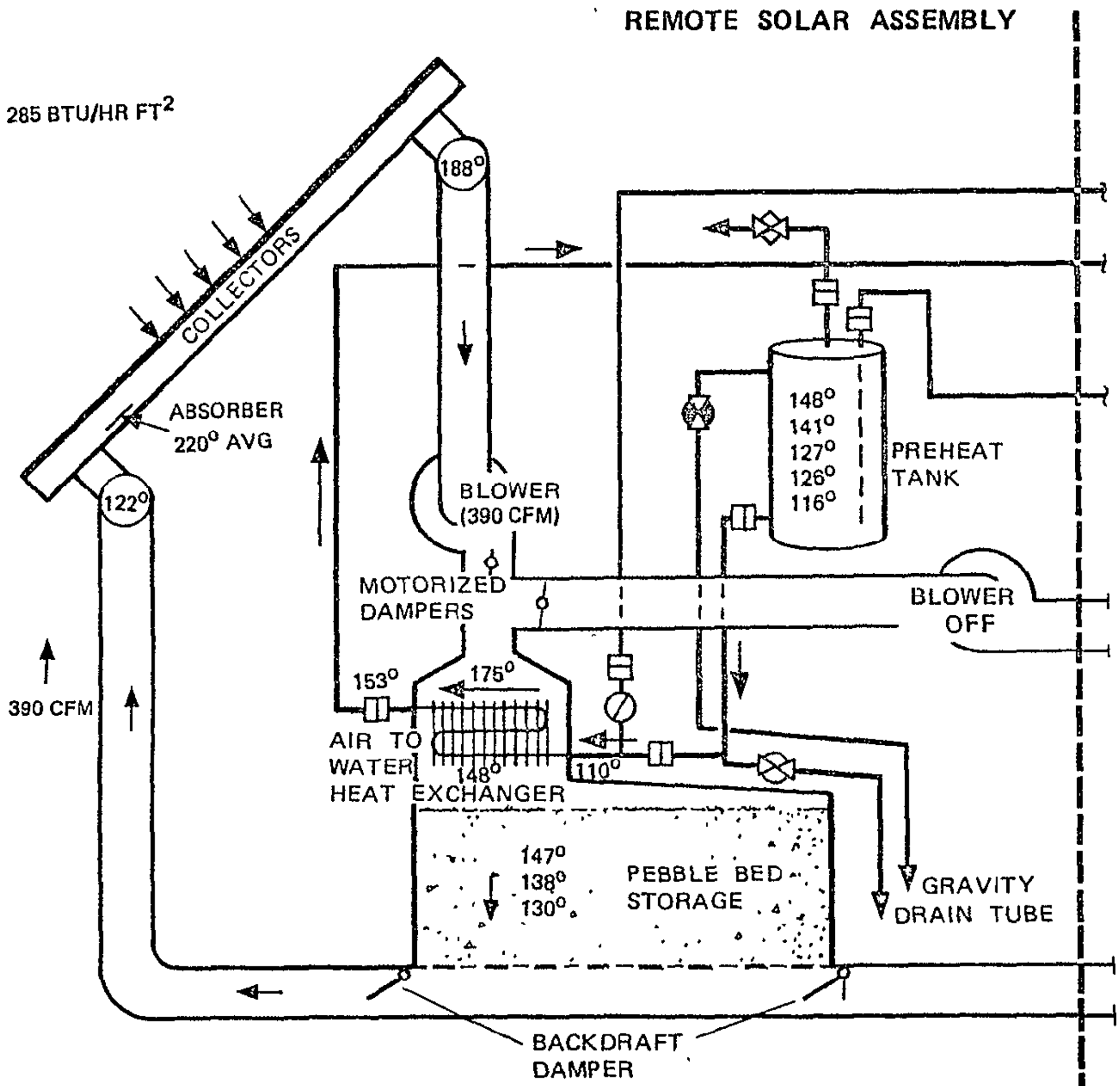

FIGURE 5 0 2 SYSTEM OPERATING MAP (COLLECTOR TO STORAGE MODE)

4/25/78 @ 9:30 AM
AMBIENT TEMP 63°

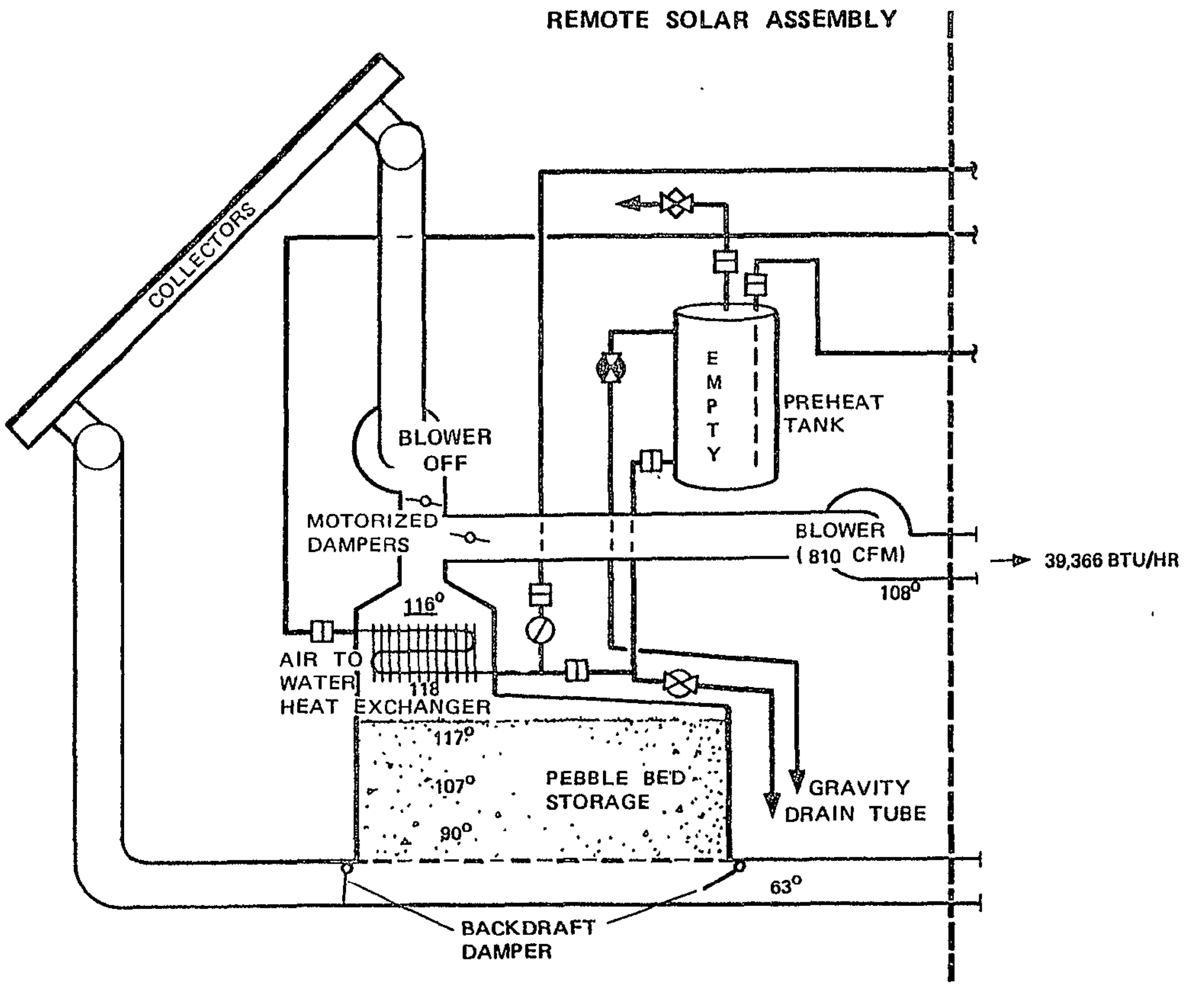

FIGURE 5 0-3 SYSTEM OPERATING MAP (STORAGE TO LOAD MODE)

6.0 SYSTEM PERFORMANCE

Summaries of daily performance of System 4 are tabulated on page A27, A28 and A29 of Appendix A. Annual performance of the system is usually required, however, in order to estimate the annual savings that can be obtained.

The total annual solar energy gathered by a solar system is based primarily on the insolation available, the ambient environment and the efficiency characteristics of the collector array. Since System 4 testing was conducted during only portions of April and May, it was necessary to extrapolate short term test data to yield yearly results.

The FCHART computer program, obtainable from the University of Wisconsin, is used for the purpose of calculating the energy that can be obtained from a solar system for a typical year. This program was used to predict System 4 performance for Huntsville using the collector vendor's efficiency curve. This prediction established the expected performance and is documented in Performance Specification 7933649. Because the System 4 collector array efficiency is uniformly overall somewhat better than the collector vendor's efficiency curve (See Figure 4.1-1), somewhat better performance or at least equal performance to that stated in the performance specification and as stated below is expected.

Performance Specification for Huntsville, Alabama

A1-0 SYSTEM IDENTIFICATION

This appendix defines the system performance prediction for SIMS Prototype Heating and Hot Water System, Model Number 4, as installed in Huntsville, Alabama at the MSFC Solar Heating and Cooling Test Facility. The design daily average horizontal insolation (typical winter mean) is 1062 BTU/Ft^2 and the typical annual heating degree day (^{o}F winter mean) is 3270. The system solar hardware configuration for this site is defined by assembly drawing 7934940-2. The system was not tested with auxiliary space heat or with a DHW tank. The simulation capability of the test facility was used to maintain return air duct temperatures at 70° while exhausting heat to the ambient environment. Hot water from the solar system preheat tank is piped to a holding tank for measuring preheat water temperature and quantity during the tests.

A1-1 SYSTEM PERFORMANCE SHEETS

Space Heating Capacity

The system will provide solar energy for 28 percent of the total space heating load during the heating season based on an average annual space heating load of 43.63 MM BTU and a peak space heating load of 36, 140 BTU/Hr.

Cooling Capacity

The system will provide solar energy for N/A percent of the average total cooling during the cooling season, based on an average total cooling load of N/A BTU/month and a peak cooling load of N/A BTU/Hr.

Auxiliary Energy

The average annual rate of auxiliary energy supplied to the heating and hot water load shall be no greater than 44.77 MM BTU. This shall be no greater than 60 percent of the total energy required for heating and hot water. The average rate of auxiliary energy used for cooling during the cooling season shall be no greater than N/A BTU/Month. This shall be no greater than N/A percent of the total energy required for cooling.

Hot Water

N/A (1) gallons of potable (or usable) hot water shall be delivered at no less than N/A (1) gal/min at temperature no less than $140^{\circ}F$. Recovery time shall be no greater than N/A (1) hours. The average hot water heating load will be 2.61 MM BTU/Month of which 45 percent is provided by auxiliary energy.

Operating Requirements

The maximum electrical energy required to drive the solar portion of the system at its rated capacity shall be no greater than 0.6 K.W. The maximum electrical energy required to drive the complete system shall be no greater than 1.5 (2) K.W. The average yearly electrical energy required to drive the system shall be no greater than 2,410 (2) K.W.H. Water requirements for cooling condensers and/or air humidification shall be no greater than N/A gal/hr.

NOTES:

(1) A domestic hot water heater is not used in the Huntsville test set up.

(2) Auxiliary strip heat and DHW Tank are not used in Huntsville test set up. No auxiliary energy is included in these values.

7.0 TEST RESULTS DISCUSSION

Long-term performance of a solar system cannot be fully evaluated from a limited number of single shift test sequences. Each single shift test is dependent on artifically establishing initial test states which approximate the operating states resulting from actual weather and system usage variations. The short-term tests were sufficient to demonstrate the suitability of the design and components for field installation. The following paragraphs amplify some of the salient test results.

7.1 COLLECTOR SUBSYSTEM

The results of the system testing showed that the collector array efficiency is somewhat better than the collector efficiency reported by the collector manufacturer. No deterioration of the collectors was evident from prolonged performance.

7.2 ENERGY STORAGE SUBSYSTEM

The Energy Storage Subsystem was found to satisfactorily store and retain heat to meet the requirements of the system.

7.3 ENERGY TRANSPORT SUBSYSTEM

The two blower Energy Transport Subsystem was found to have marginal blower motors. The increase in the blower motor sizes to eliminate this concern as described in 4.3 was a direct result of the system testing.

7.4 DOMESTIC HOT WATER SUBSYSTEM

The Domestic Hot Water Subsystem with its thermosyphon design was found to satisfactorily collect and retain hot water to meet the requirements of the system.

7.5 CONTROL SUBSYSTEM

The initially planned control system was found to perform satisfactorily except that storage was quickly saturated when the heating load was eliminated. Since the collector blower would shut down after storage saturation and thereby starve the domestic hot water system, the control system was changed to the differential temperature control system described in 4.5.

Controller No. 1 which is the primary mode of control, performed satisfactorily. Controller No. 2, which is used in conjunction with a summer mode switch, performed marginally. Performance in the summer mode requires continued performance monitoring at the field test site where performance with the actual domestic hot water load can be evaluated.

APPENDIX A

TEST PROGRAM

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TABLES

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FIGURES

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FIGURES (Continued)

PHOTOGRAPHS

1.0 SCOPE

This appendix describes the test program conducted to evaluate the SIMS Prototype Solar Energy Heating and Hot Water System 4 to the requirements specified in Reference 2.1 in accordance with Reference 2.2. Methods and Standards of References 2.3 through 2.5 were implemented as applicable in performance of testing.

2.0 REFERENCES

2.1	NBSIR 76-1137	Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program
2.2	IBM-7933648	Verification Plan/Procedure for Prototype Solar Energy Heating and Hot Water System Model No. 4
2.3	ASHRAE 93-77	Methods of Testing to Determine the Thermal Performance of Solar Collectors
2.4	ASHRAE 94-77	Methods of Testing Thermal Storage Devices Based on Thermal Performance
2.5	NBS TN 899	Proposed Standards for Testing Solar Collectors and Thermal Storage Devices
2.6	MSFC MMI 5300.4C	Metrology and Calibration
2.7	WYLE TM-531-21	NASA/MSFC Solar Heating and Cooling Test Facility - Test Systems, Test Loops, and Load Simulation Subsystem Schematics

3.0 MANUFACTURER

The equipment list below designates the major system components. A detailed materials listing of the Remote Solar Assembly is provided in IBM Parts List 7934940-2 and the IBM ASM design drawings.

Equipment	Manufacturer	Model No.
Collectors	Solaron Corporation Stapleton Field Indus- trial Part Commerce City, Colorado	2001
Single Inlet 4-Way Discharge Blower with 1/4 HP Drive Motor	Graingers Birmingham, Alabama	7C808
Single Inlet 4-Way Discharge Blower with 1/2 HP Drive Motor	Graingers Birmingham, Alabama	7C812
Fabric Blade Back Pressure Damper	American Warming Jared & Associates Birmingham, Alabama	Dwg. No. SHB-D-1217
Control Damper	Ruskin Mfg. Co. Birmingham, Alabama	Type CD454PM w/MP1161 motor
Heat Exchanger	Halstead & Mitchell	SW-18-18-8
Hot Water Heater	Jackson Mfg. Co.	UC05225
Balancing Dampers	American Warming	DAA-P-8150
Thermostat Switch	Elmwood Cranston, R.I.	3100
Thermal Limit Switch	MG Electronics Birmingham, Alabama	ASCO SD10A Enclosure 1 QF10A4 probe
Thermal Limit Switch	MG Electronics Birmingham, Alabama	ASCO SD10A Enclosure 1 QF 11A4 probe

4.0 TEST CONFIGURATION

Presented in Figure 1 is a schematic of the Solar Energy Heating and Hot Water System No. 4. The completed assembly was tested at the Marshall Space Flight Center Solar Heating and Cooling Facility. The system was located adjacent to the Facility Test Article Building, S4641, with the collector array facing south (Reference 2.7). An array of 12 Solaron collectors with an accumulative aperture area of 203 ft^2 provides the primary heating source for the system. The heat transfer medium for the collector loop is air. An air-to-water heat exchanger is used to interchange energy to the hot water subsystem where the water is circulated through the heat exchanger and the hot water preheat tank by natural means. The collector and the space heating loops contain separate blowers which are actuated by associated controllers. Electrical schematics of the controller circuits are presented in Figure 2. For purposes of these tests, the space heating controller utilizes a toggle switch to replace the function of the room thermostat. The switch was used to manually actuate the space heating loop blower during test activities under simulated load conditions. Space heating loads were simulated, independent of climatic conditions, by use of cooling/heating equipment as located in the Facility Test Article Building S4641.

Photographs 1 through 3 show views of the exterior and interior of the system which was assembled by Wyle Laboratories at the test site.

5.0 TEST CONDITIONS

The collector arrays were operated under the existing natural environment. The thermal storage unit, hot water subsystem, ducting, fans and controls are located within the remote solar assembly shelter.

5.1 Instrumentation and Equipment

All transducers with the exception of the Eppley PSP pyranometer used in recording test data are calibrated by either NASA or AMC calibration laboratories as required by MSFC MMI 5300.4C. The PSP pyranometer is calibrated by Eppley.

The end-to-end accuracy of data derived from system testing is subject to an error analysis which accounts for all inaccuracies in the transducer, signal conditioning, signal transmission and computer processing methods. Since a formal systems error analysis will not be done, confidence in printout accuracies will be established by installing calibrated "parallel" transducers and direct readouts at key points in the system and performing comparison checks from time to time before, during, and after tests. The results of such checks together with a review of the data for anomalies will indicate that the data presented is suitable for the purpose intended.

A listing of the equipment to be used in the system test is provided below:

Apparatus	Manufacturer/Model	Range/Accuracy
Digital Thermometer	Fluke/2175A	-99 to 999°F ± 1%
Volt Ammeter/Ohmeter	Amprobe/RS3A	0-300A, 0-300V/ ± 5%
Digital Multimeter	Hewlett-Packard/ 3465A	4-1/2 digits/ 0.05% ± 1 count
Pyranometer	Eppley/PSP	0-400 BTU/Hr·Ft^2 ± 3%
Relative Humidity Sensor	Thunder Scientific/ SC-4021L	0-100%/± 1%
Wind Velocity Sensor	Teledyne Geotech/ M1567	0.75 - 60 mph ± 1/2%
Wind Direction Sensor	Teledyne Geotech/ M1567	0-360/± 1%

5.0 TEST CONDITIONS (Continued)

5.1 Instrumentation and Equipment (Continued)

Apparatus	Manufacturer/Model	Range/Accuracy
Air Velocity Meter	Sierra/440	0-2000 FPM ± 3%FS
Two-Terminal IC Temperature Sensor	Analog Devices/ 5AD590-L	0-250°F ± .25°F
Platinum Resistance Temperature Sensors	Hy-Cal/4135 Hy-Cal/4175 Minco Products	60-250°F ± 0.5°F 60-250°F ± 0.5°F 60-250°F ± 0.5°F
Air Velocity Sensors	Sierra/441 Kurz Instruments/ 430-3	0-2000 FPM ± 3%FS 0-2500FPM/± 0.25% of reading + 2 FPM
Liquid Flowmeter	Potter/1/2-5440	0 - 10 GPM ± .1 GPM
Watt Transducers	Ohio Semitronics/ PC5-10F	0-1200W ± 0.5% FS
Inclined Manometer	Dwyer/102AV	.2 - 2 in. H_2O

5.1.1 Instrumentation Designation

Instrumentation designations and locations are shown in the System 4 schematic in Figure 1. Part of the system instrumentation to be used in the site demonstration are specified in the schematic by the Suffix "A". Switch position indicator measurements which were recorded during these tests are shown in Figure 2. Location of temperature sensors in the thermal storage unit is depicted in Figure 3. Temperature sensor locations on the collector array are indicated in Figure 4.

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 System Operational Functional Test

Tested By: B Henderson P.E.
Started: 3/27/78
Completed: 4/12/78

6.1.1 Performance Criteria Requirements

A system operational functional test was conducted on prototype System 4. The test was conducted to ensure that the major components of the system are operating properly after installation. The operational functional test consists of the following individual tests:

Test 1. Perform a component test of the freeze protection bleeder valve to determine that the valve functions to open at approximately 34°F.

Test 2. Limit switches shall be adjusted according to System 4 Design Description Drawing, 7934983.

Test 3. Checkout of system controllers and wiring circuits.

Test 4. Blower speed and damper adjustments shall be made in accordance with System 4 Design Description Drawing, 7934983.

Test 5. Perform evaluation of the collector thermoswitch operation relative to the collector absorber and air outlet temperatures.

Test 6. Perform an evaluation of the storage temperature high limit switch to define the temperature levels at which the switch actuates.

In tests 4 through 6 above, the test data was recorded on magnetic tape through the data acquisition system. Operators of the data acquisition system were notified at initiation and completion of these tests.

6.1.2 Test Procedure

Test activities required to accomplish the tests described in the above paragraph are delineated below:

Test 1. Install the freeze protection bleeder valve inlet port to a city water supply. Attach a temperature sensor to the valve body and immerse the valve in a container of ice water. Monitor and record the temperature at which the valve actuates to open and close.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 System Operational Functional Test (Continued)

6.1.2 Test Procedure (Continued)

Test 2. Using the oil bath calibration source, adjust the following limit switches to their specified values.

Limit Switch	Actuation Temperature, °F	
	Open	Closed
Storage High Temperature	150 110*	140 105*
Storage Low Temperature	95	90
Preheat Tank High Temperature	150	140

* Limit switch reset to these values at completion of Functional Tests.

Test 3. Checkout of system control and wiring circuits were performed by shunting the appropriate switches in load loop and the collector loop control circuits and monitoring the function of the system blowers and dampers. To accomplish this, the following tests were performed:

A. Load Loop Control Circuit Checkout Procedure

1. Apply 120 VAC power to load loop control transformer primary coil.

2. Operate room thermostat switch to closed position.

3. The motorized damper in the space heating loop should actuate to the open position.

4. Operate the room thermostat switch to the open position.

5. The motorized damper in the space heating loop should actuate to the closed position.

6. Remove power from load loop control transformer.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 System Operational Functional Test (Continued)

6.1.2 Test Procedure (Continued)

B. Collector Loop Control Circuit Checkout Procedure

1. Apply 120 VAC power to collector loop control transformer primary coil.

2. Perform independent tests of the collector thermoswitch, storage temperature high limit switch and preheat water high limit switch by replacing each by a manual switch. By operating the manual switches, ascertain that the collector blower activates and collector loop damper opens when all three switches are closed. Deactivate the blower and collector loop damper in separate tests by sequentially opening a single switch in the circuit.

3. Remove power from load loop control transformer and remove manual switches. Connect wiring to respective control circuit switches.

Test 4. Blower speed and damper adjustments were made to obtain flowrates of 406 cfm in the collector loop and 800 cfm in the space heating loop. To accomplish these adjustments, perform the following procedure.

1. Turn on the collector loop blower and open the motorized damper by shunting the collector thermoswitch. Utilizing the velocity probe sensors (V101E, V101W, V102), determine the uniformity of the air velocity and the probe position which corresponds to the average velocity which exists within the flow passage.

2. Position the velocity sensors within the flow passage at the average velocity position. Adjust the pulley diameter ratio on the motor/blower as necessary to achieve the required flowrate.

3. Adjust the balancing dampers as necessary to obtain equal flowrates through the two collector manifolds.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 System Operational Functional Test (Continued)

6.1.2 Test Procedure (Continued)

4. Verify that the total flowrate remains at the specified condition after the above adjustments are made. If necessary, repeat the procedures of Steps 2 and 3 to achieve the required balanced flowrates.

5. Measure the power input to the blower motor to ensure that the full load rating is not exceeded (5.2 amps @ 115 volts). Deactivate blower/damper controller.

6. Operate the space heating loop blower by the room thermostat switch.

7. Measure velocity at velocity sensor V400 to determine the flowrate.

8. Adjust the pulley diameter ratio between the blower/motor to achieve the required flowrate. Monitor the power input to the motor to ensure that the full load rating of the motor is not exceeded (7.4 amps @ 115 volts).

9. If necessary, operate the test article fan and damper (Building S4641 equipment) to increase the flow as necessary to compensate for pressure losses in the load simulation equipment.

10. Activate the collector loop controller by shunting the collector thermoswitch.

11. Measure and record the flowrates through the collector and space heating flow circuits.

Test 5. The following test procedure was performed to evaluate the performance of the collector thermoswitch operation relative to the collector absorber plate temperature and the collector outlet air temperature.

1. When weather conditions exist with high solar insolation rates, activate collector loop controller and operate system for a period of approximately 8 hours. Monitor and record the collector absorber plate temperature (T104A), outlet air temperature (T107E and T107W), and the collector thermoswitch position.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 System Operational Functional Test (Continued)

6.1.2 Test Procedure (Continued)

Test 6. In this test, the load simulator equipment in Building S4641 was utilized to charge the thermal storage unit to 110°F. Operation of the following temperatures shall be monitored and recorded.

T403 - Storage inlet temperature

T200A through T202A - Thermal storage temperatures

T231 - Storage temperature high limit switch temperature.

6.1.3 Functional Test Results

Results of functional tests as performed under paragraph 6.1 of the System 4 test procedure are summarized by individual test as follows:

Test 1:

The freeze protection bleeder valve opened at 34°F and fully closed at 38°F.

Test 2:

Limit switches operated at the following range.

Limit Switch	Actuation Temperature, °F	
	Open	Closed
Storage High Temperature	110 ± 3	105 ± 3
Storage Low Temperature	95 ± 1	90 ± 1
Preheat Tank High Temperature	150 ± 5	140 ± 5

Preheat tank high temperature switch cannot be set to a high degree of accuracy.

6.1.3 Functional Test Results (Continued)

Test 3:

A. Room thermostat switch and the damper in the space heating loop functioned properly.

B. Collector loop control circuit operated properly.

Test 4:

When only collector blower is on, the collector loop is set at 390 cfm; but when the load blower is on simultaneously, the collector loop flowrate increases to 450 cfm. The collector blower motor and damper motor combined power measurements were 5.4 amps, 122 volts, and 315 watts. The space heating blower motor power measurements were 7.1 amps, 122 volts, and 580 watts.

The flowrate at collector and space heating flow circuits obtain 800 cfm without adding in article fan.

Test 5:

The following temperatures are representative of the collector loop for days of high solar insolation.

Collector absorber plate T104 = 200°F

Outlet air T107 = 158°F

Thermoswitch in automatic mode is on.

Test 6:

Storage temperature high limit switch operates at following conditions:

T403 = 129.5°F	T201A = 90.0°F
T200A = 84.7°F	T202A = 120.7°F (high limit switch sensor)

In the functional test, the rock bed was heated from the bottom, opposite to normal operation.

6.0 TEST REQUIREMENTS AND PROCEDURES (continued)

6.2 Operational System Test

Tested by William E. Sholey
Started 4-12-78
Completed 5-11-78

6.2.1 Performance Criteria Requirements

System 4 operational tests were performed when weather conditions with high solar insolation were available during the test period. Results of the tests will be used to determine the system's operational capacity for control, storage and distribution to the load. Separate tests were conducted as specified in the following paragraphs.

Domestic Hot Water (DHW) heating system tests were performed under two initial thermal conditions of the thermal storage unit. The first test was initiated with the thermal storage unit preconditioned such that the storage is approximately uniform at 70°F. The second DHW system test was initiated with the storage unit preconditioned to 110°F at the location of the high temperature limit switch. In this test, the low temperature limit switch was bypassed in the control circuit. Preheat tank hot water loads correspond to the following daily schedules.

Schedule 1 - 52 gallons prior to activation of collector loop blower followed by 12 gallons at 10 AM, 12 Noon, 2 PM and 3 PM.

Schedule 2 - 52 gallons prior to activation of collector loop blower followed by 10 gallons at 10 AM and 12 Noon, 20 gallons at 2 PM and 3:30 PM.

Supply water to the preheat tank was maintained as uniform as possible during the DHW system loads.

Systems tests were conducted to accomplish the following test requirements:

1. Precondition storage unit to 70°F and initiate collector loop operation to charge the storage unit to 110°F at the high temperature limit switch. The DHW system was inactive in this test.

2. After charging the storage unit to conditions stated above, the collector loop was deactivated and a continuous space heating load used to discharge storage to approximately 70°F. Return air from the load

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Operational System Test (Continued)

6.2.1 Performance Criteria Requirements (Continued)

simulator was introduced to the storage unit at approximately 70°F during this test. The DHW system was inactive in this test.

3. Intermittent space heating loads were applied by manual control of the space heating loop blower with air being supplied on demand to the storage unit at 70°F. This test was conducted as high solar insolation days were available, and the collector control circuit was activated. The schedule for application of space heating loads corresponds to a 30 minute cyclic period with the space heating blower operational for 20 minutes and deactivated for 10 minutes. At least 2 days system operation was accomplished under the above conditions without operation of the DHW system and 2 days system operation with the DHW system active with DHW loads corresponding to Schedule 1.

During the system test, weather records were kept. These will include total solar radiation, ambient temperatures, wind speed and direction, relative humidity, barometric pressure and cloud cover.

In addition, System 4 was monitored to provide the following calculated parameters on a daily basis.

- Total available solar flux.
- Total solar energy collected.
- Total energy supplied/rejected to the storage unit.
- Temperature stratification profiles in the DHW tank and the storage unit.
- Total space heating load.
- Total DHW subsystem load.
- Total energy transported to DHW subsystem.
- Overall thermal coefficient of the DHW tank and the storage tank.
- Bulk average temperature of the DHW tank and the storage unit as a function of time.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Operational System Test (Continued)

6.2.1 Performance Criteria Requirements (Continued)

- Ambient average temperature of the storage unit and the collectors.
- Total electrical power of the
  - Collector blower
  - Space heating blower
- Switch positions on the collector loop and the space heating loop control circuit.

6.2.2 Test Procedure

6.2.2.1 Domestic Hot Water System Tests

1. Operate load simulator loop in Test Article Building to establish control at 70°F as measured at T403.
2. Activate System 4 space heating blower and circulate air to precondition the storage unit to approximately uniform temperature of 70°F. The low temperature limit switch was jumpered for these tests.
3. Deactivate space heating blower controller.
4. When high solar insolation is available, initiate DHW load schedule 1.
5. Activate collector loop control circuit.
6. Deactivate controllers at completion of the day's test.
7. Repeat steps 1 through 6 using 110°F as the temperature in steps 1 and 2.
8. Repeat steps 1 through 7 for DHW load schedule 2.

6.2.2.2 Storage Unit Charge and Discharge Tests

1. Operate load simulator loop in Test Article Building to establish control at 70°F. Drain DHW system.
2. Actuate System 4 space heating blower and circulate air to precondition the storage unit to an approximately uniform temperature of 70°F.

6.2.2.2 Storage Unit Charge and Discharge Tests (Continued)

3. Deactivate space heating loop controller.

4. When high solar insolation is available, initiate charging of the storage unit by activating the collector loop control circuit.

5. Continue the test until the temperature sensor at the storage unit high temperature limit switch reaches 110°F. Deactivate collector loop control circuit when this condition has been achieved.

6. Activate space heating loop control circuit and circulate air through storage to the simulated load. Return air from the simulated load is controlled to 70°F.

7. Continue to discharge the storage unit until the storage unit is approximately uniform at 70°F.

8. Deactivate system and test facility controllers after completion of step 7.

6.2.2.3 System Operation with Intermittent Loads Test

1. Precondition the storage unit to a uniform temperature of approximately 70°F by operation of the space heating blower and the test facility load simulation equipment. The inlet temperature to the storage unit is to be controlled to 70°F.

2. Deactivate space heating control circuit and drain DHW system.

3. Initiate tests when high solar insolation rates are available by activation of the collector control circuit.

4. Apply intermittent space heating loads by periodically activating the space heating control circuit. The schedule for application of space heating loads is as follows:

   blower circuit activated - 20 minutes
   blower circuit deactivated - 10 minutes

   Total Cyclic Period - 30 minutes

5. Repeat intermittent space heating loads through normal working period from 8:00 A.M. till 4:00 P.M.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Operational System Test (Continued)

6.2.2.3 System Operation with Intermittent Loads Test (Continued)

6. At the end of each normal working period, deactivate all system and facility controllers.

7. Repeat steps 3 through 6 until an accumulative testing interval of 16 hours has been accomplished.

8. Repeat steps 1 through 7 with the exception that the DHW system shall be refilled and operational. Space heating and DHW loads will be applied in this test. The space heating loads are as specified in Step 4 and the DHW loads correspond to schedule 1 of paragraph 6.2.1

6.2.3 Operational Test Results

All test data was collected on magnetic tape with the data system located in Building 4646. Parameters which were measured and recorded during this evaluation are shown in Table I. Computer plots and integrated test parameters were prepared from data contained on the magnetic tapes by post-test processing on the UNIVAC 1108 computer. The data was compiled in graphical form and is shown in Appendix II. The integration data that was available is also shown in tabular and graphical form in compliance with the performance criteria requirements in Tables II through IV. Computer plots as deemed representative by the test conductor were included in this main body of the report and the remainder of the plots were included in the data comprising Appendix II.

Separate test data summaries are provided for operational tests in the following paragraphs.

6.2.3.1 Domestic Hot Water Subsystem Tests

Presented in Table II are the measured/computed daily performance parameters which were derived for the incicated test dates. Test conditions and controller switch positions for these tests are also specified in Table II.

Computer plots of measurements and calculated values of System 4 which are relevant to the DHW subsystem tests are provided in Figures 5 through 21. The time dependent parameters are presented graphically for the identified test dates:

- Total solar flux.
- Temperature profiles in the DHW preheat tank and thermal storage unit.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Operational System Test (Continued)

6.2.3.1 Domestic Hot Water Subsystem Tests (Continued)

- Bulk average DHW preheat tank and thermal storage unit temperature.
- Ambient temperature to the storage unit and the collectors.
- Total electrical power of
  - Collector blower.
  - Space heating blower.
- Switch positions of
  - Collector thermoswitch.
  - Storage high temperature limit switch.
  - Storage low temperature limit switch.

Complete computer plots of all measured test data are contained in a separate appendix to this report.

The overall heat transfer loss coefficient of the DHW preheat tank was evaluated and determined to be 5.3 BTU/Hr·°F.

6.2.3.2 Storage Unit Charge and Discharge Tests

Results of thermal storage unit charge and discharge tests are summarized in Table III. Initial test conditions, calculated performance parameters, and the operational system mode are included in the summary table. Representative transient data which was relevant to these tests are presented in Figures 22 - 31 for the stated test date. These computer plots graphically represent the following parameters as functions of time.

- Available solar flux
- Space Heating load (discharge test)
- Total solar energy collected (charge test)
- Bulk average temperature of the storage unit

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Operational System Test (Continued)

6.2.3.2 Storage Unit Charge and Discharge Tests (Continued)

- Temperature profiles in the storage unit.
- Ambient temperature of the storage unit and the collectors.
- Electrical power of the
  - collector blower
  - space heating blower

Complete computer plots of all measured test data are contained in a separate appendix to this report.

The overall heat transfer loss coefficient of the thermal storage unit was evaluated and found to be 18.2 BTU/Hr·°F.

6.2.3.3 System Operation with Intermittent Load Tests

A summary of computed/measured performance parameters for the Intermittent Load Tests is presented in Table IV. This table includes results of tests for intermittent space heating loads with and without DHW Subsystem loads. Conditions of the thermal storage unit and DHW preheat tank at initiation of testing are specified for each test. The collector loop controller was maintained in the automatic mode and the space heating control was activated manually through each day's test. Computer plots of data as relevant to these tests are presented in Figures 32 through 44. The following measured/computed parameters are included in the plots as a function of time:

- Available solar flux
- Energy collected
- Thermal storage unit average temperature
- Temperature profiles in thermal storage unit
- Space heating load
- DHW subsystem preheat tank average temperature
- Electrical power
  - collector blower
  - Space heating blower

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Operational System Test (Continued)

6.2.3.3 System Operation with Intermittent Load Tests (Continued)

- Switch positions of
  - collector thermoswitch
  - storage high temperature limit switch
  - storage low temperature limit switch

Computer plots of all data recorded during System 4 testing are provided in a separate appendix to this report.

7.0 DATA PROCESSING

Post test data processing was performed to determine the energy consumption and the amount of energy transferred to various subsystems. Methods and equations used to evaluate the system/subsystem thermal performance are described in the following paragraphs.

7.1 Total Daily Available Solar Flux

The total available solar flux was determined over the operational period for each days test as follows:

$$Qs = Ac \int_{t_1}^{t_2} I001 \; dt \qquad (1)$$

where,

QS = Total available solar flux over time interval

Ac = Total aperture area of collector arrays

I001 = Measured total solar insolation

t = Time

7.2 Total Daily Solar Energy Collected

Evaluation of the total daily solar energy collected was made using the equation,

$$Qc = \int_{t_1}^{t_2} \rho \; A_D (V102) C_p (To,f - Ti,f) \; dt \qquad (2)$$

where,

Qc = Total energy collected over time interval

ρ = Density of air at standard pressure and temperature equal to To,f

A_D = Sectional flow area of duct

V102 = Measured velocity

C_p = Specific heat of air

Ti,f = Temperature of fluid at the inlet to collector array (T106E, T106W)

To,f = Temperature of fluid at the outlet to collector array (T107E, T107W).

t = Time

7.2 Total Daily Solar Energy Collected (Continued)

In the preceding evaluation, the velocity and temperature measurements data were erratic. Air temperature at the collector inlet and outlet were selected from measured data which appeared to be consistent through the test program. Four velocity measurements in the collector loop were provided; however, the sensor as located at the blower inlet (V102) was selected for these evaluations. To yield the best results, 1242 ft/min was used for the collector only, and 1433 ft/min was used when both the collector and the space heating blowers were on, for the tabulated data.

7.3 Total Supplied/Rejected Energy to Storage Unit

Bulk average temperatures of the storage unit were used in computation of the storage energy balance. Bulk average temperature of the storage was determined by,

$$\overline{T}s = (T201+T202+\cdot\cdot+T208+T211+T212+\cdot\cdot+T218+ T221+T222+\cdot\cdot+T228)/24 \quad (3)$$

The quantity of energy supplied or rejected from storage during a daily test was then estimated by,

$$Qs = M_R\, C_{PR}(\overline{T}_{s,f} - \overline{T}_{s,i}) \quad (4)$$

where,

Qs = Quantity of energy stored (negative values indicate quantity of energy rejected from storage)

M_R = Mass of rocks in storage

C_{PR} = Specific heat of rock

$\overline{T}_{s,i}$ = Bulk average storage temperature at initial time

$\overline{T}_{s,f}$ = Bulk average storage temperature at final time

7.4 Energy Supplied to DHW Preheat Tank

The energy supplied to the preheat tank was not directly measured since the thermal syphon loop flow rate could not be measured without perturbing the flow. Energy transported to the preheat tank was estimated by,

$$Q_{DHW} = Q_{PH} + Q_{Loss} + Q_{Load} \quad (5)$$

where,

7.4 Energy Supplied to DHW Preheat Tank (Continued)

Q_{DHW} = Energy transported to preheat tank

Q_{PH} = Energy stored in preheat tank

Q_{Loss} = Overall heat transfer loss from preheat tank

Q_{Load} = Energy transported to DHW load

The quantity of energy stored in the preheat tank was evaluated using the equation,

$$Q_{PH} = \rho\, vC_p\ (\overline{T}_{PH,f} - \overline{T}_{PH,i}) \qquad (6)$$

where,

Q_{PH} = Energy stored in preheat tank

ρ = Density of water

v = Volume of tank

Cp = Specific heat of water

$\overline{T}_{PH,f}$ = Bulk average preheat water temperature at final state point

$\overline{T}_{PH,i}$ = Bulk average preheat water temperature at initial state point

Preheat water bulk average temperature levels were calculated by,

$$\overline{T}_B = \sum_{i=305}^{i=314} Ti \Big/ 10 \qquad (7)$$

The overall heat transfer loss coefficient was previously evaluated under non-operational conditions. Evaluation of the overall heat transfer loss coefficient was made using the following relation,

$$U_L = \frac{Q_{PH}}{\overline{T}002 - \overline{T}_{BA}} \qquad (8)$$

where,

7.4 Energy Supplied to DHW Preheat Tank (Continued)

Q_{PH} = Energy stored in preheat tank during test interval

$\overline{T}002$ = Average ambient room temperature during test interval

$\overline{T}_{BA}$ = Bulk average temperature of preheat tank water during test interval,

$$\int_{t_1}^{t_2} \overline{T}_B \, dt \Big/ \left(t_1 - t_2\right)$$

The DHW load was determined by the following equation,

$$Q_{Load} = \rho \, Cp \sum_{i=1}^{i=n} Vi(\overline{T}300 - \overline{T}301)i \qquad (9)$$

where,

Q_{Load} = Accumulative DHW loads over daily test interval

ρ = Density of water

Cp = Specific heat of water

Vi = Periodic volume of water drained

$\overline{T}300_i$ = Average temperature of heated water during load, i

$\overline{T}301_i$ = Average temperature of water supply during load, i

7.5 Evaluation of The Space Heating Load

Evaluation of the space heating load was performed using the equation,

$$Q_{SH\ Load} = \int_{t_1}^{t_2} Cp \ V400 \rho (T400-T403) dt \qquad (10)$$

where,

$Q_{SH\ Load}$ = Accumulated space heating load for daily test interval

7.0 DATA PROCESSING (Continued)

7.5 Evaluation of The Space Heating Load (Continued)

ρ = Density of air

Cp = Specific heat of air

V400 = Measured air volumetric flowrate in ASHRAE standard section

T400 = Outlet air temperature from system to load

T403 = Return air temperature to system from load

t = Time

7.6 Ambient Average Temperature

Ambient average air temperature of the collector array was computed over the daily test interval by,

$$\overline{T}_{oo,c} = \int_{t_1}^{t_2} T001\, dt \Big/ (t_2 - t_1) \qquad (11)$$

Ambient average air temperature of the thermal storage unit was computed over the daily test interval by,

$$\overline{T}_{oo,ts} = \int_{t_1}^{t_2} T002\, dt \Big/ (t_2 - t_1) \qquad (12)$$

7.7 Electrical Power Consumption

Electrical energy of the collector loop blower and the space heating loop blower were computed as follows,

$$Q_{EP,CL} = \int_{t_1}^{t_2} EP101A\, dt \qquad (13)$$

where,

$Q_{EP,CL}$ = Collector loop blower energy used in time interval t_1 to t_2

Electrical energy utilized over the daily test interval by the space heating blower was evaluated by,

$$Q_{EP,SH} = \int_{t_1}^{t_2} EP400A\, dt \qquad (14)$$

7.7 Electrical Power Consumption (Continued)

where,

$Q_{EP,SH}$ = Space heating loop blower energy used in time interval t_1 to t_2

TABLE I

LISTING OF SYSTEM MEASURED/PLOTTED PARAMETERS

MEASUREMENT	PLOT PARAMETERS
Solar flux	$BTU/Hr \cdot Ft^2$ vs hours
Outside ambient temperature	°F vs hours
RSA inside ambient temperature	°F vs hours
Wind speed/direction	MPH/degrees vs hours
Collector inlet temperature	°F vs hours
Collector outlet temperature	°F vs hours
Collector absorber temperature	°F vs hours
Thermal storage temperature profiles	°F vs inches and hours
DHW HEX air temperature - collector side	°F vs hours
DHW HEX air temperature - storage side	°F vs hours
DHW water supply temperature	°F vs hours
DHW water outlet temperature	°F vs hours
DHW preheat tank temperature profile	°F vs inches and hours
Space heating load outlet air temperature	°F vs hours
Space heating load inlet air temperature	°F vs hours
Air flow rate through collectors	LFM vs hours
Air flow rate through space heating loop	CFM vs hours
Water flow rate to DHW system	GPM vs hours
Collector blower power	Watts vs hours
Space heating blower power	Watts vs hours
Storage high temperature limit switch position	Closed/open vs hours
Storage low temperature limit switch position	Closed/open vs hours
Collector thermoswitch position	Closed/open vs hours
Storage high temperature limit switch temperature	°F vs hours
Storage low temperature limit switch temperature	°F vs hours
Collector absorber plate temperature	°F vs hours

TABLE II

SUMMARY OF DHW SUBSYSTEM TESTS

Test Date	4-13-78	4-14-78	4-17-78	4-24-78	5-9-78	5-11-78
Measurement	DHW	DHW	DHW	DHW	DHW	DHW
Test initiation time	0830	0830	0830	0830	0830	0830
Test completion time	1600	1600	1600	1600	1600	1600
Collector loop control switch position	Auto.	Auto.	Manual	Auto.	Auto.	Auto.
Loop space heating control switch position	Off	Off	Off	Off	Off	Off
Initial bulk average DHW preheat tank temperature	70°F	73°F	75°F	68°F	68°F	72°F
Preconditioned average thermal storage temperature	90°F	60°F	100°F	67°F	70°F	94°F
DHW load schedule	1	1	2	2	2	2
Total daily DHW load (BTU)	13894	14294	23990	19969	20409	23075
Total daily available solar energy (BTU)	379610	339010	289275	302470	341040	328048
Total daily solar energy collected (BTU)	200415	184601	138489	161040	180550	113063
Total energy transported to DHW subsystem, $Q_{Load}+Q_{Stored}+Q_{Loss}$ (BTU)	36040	23553	45740	38358	30000	40294
Total daily electrical power (BTU)						
- Collector loop	8646	8402	12480	3833	7935	6485
- Space Heating	N/A	N/A	N/A	N/A	N/A	N/A
Total energy transported to storage (BTU)	63980	96125	47125	87080	98050	60705

TABLE III

SUMMARY OF STORAGE UNIT CHARGE/DISCHARGE TESTS

Test Date	4/21/78	4/25/78
Measurement		
Test initiation time	0820	0920
Test completion time	1230	1230
Collector loop control switch position	Off	Off
space heating loop control switch position	On	On
Preconditioned average thermal storage temp.	109°F	108°F
Total solar energy available	N/A	N/A
Total energy supplied to space heating load from storage	80200 BTU	88000 BTU
Total energy collected/ stored	N/A	N/A
Total electrical power		
- collector blower	N/A	N/A
- space heating blower	6400 BTU	4114 BTU

NOTES: Discharge of 4-21-78 was from preconditioned rock bed for overnight heat loss calculation. Due to rain on 4-25-78, the previous day's charge was used for the discharge test.

TABLE IV

SUMMARY OF INTERMITTENT LOAD TESTS

Test Date	4-27-78	4-28-78	5-2-78	5-10-78
Measurement				
Test initiation time	0830	0830	0830	0830
Test completion time	1600	1600	1600	1600
Preconditioned average storage temperature, °F	68	72	69	110
Daily solar flux available, BTU	371490	359310	334950	355250
Daily space heating load, BTU	140000	147000	132000	139000
Daily DHW Subsystem load, BTU	N/A	N/A	*	27000
Thermal storage unit, energy stored, BTU	7400	5550	5550	-25900
Total daily electrical power, BTU				
- Collector loop blower	7935	7935	7935	7935
- Space heating loop blower	9898	9898	9898	9898
Total solar energy collected, BTU	237175	171635	125194	197439

* Indicates inadequate data due to Data Acquisition System problems.

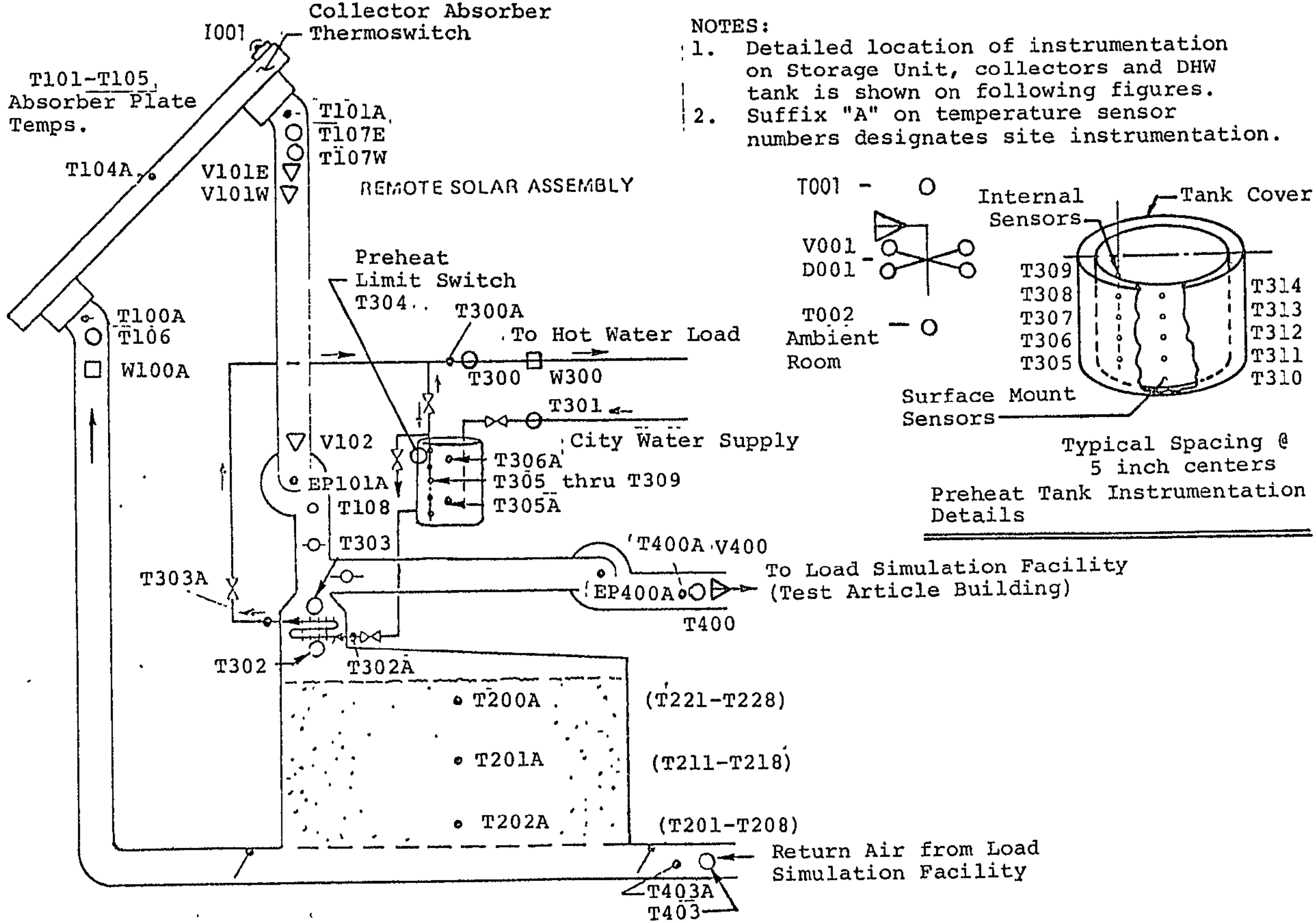

Figure 1. System 4 Flow and Instrumentation Schematic

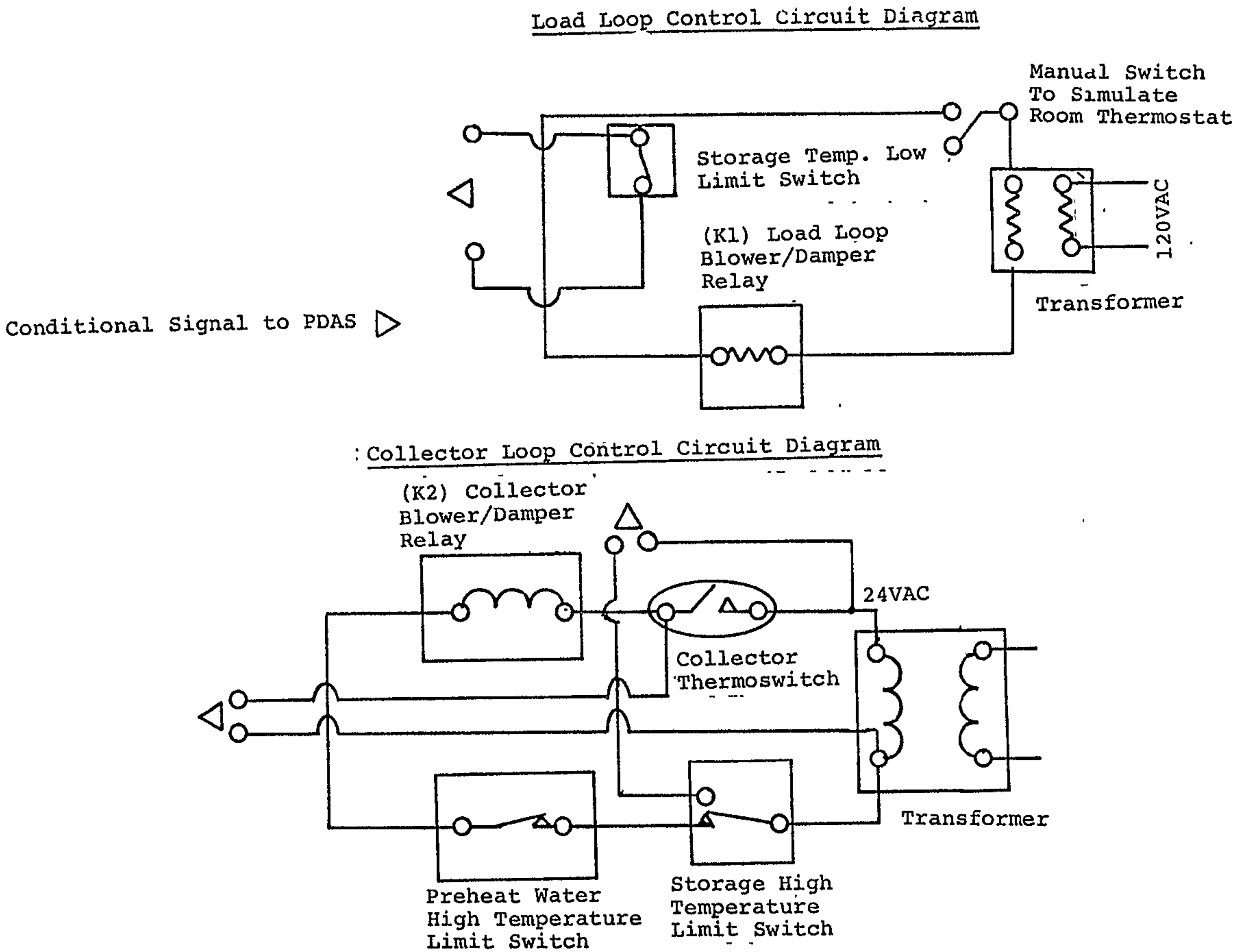

Figure 2. Schematic of Control Circuits with Switch Position Sensors

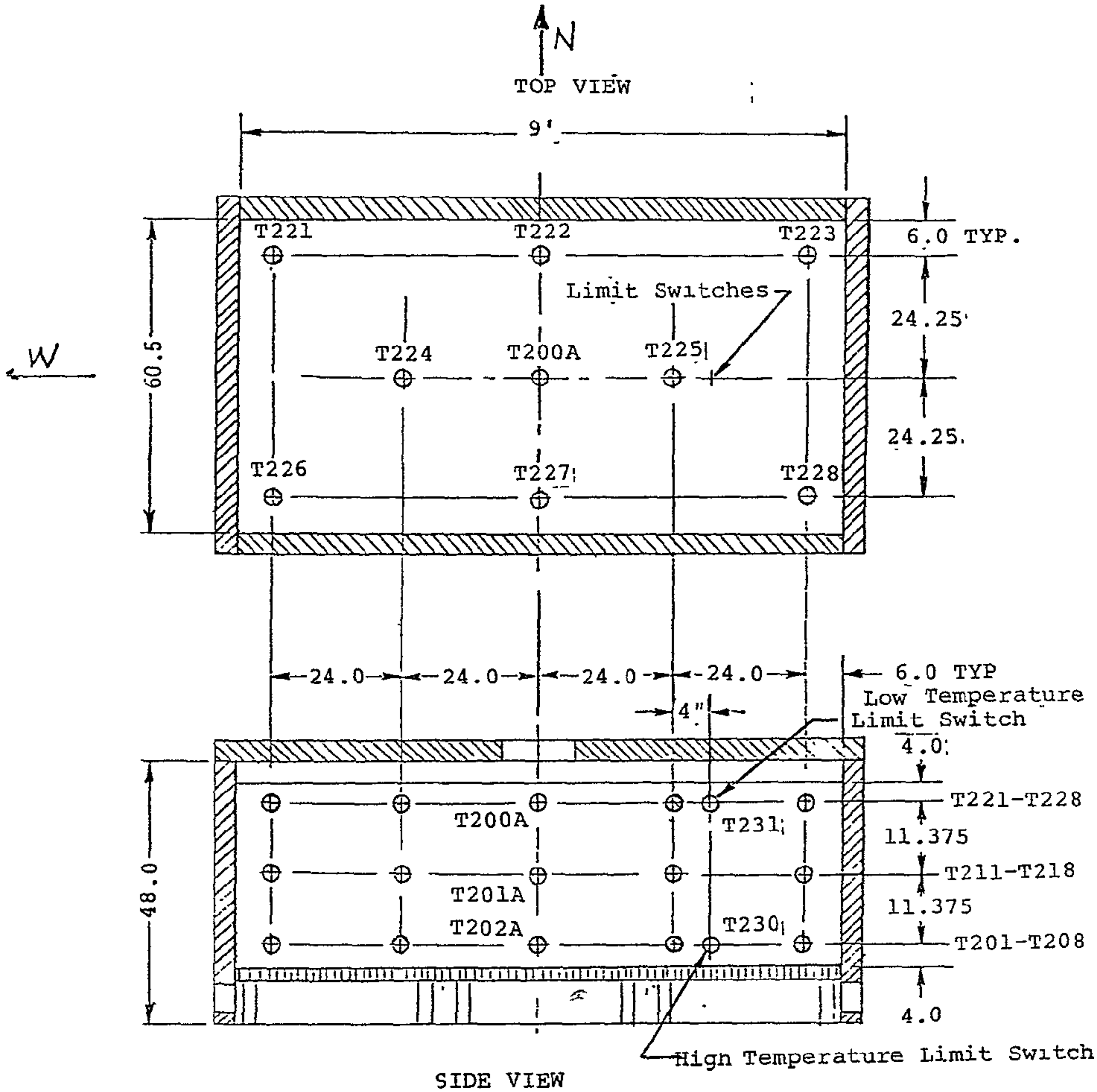

Figure 3. Temperature Sensor Locations in Storage Unit

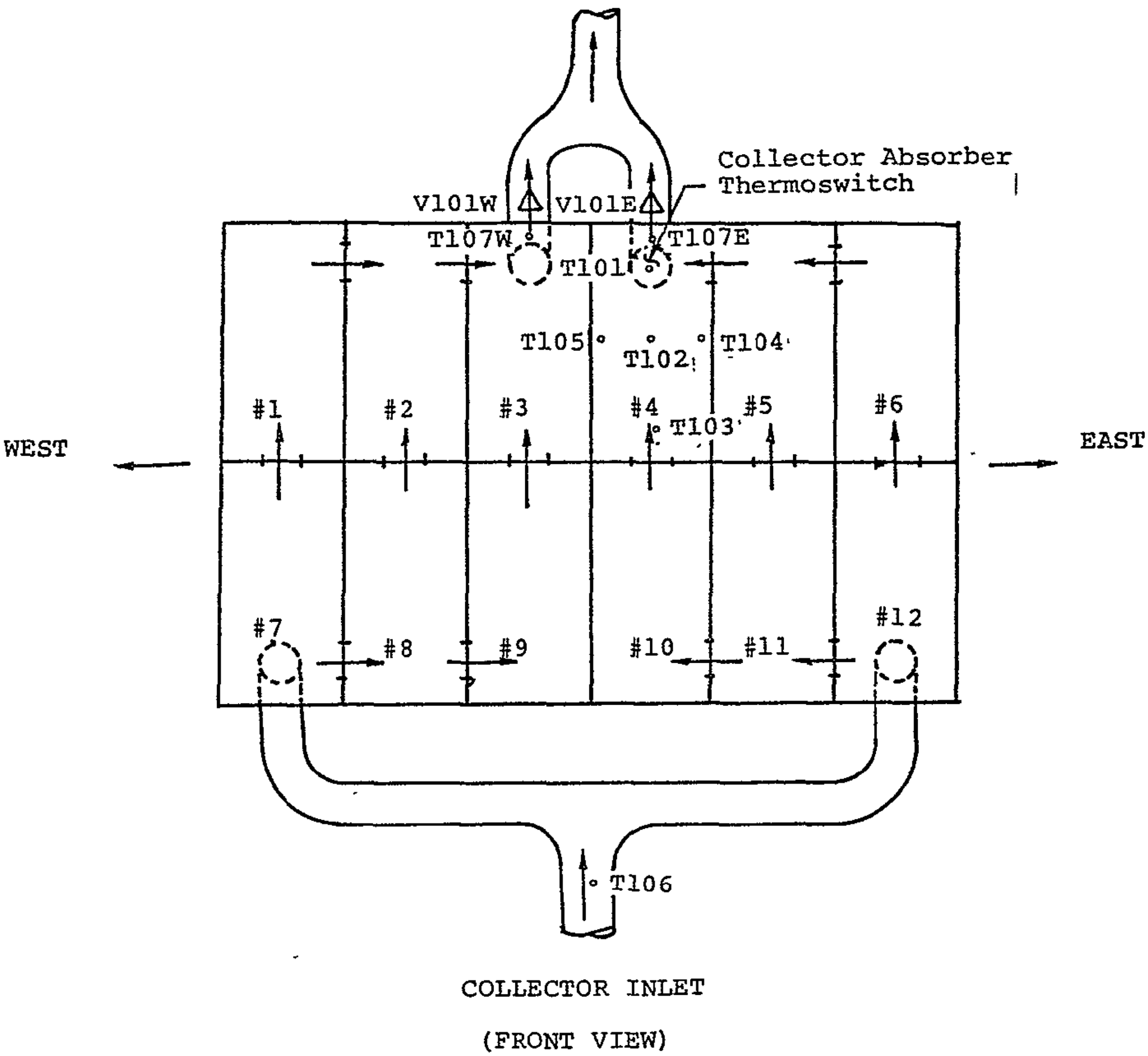

Figure 4. System 4 Collector Array Flow and Instrumentation Location Schematic

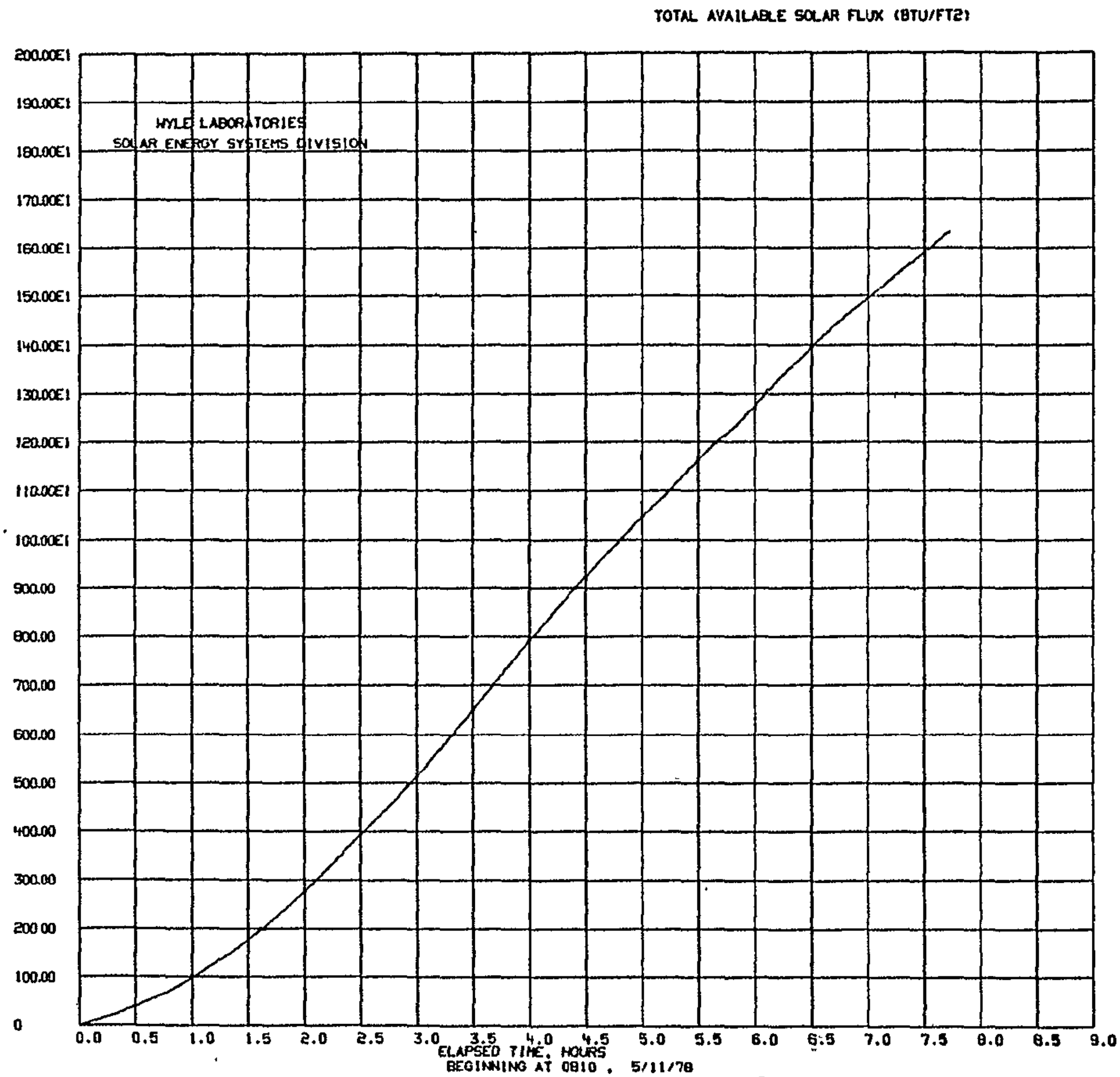

Figure 5. Total Available Solar Flux (BTU/Ft^2)

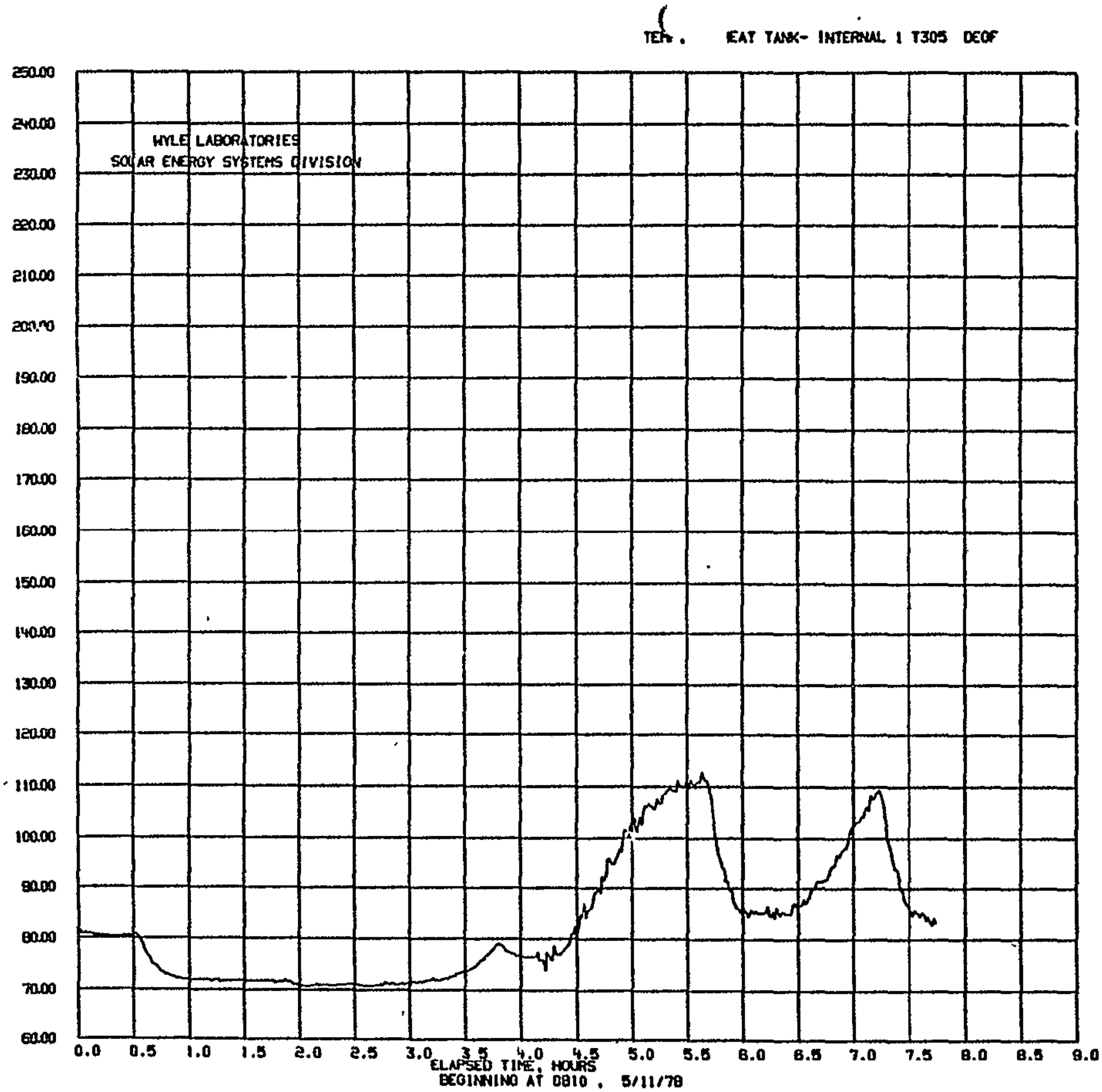

Figure 6. Temperature, Preheat Tank, Internal 1, T305, °F

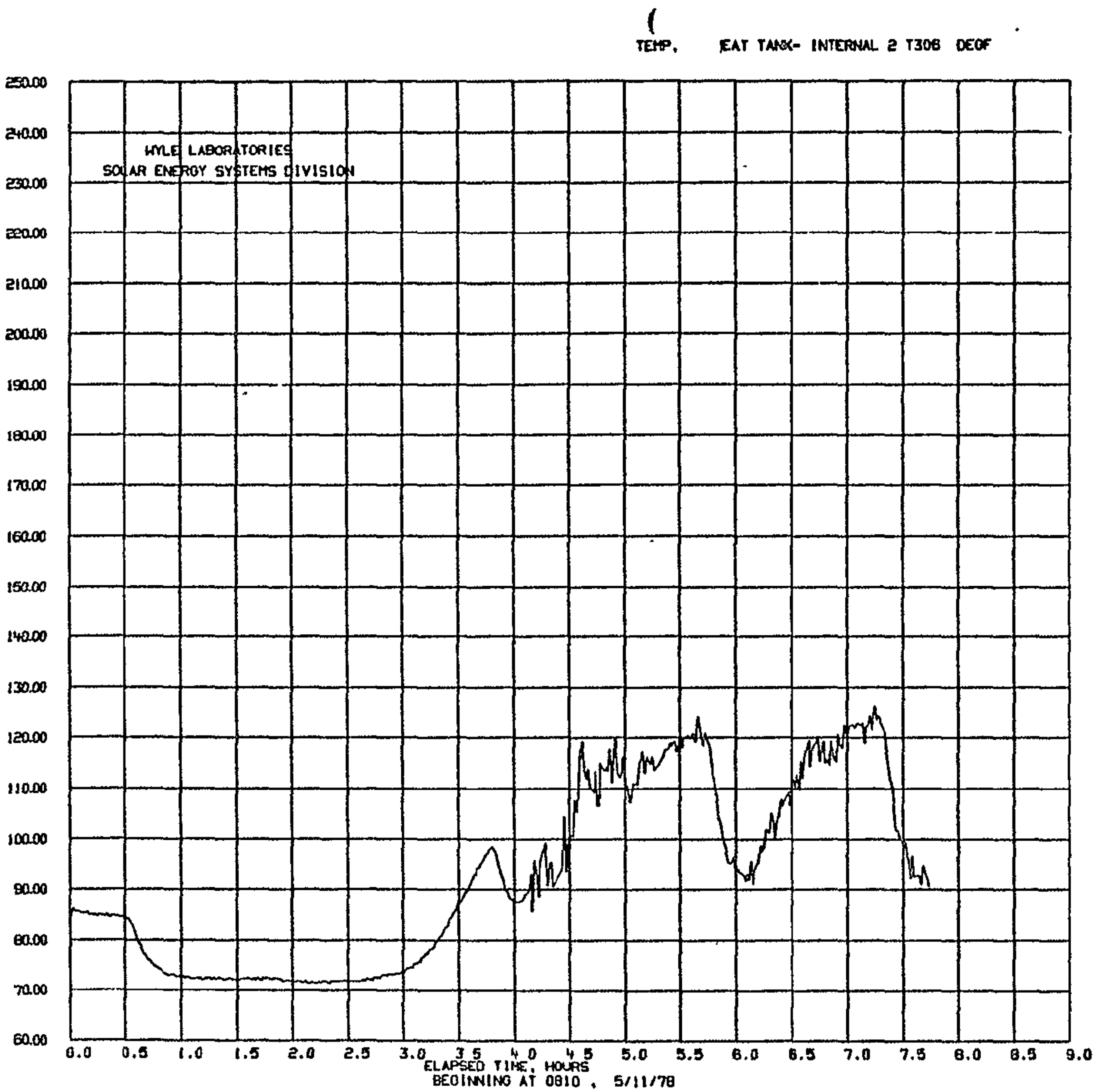

Figure 7. Temperature, Preheat Tank, Internal 2, T308, °F

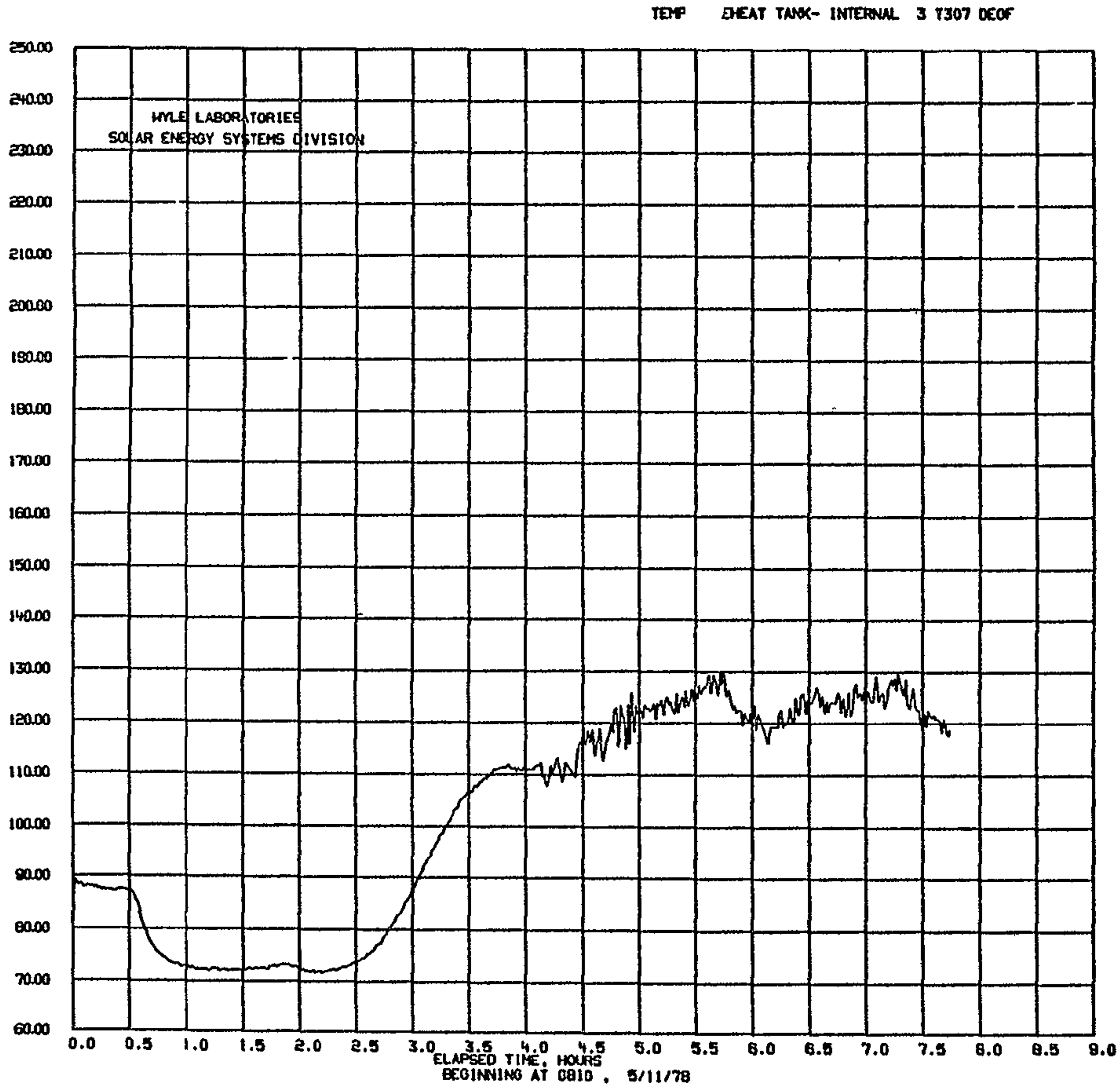

Figure 8. Temperature, Preheat Tank, Internal 3, T307, °F

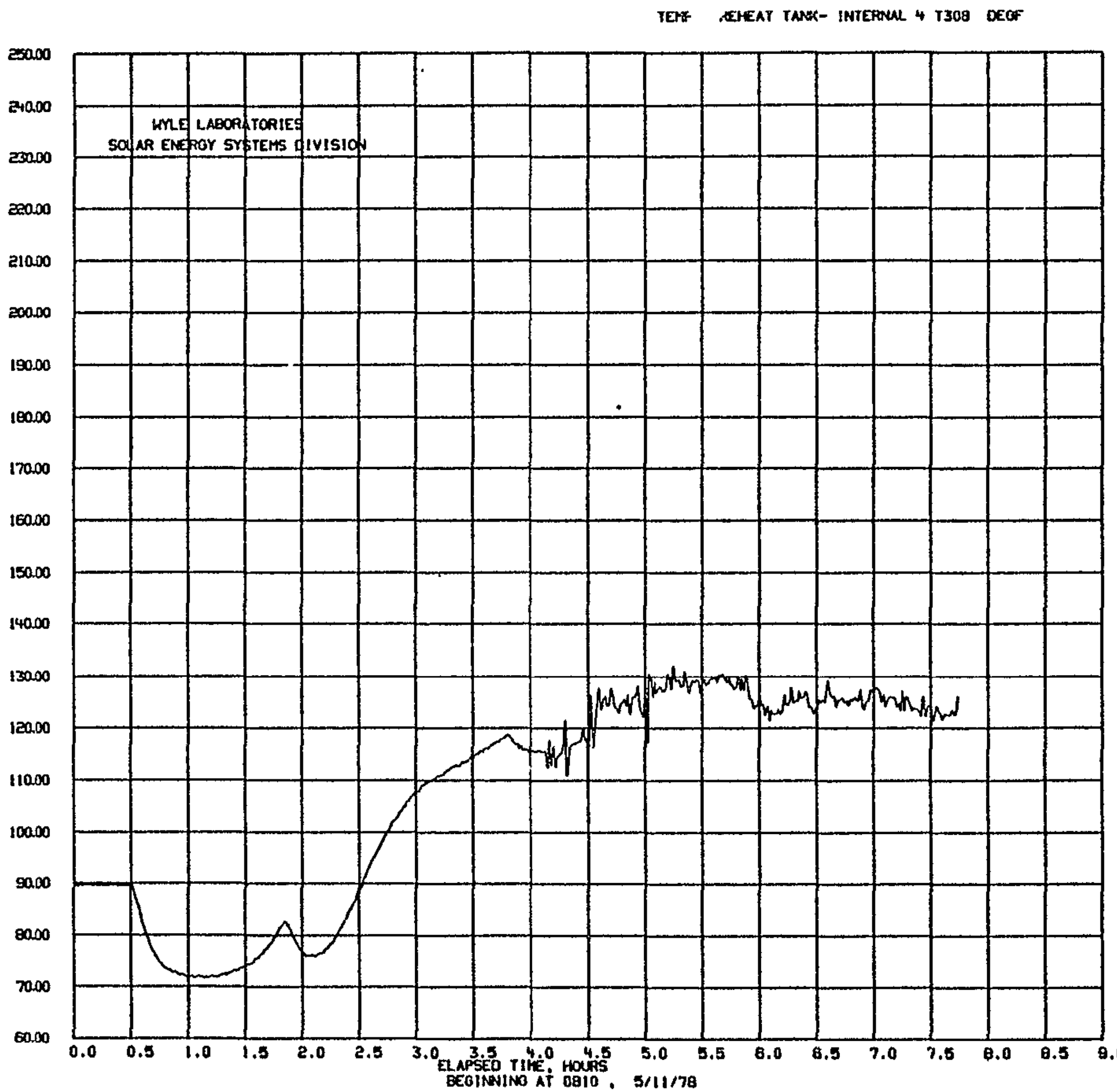

Figure 9. Temperature, Preheat Tank, Internal 4, T308, °F

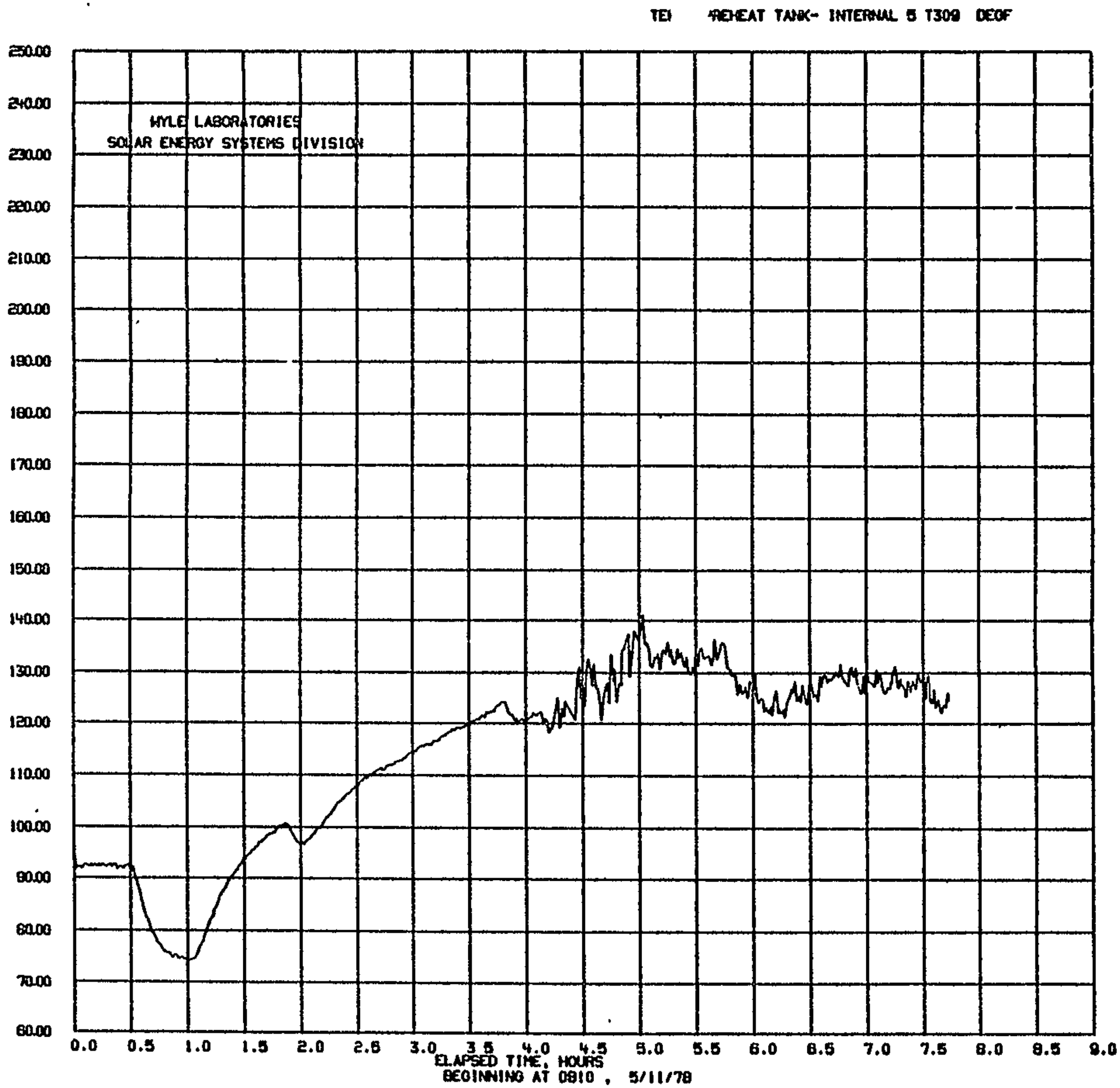

Figure 10. Temperature, Preheat Tank, Internal 5, T309, °F

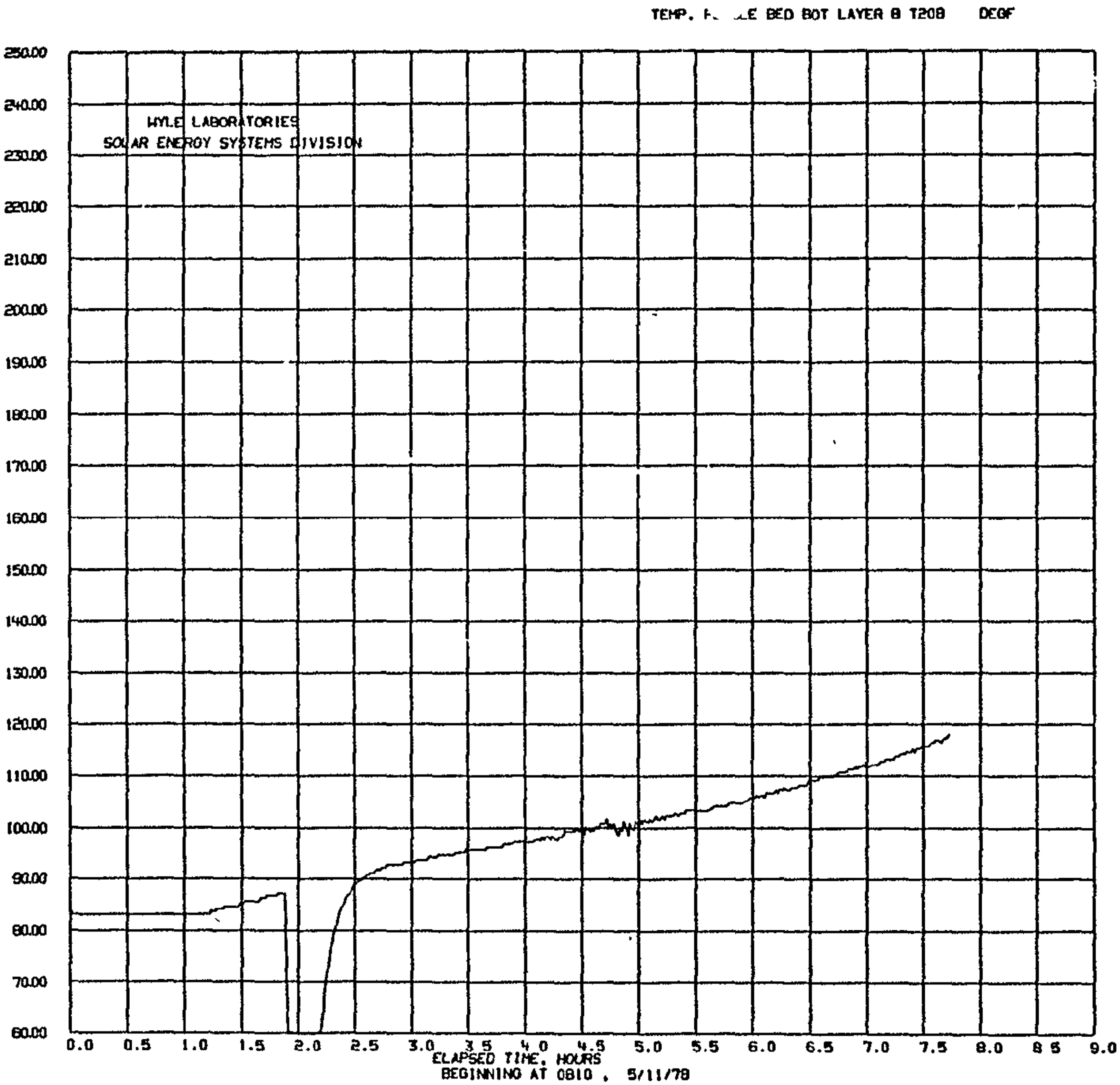

Figure 11. Pebble Bed, Bottom Layer 8, T208, °F.

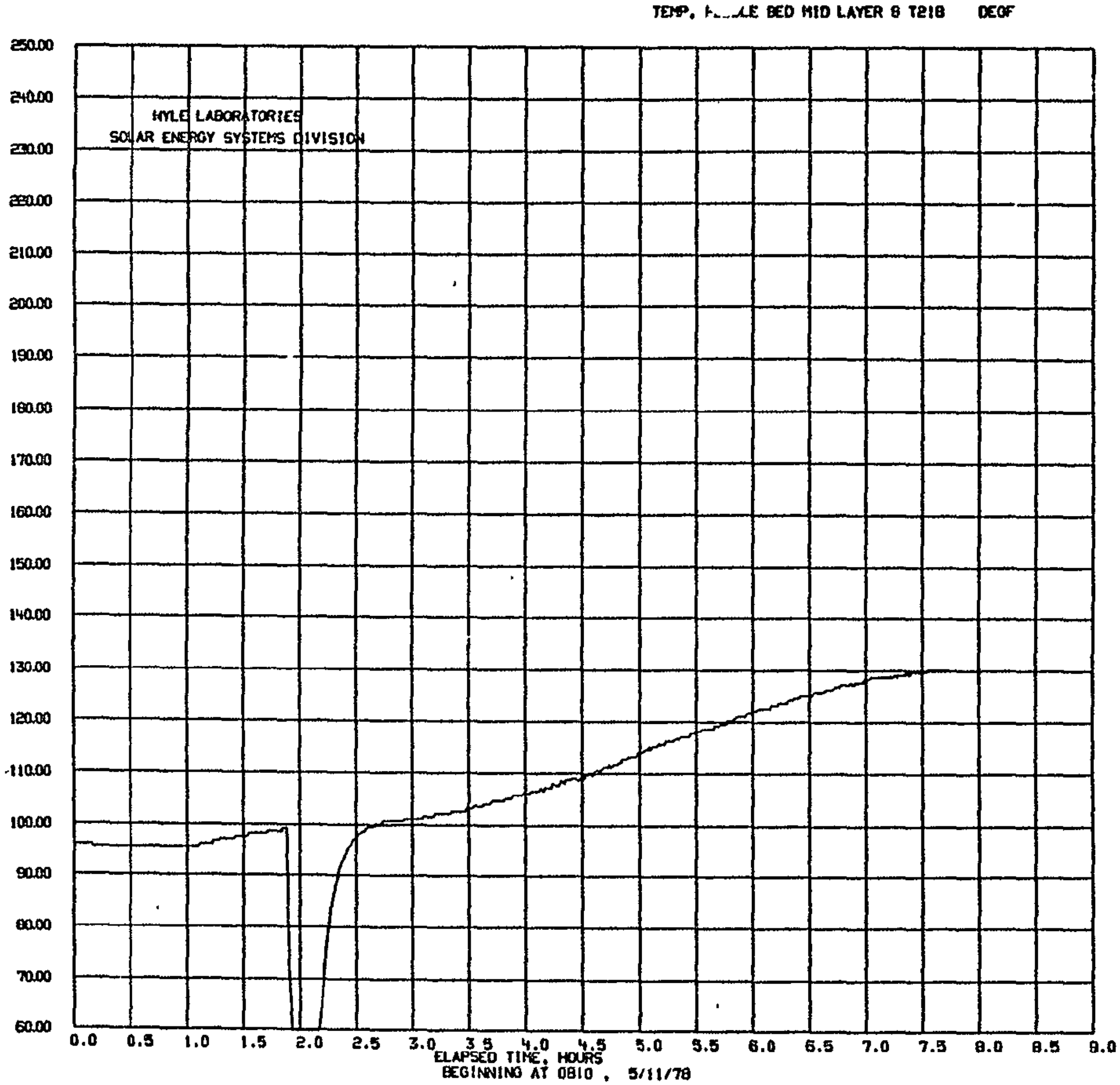

Figure 12. Pebble Bed, Middle Layer 8, T218, °F

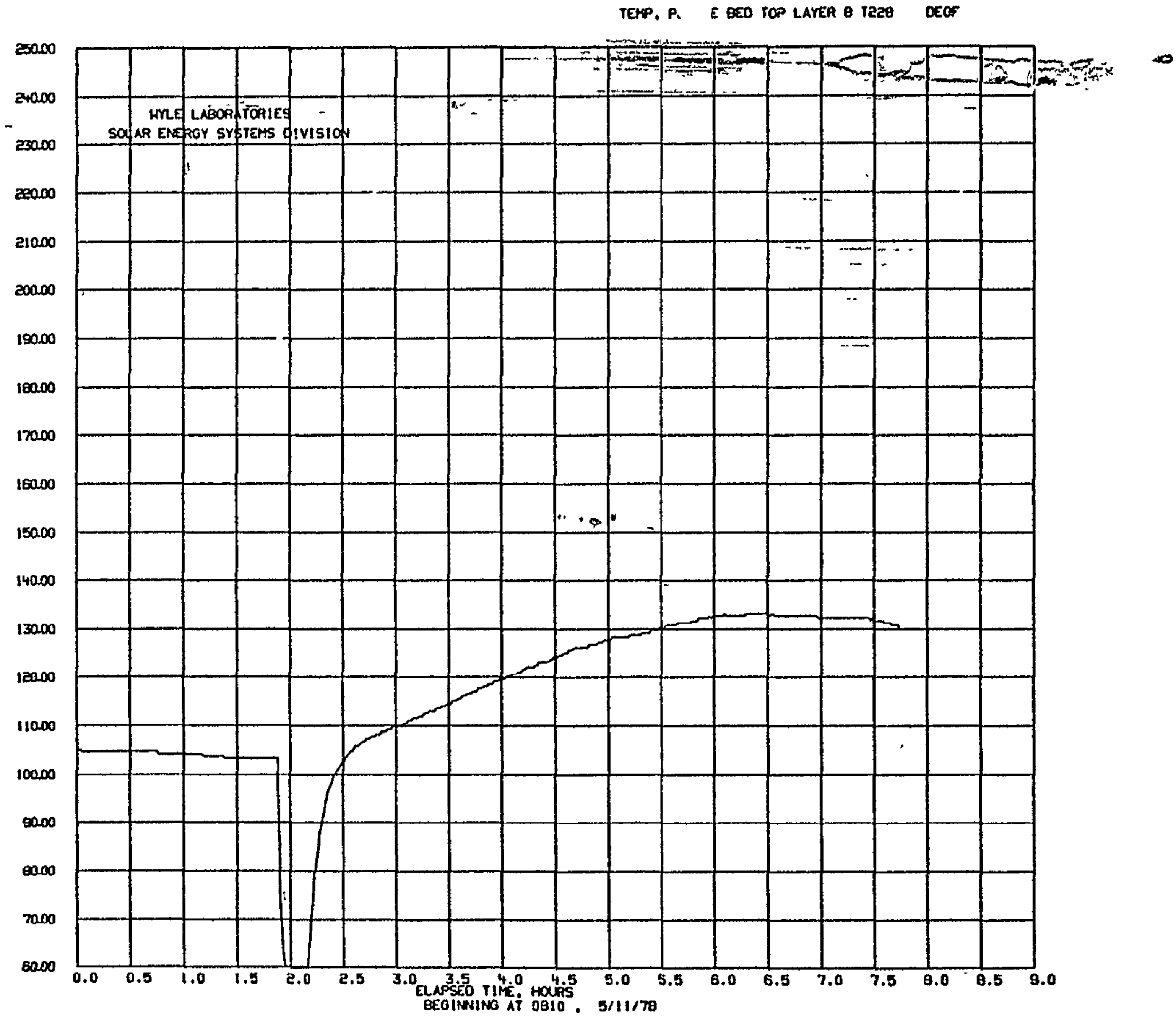

Figure 13. Pebble Bed, Top Layer 8, T228, °F

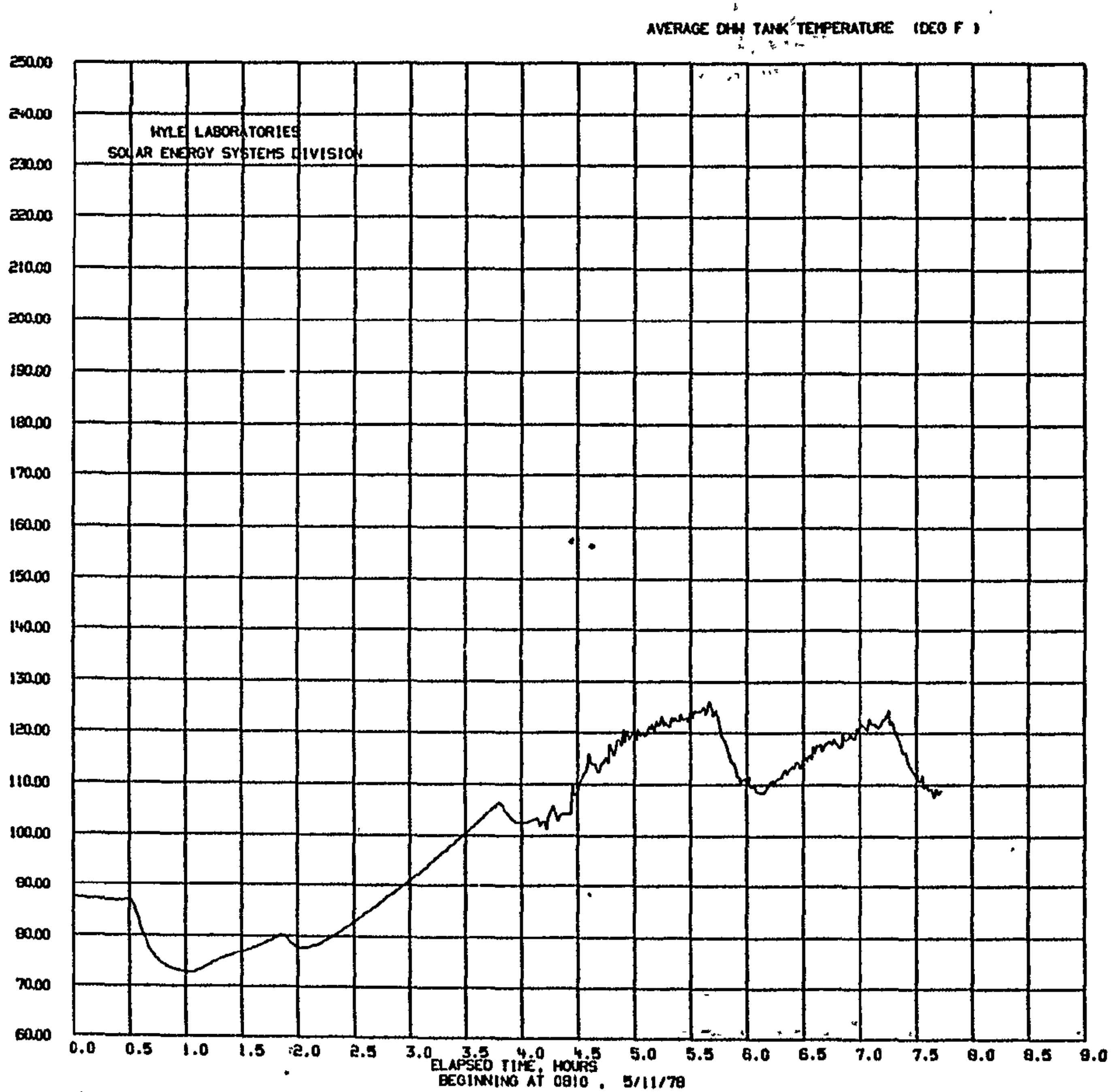

Figure 14. Average DHW Tank Temperature, °F

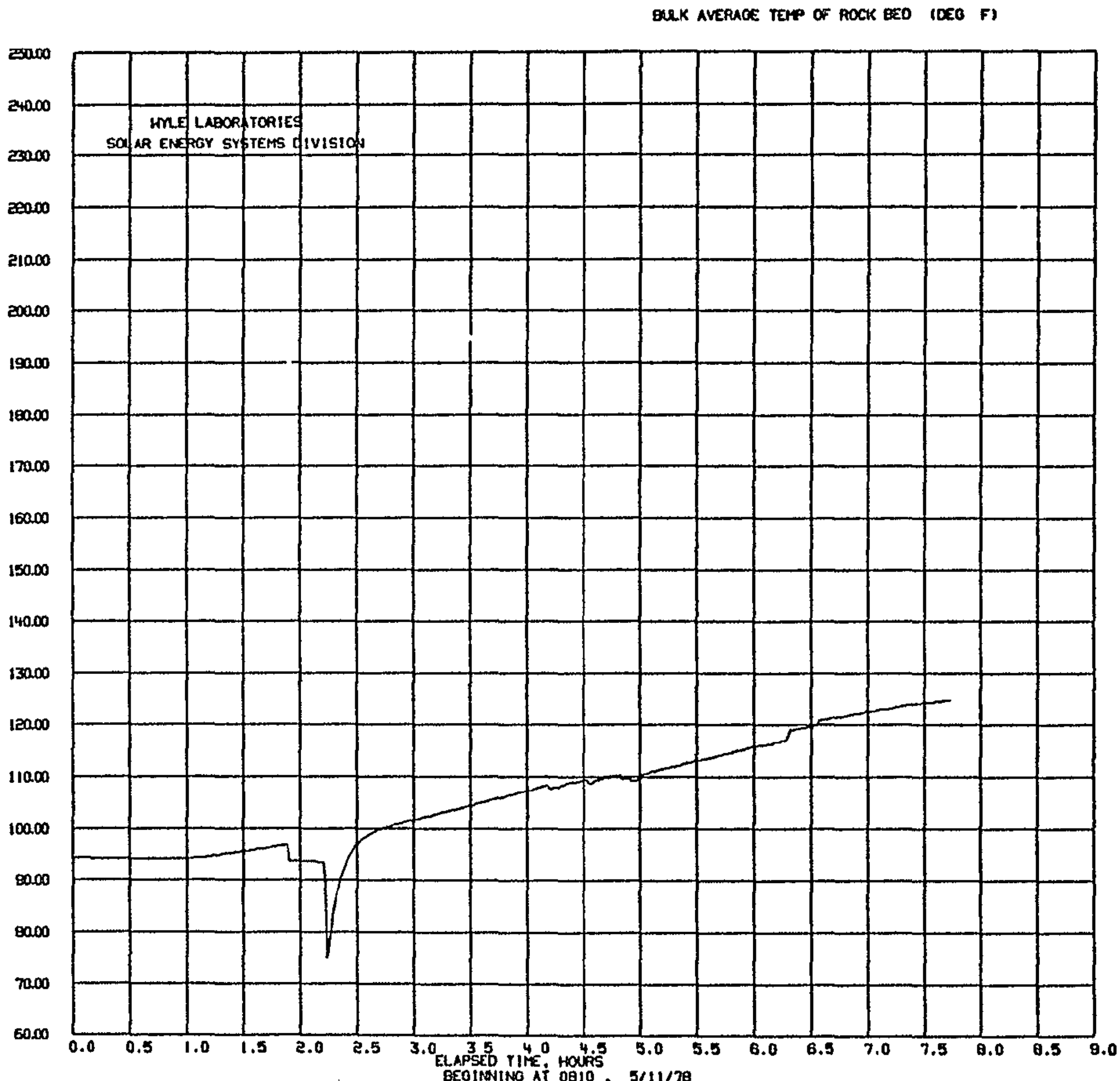

Figure 15. Bulk Average Temperature of Rock Bed, °F

C-2

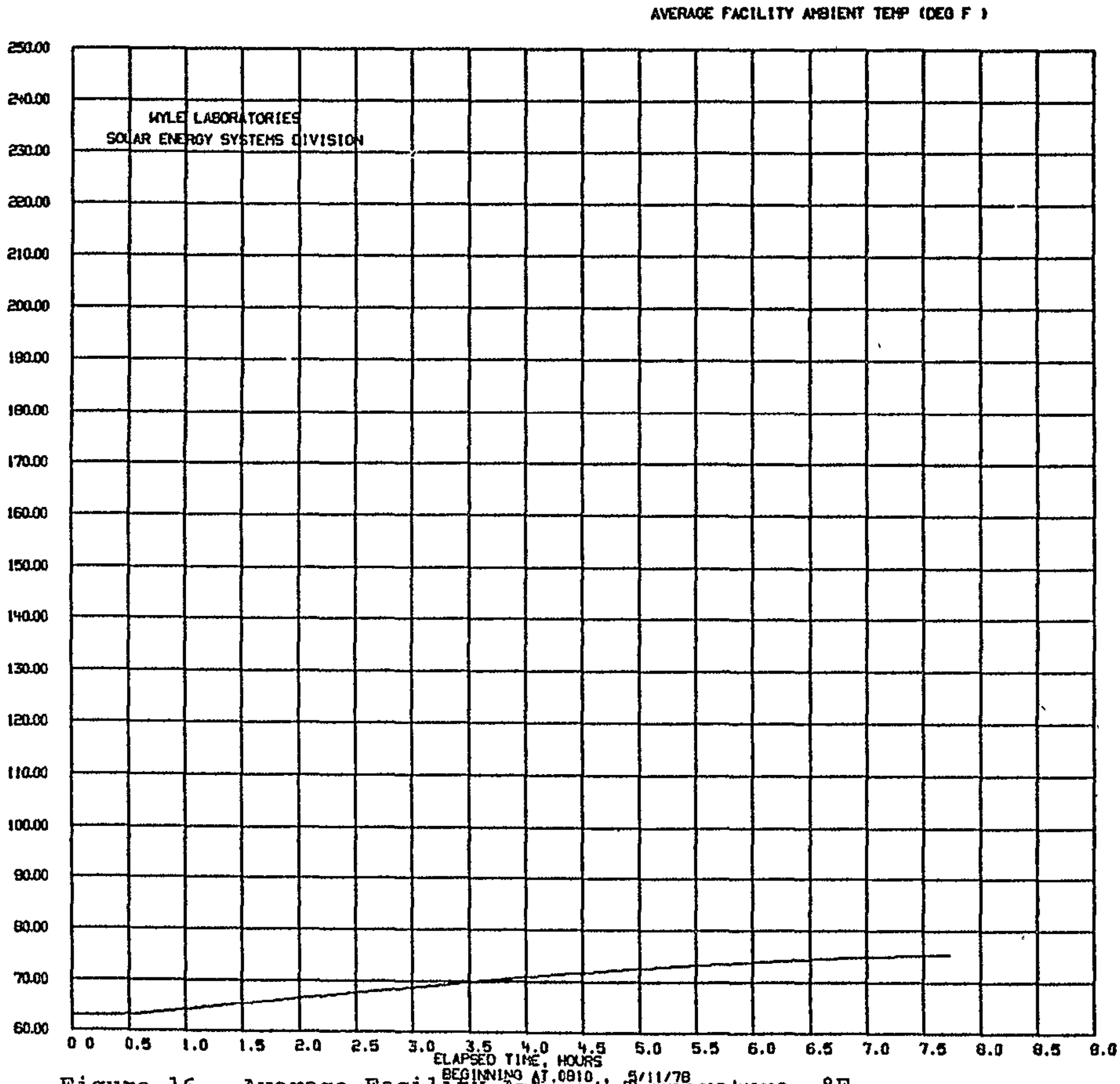

Figure 16. Average Facility Ambient Temperature, °F

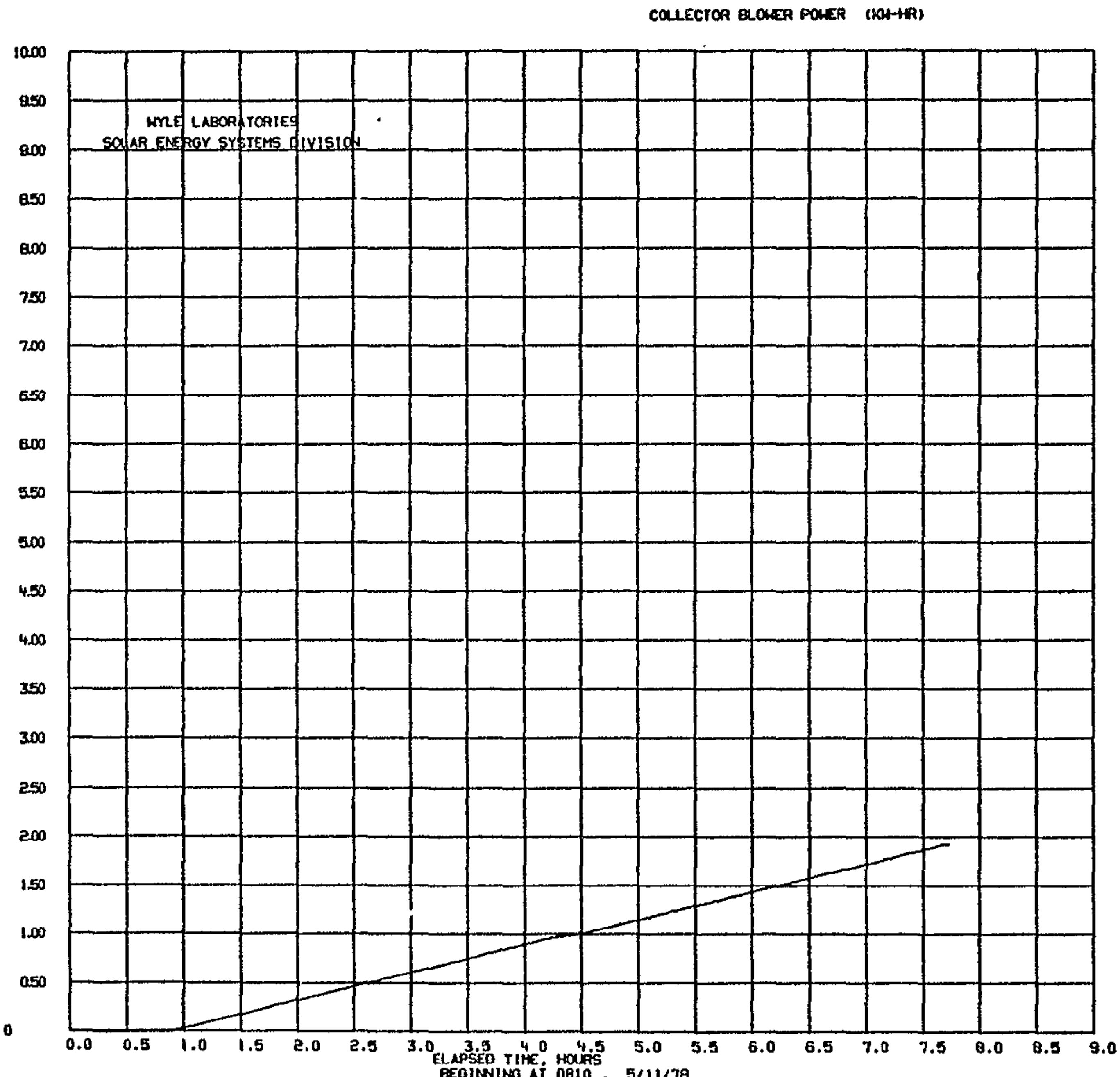

Figure 17. Collector Blower Power (KW/HR)

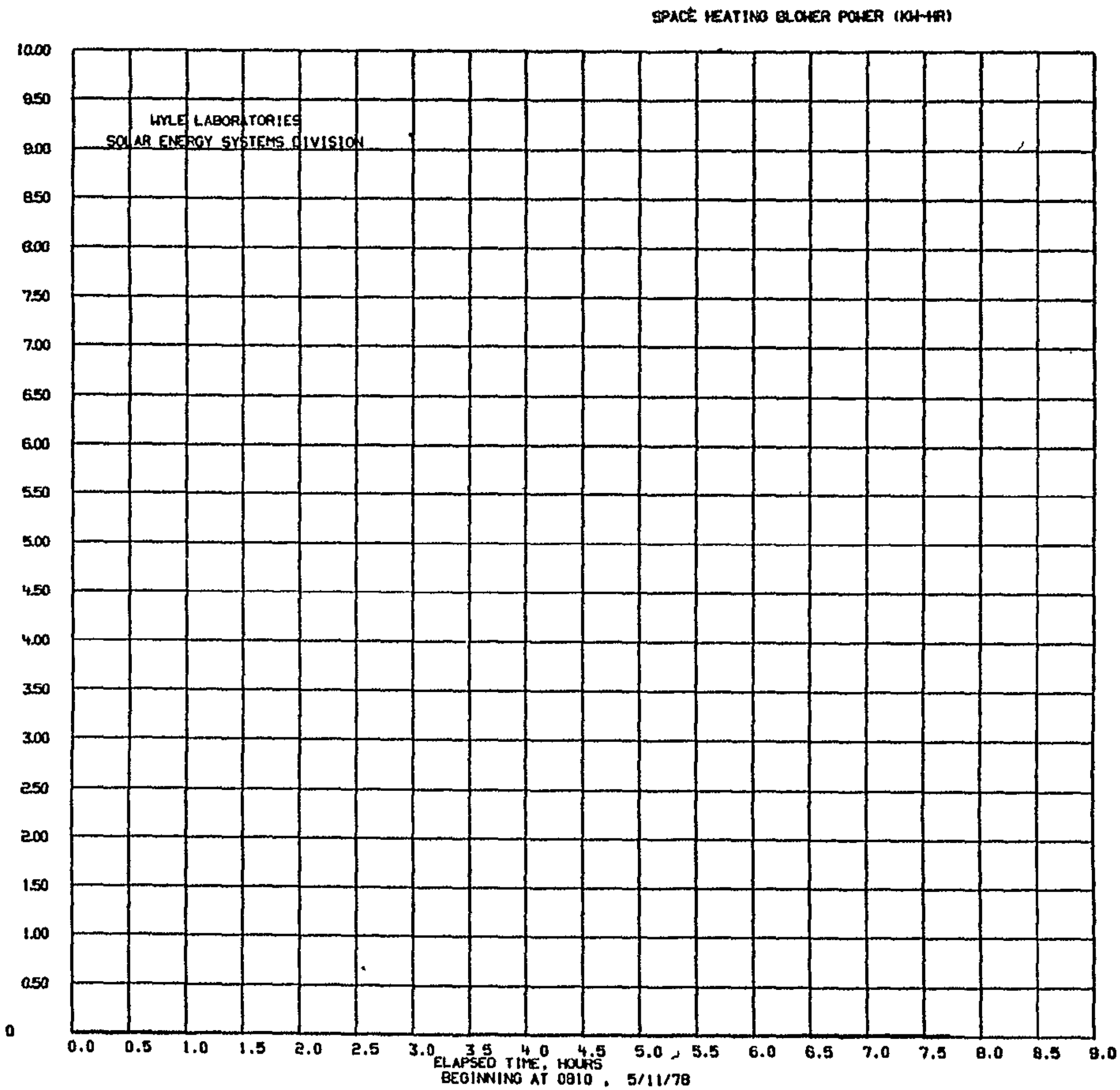

Figure 18. Space Heating Blower Power (Kw/Hr)

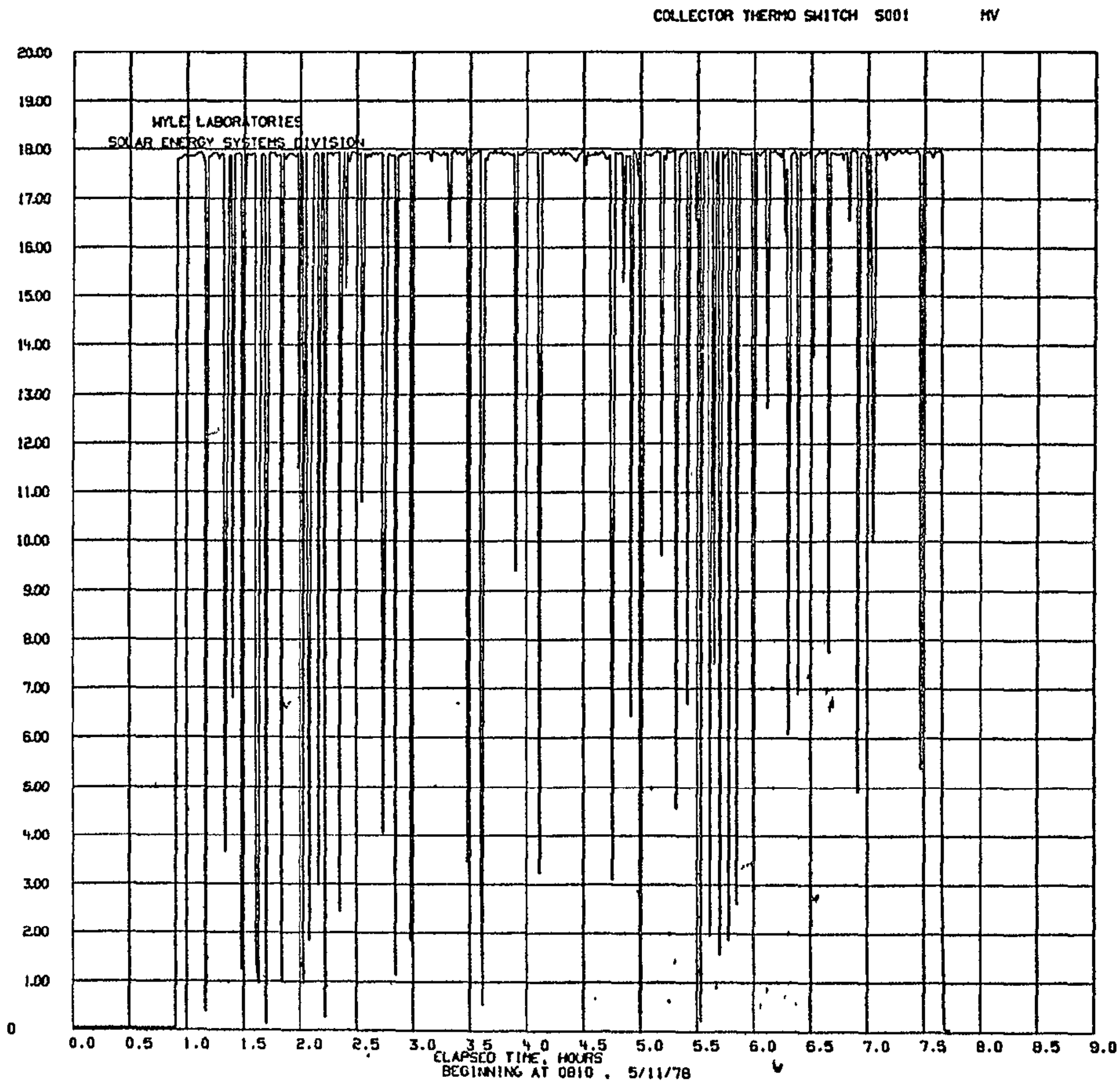

Figure 19. Collector Thermoswitch, S001 (Mv)

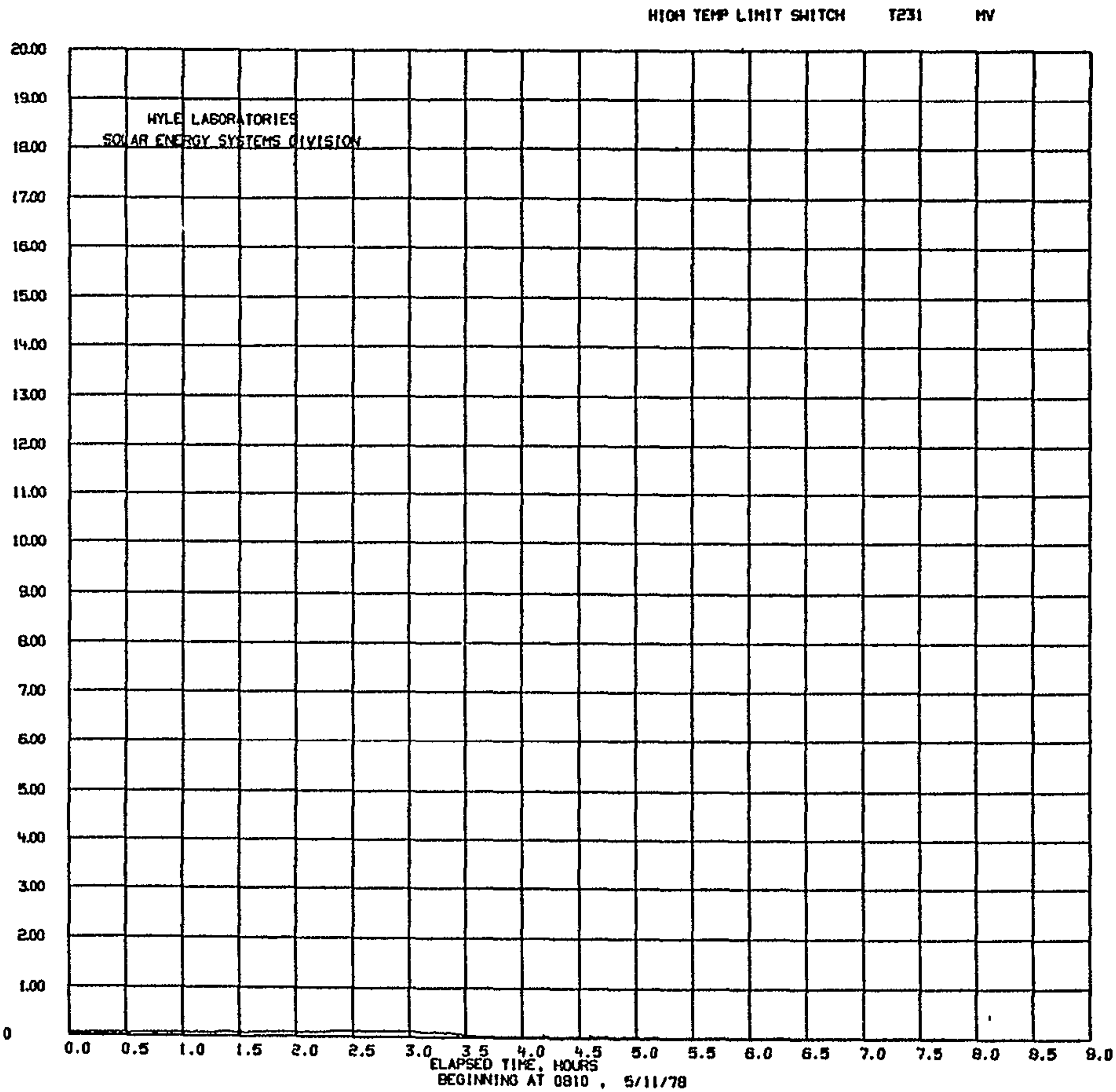

Figure 20. High Temperature Limit Switch, T231, Mv

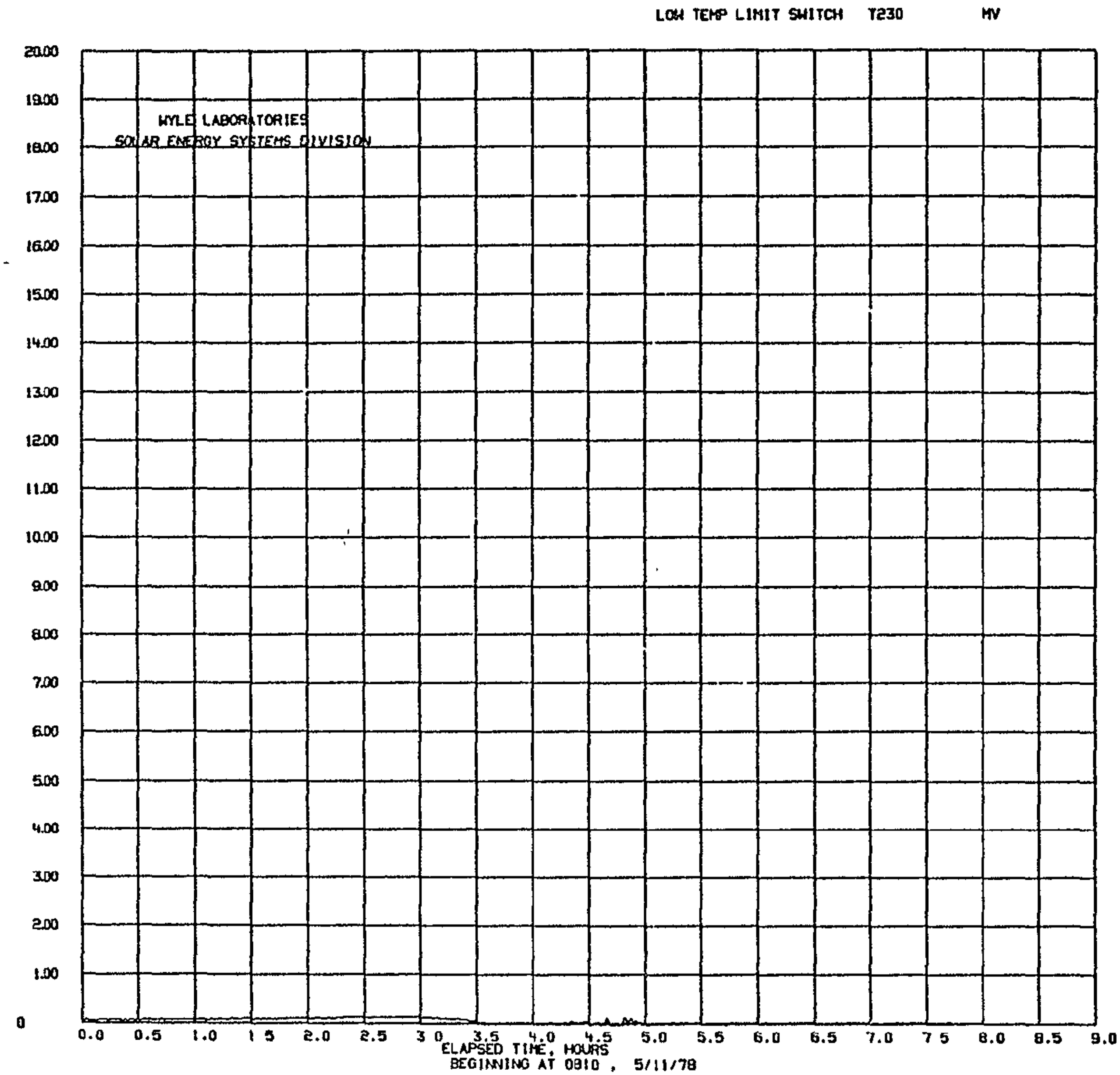

Figure 21. Low Temperature Limit Switch, T230, Mv

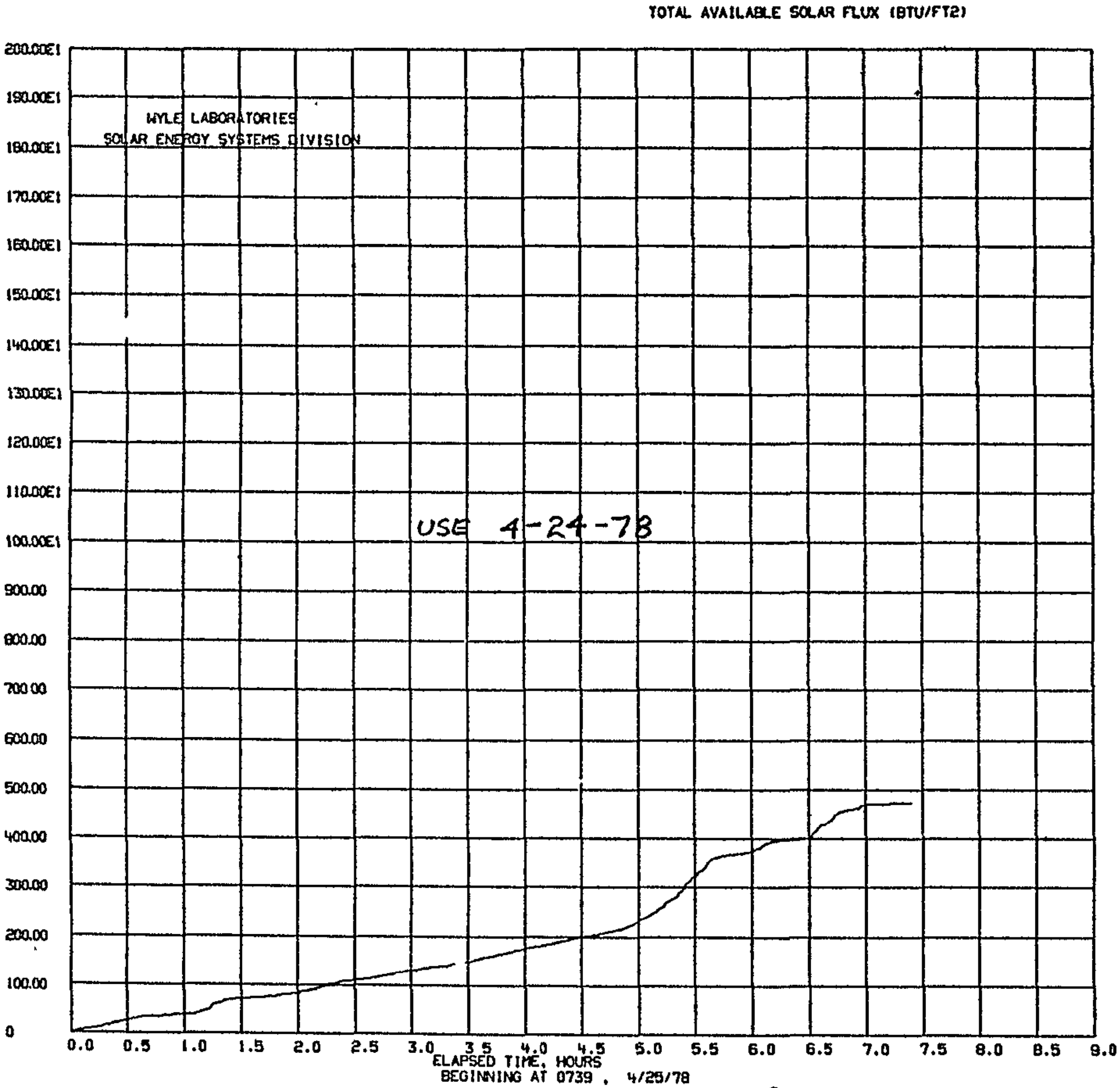

Figure 22. Total Available Solar Flux, BTU/Ft^2

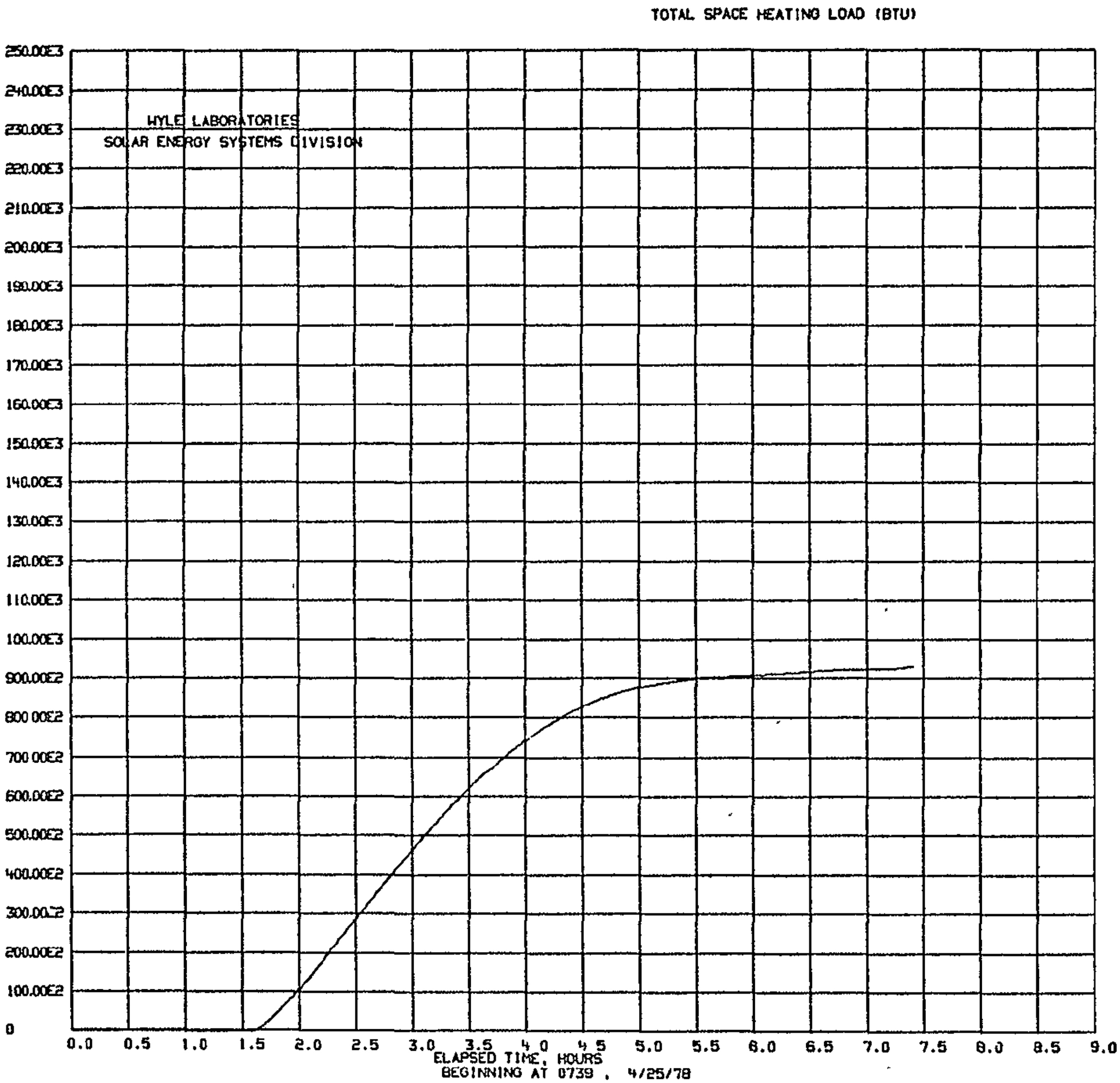

Figure 23. Total Space Heating Load (BTU)

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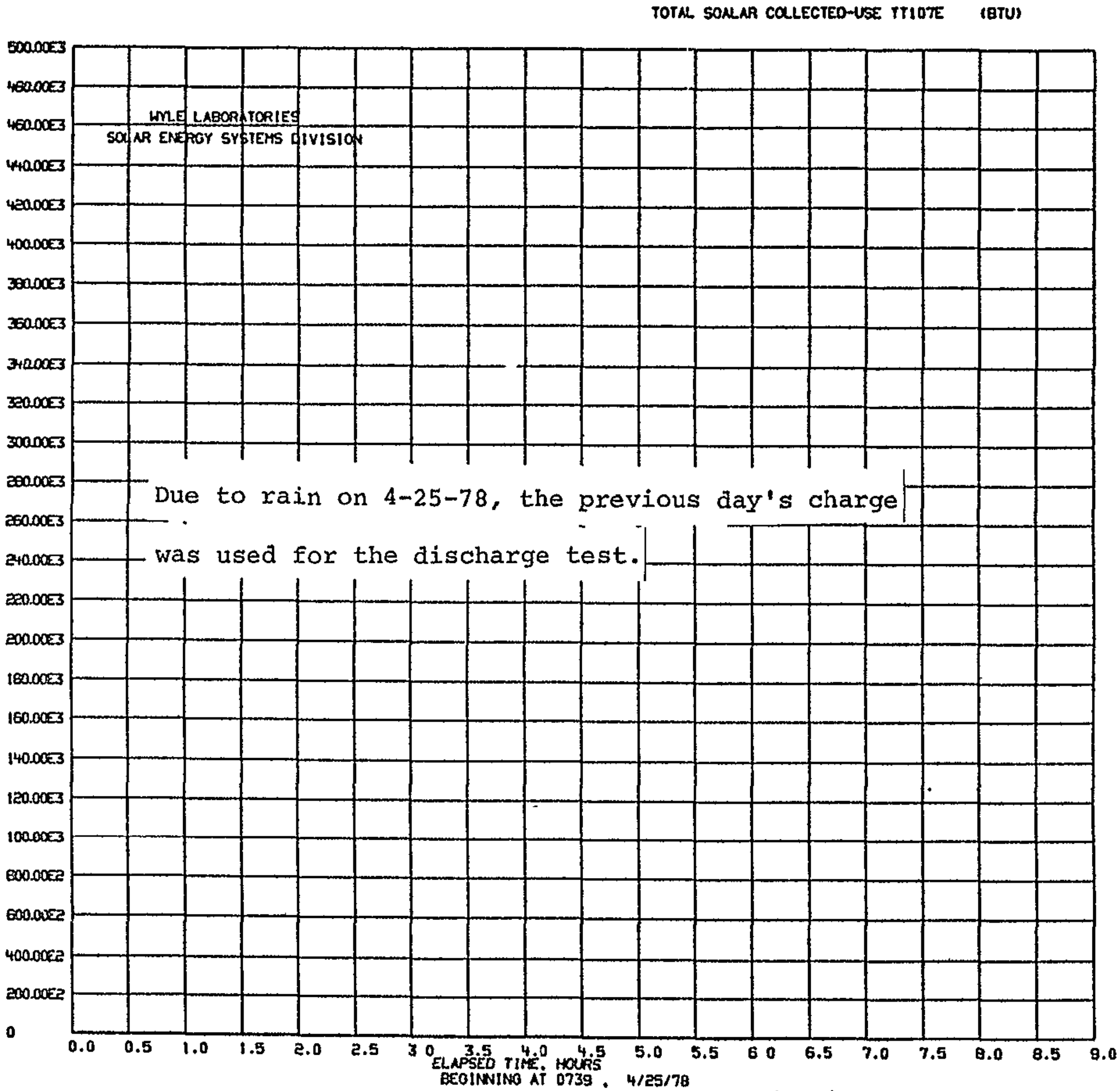

Figure 24. Total Solar Collected-Use, TT107E (BTU)

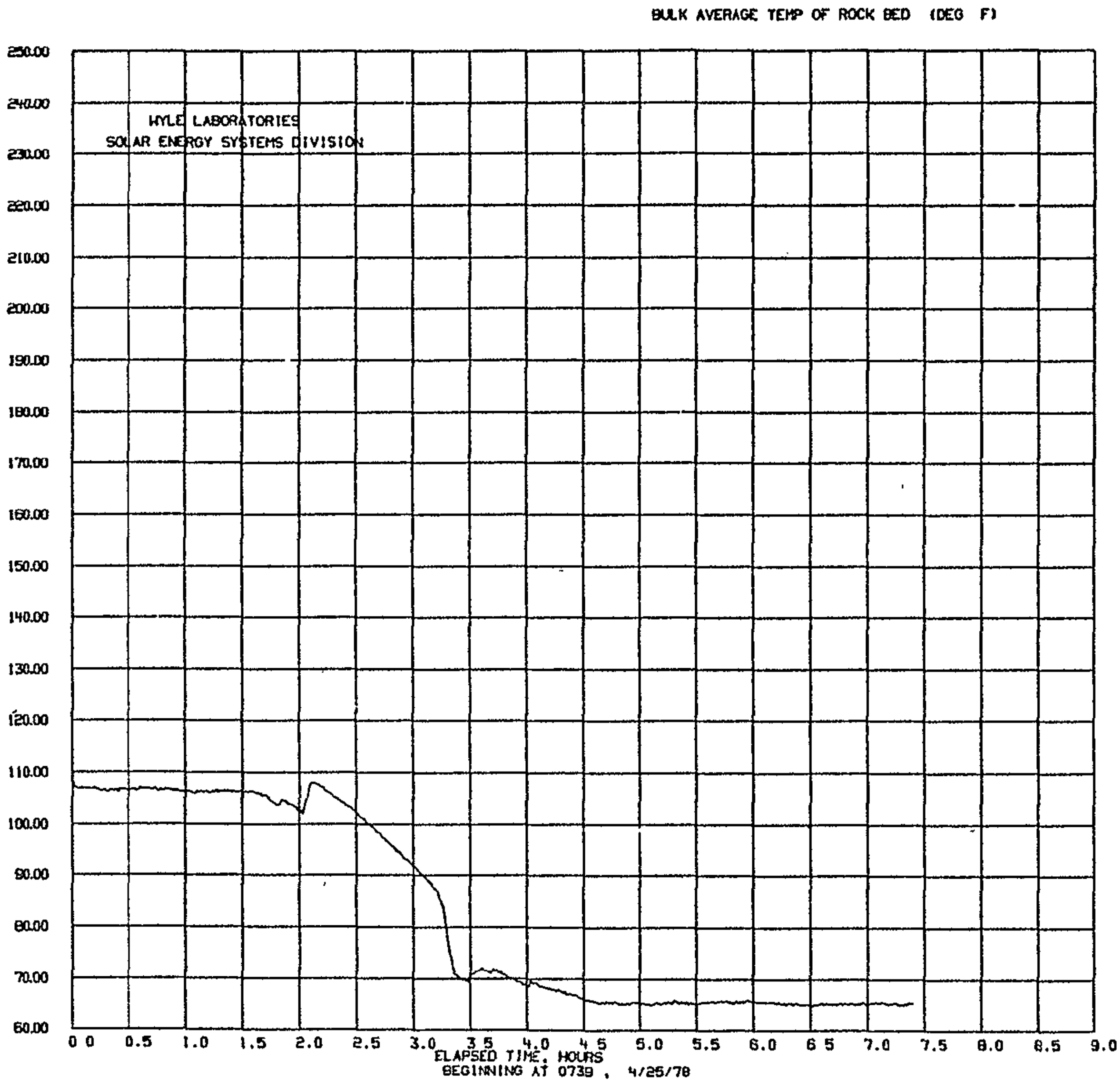

Figure 25. Bulk Average Temperature of Rock Bed, °F

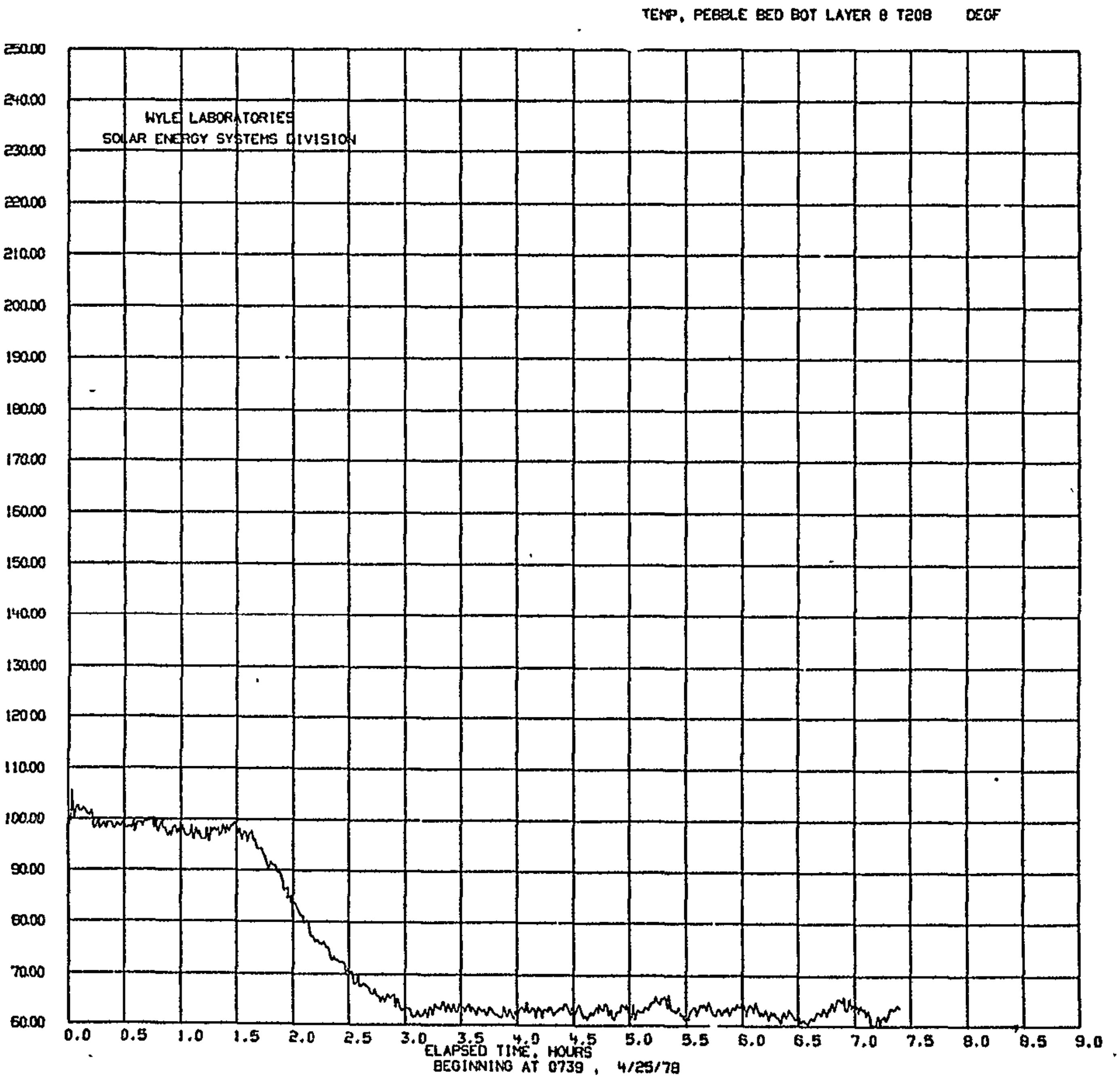

Figure 26. Temperature, Pebble Bed Bottom Layer 8, T208, °F

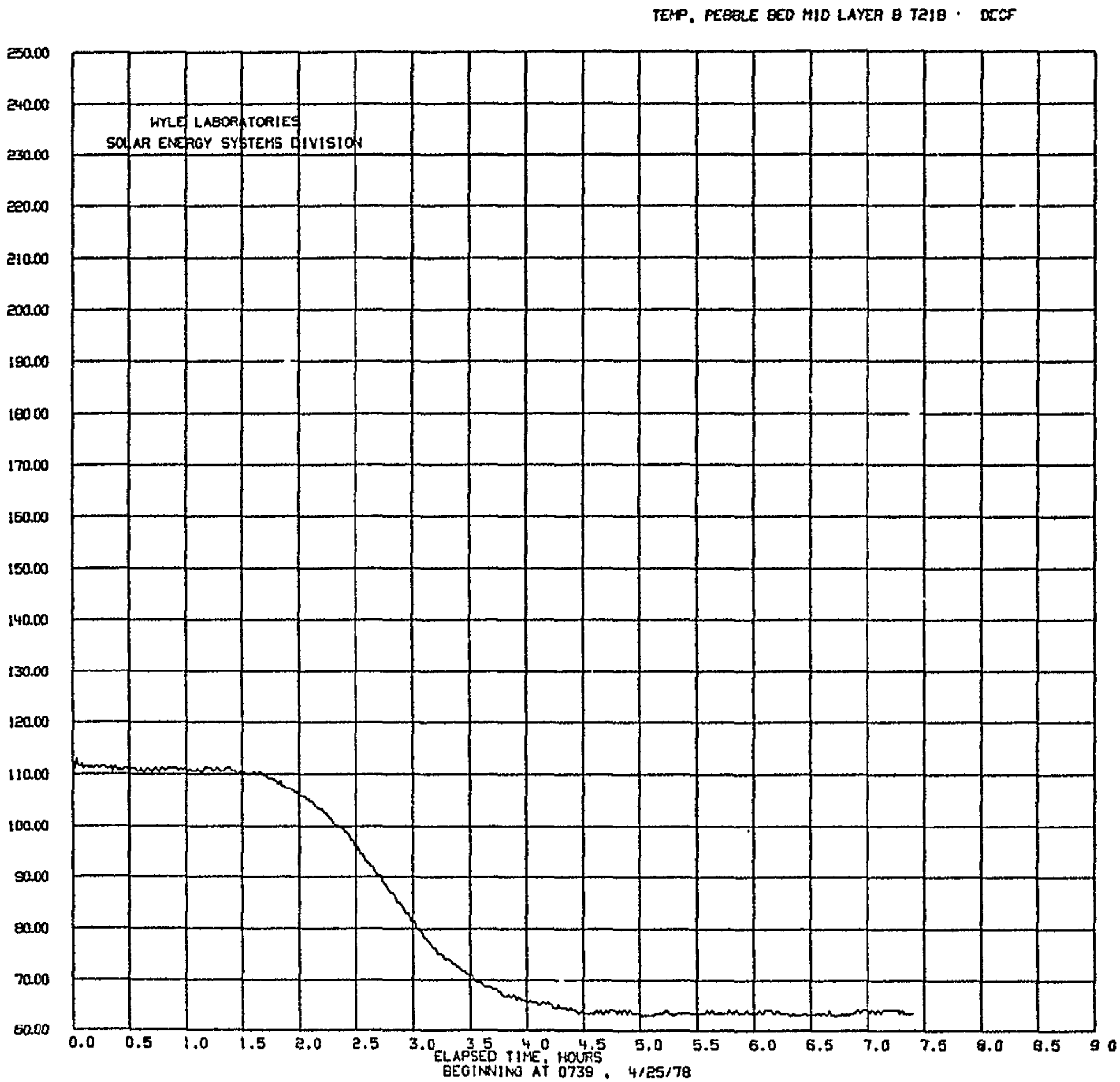

Figure 27. Temperature, Pebble Bed Middle Layer, T218, °F

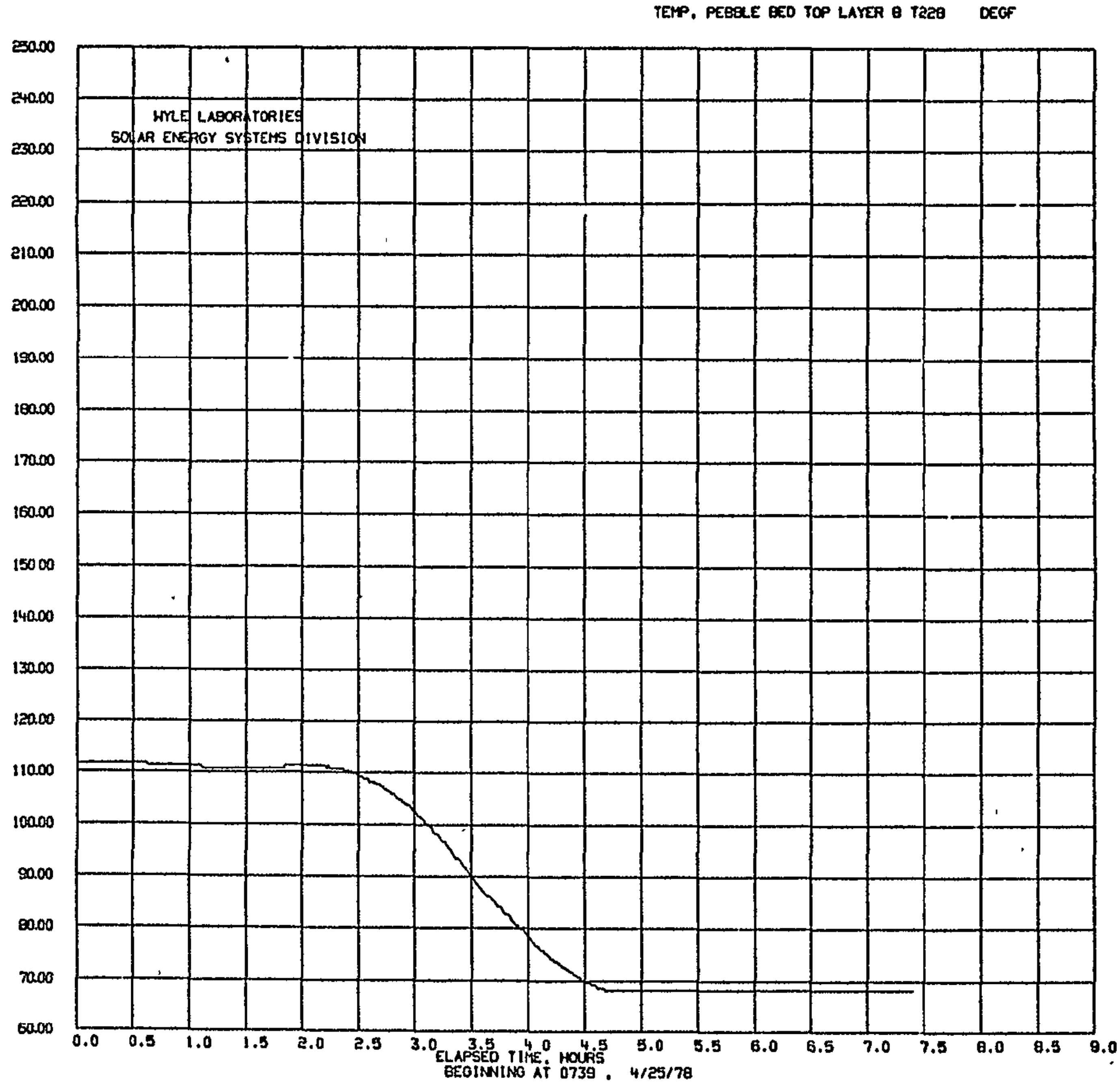

Figure 28. Temperature, Pebble Bed Top Layer 8, T228, °F

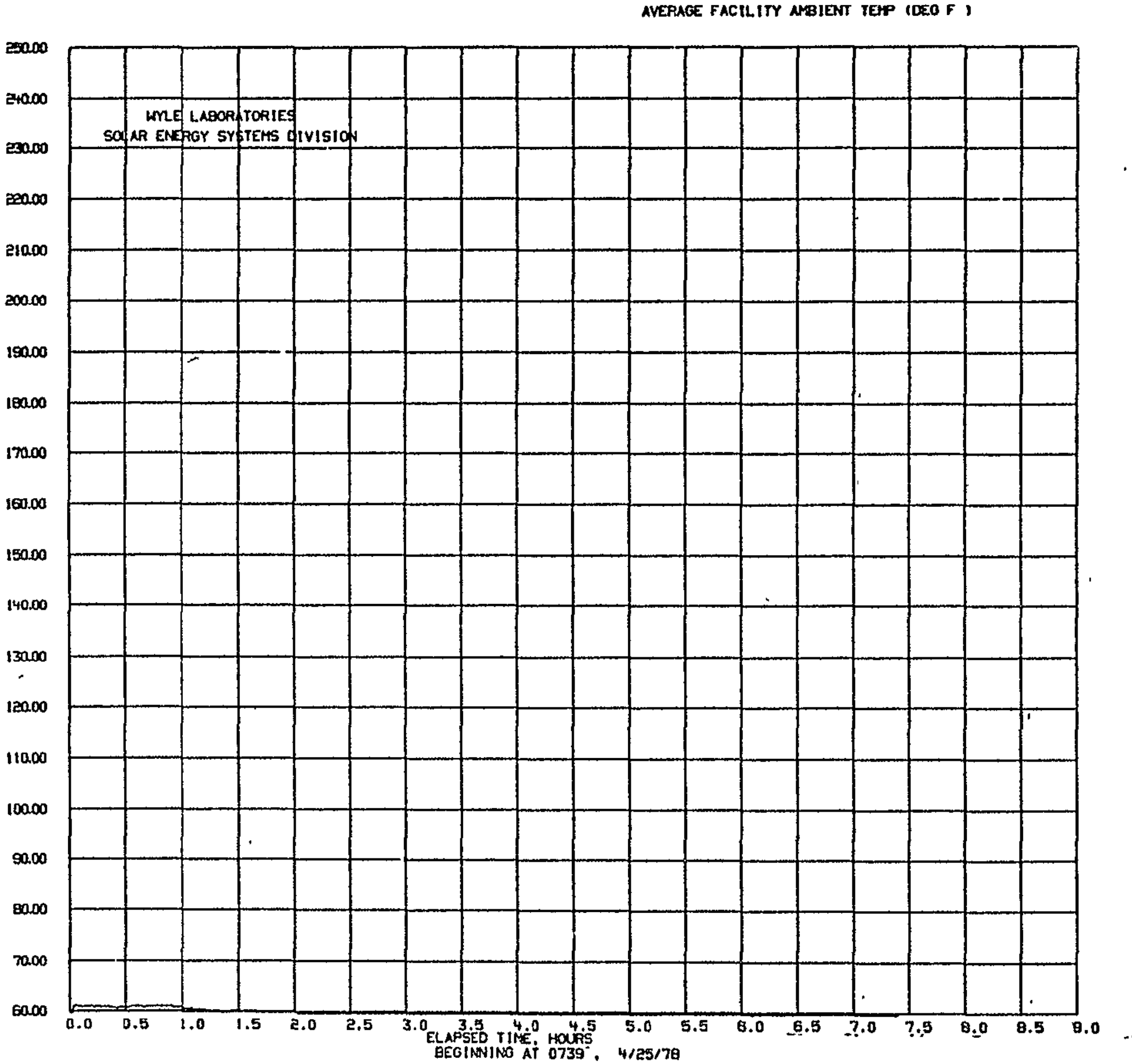

Figure 29. Average Facility Ambient Temperature, °F

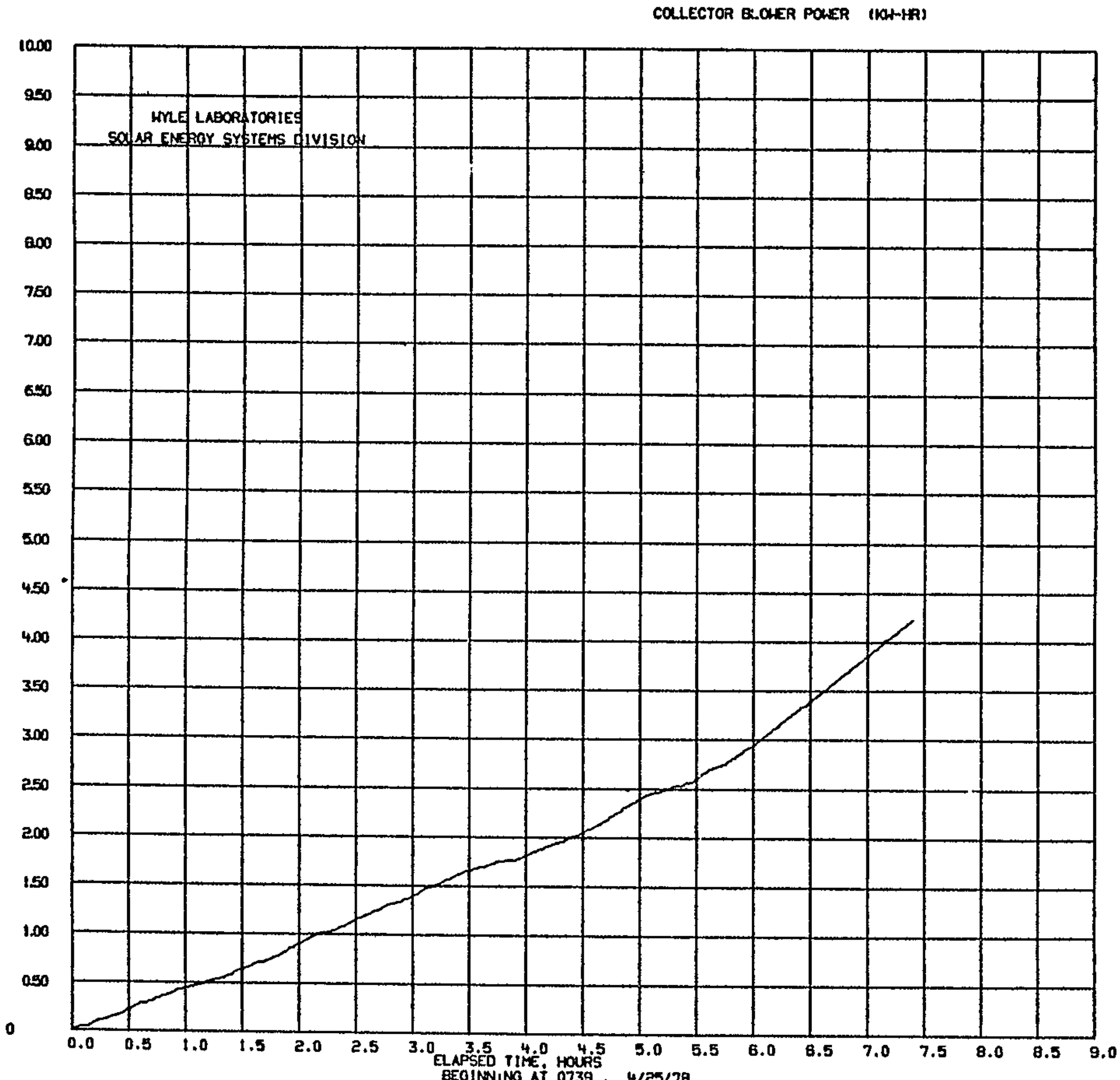

Figure 30. Collector Blower Power (Kw/Hr)

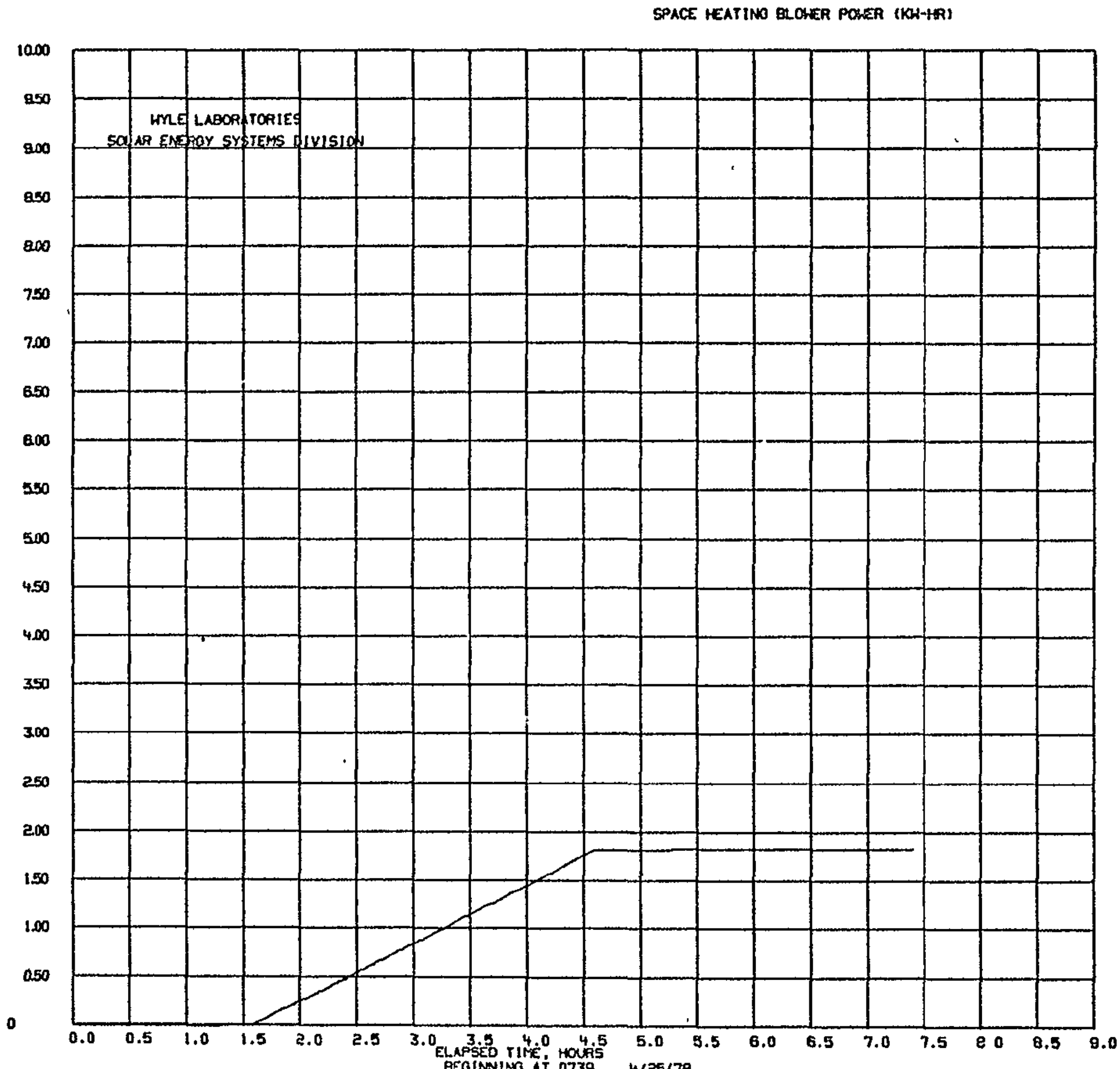

Figure 31. Space Heating Blower Power (Kw/Hr)

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OF POOR QUALITY

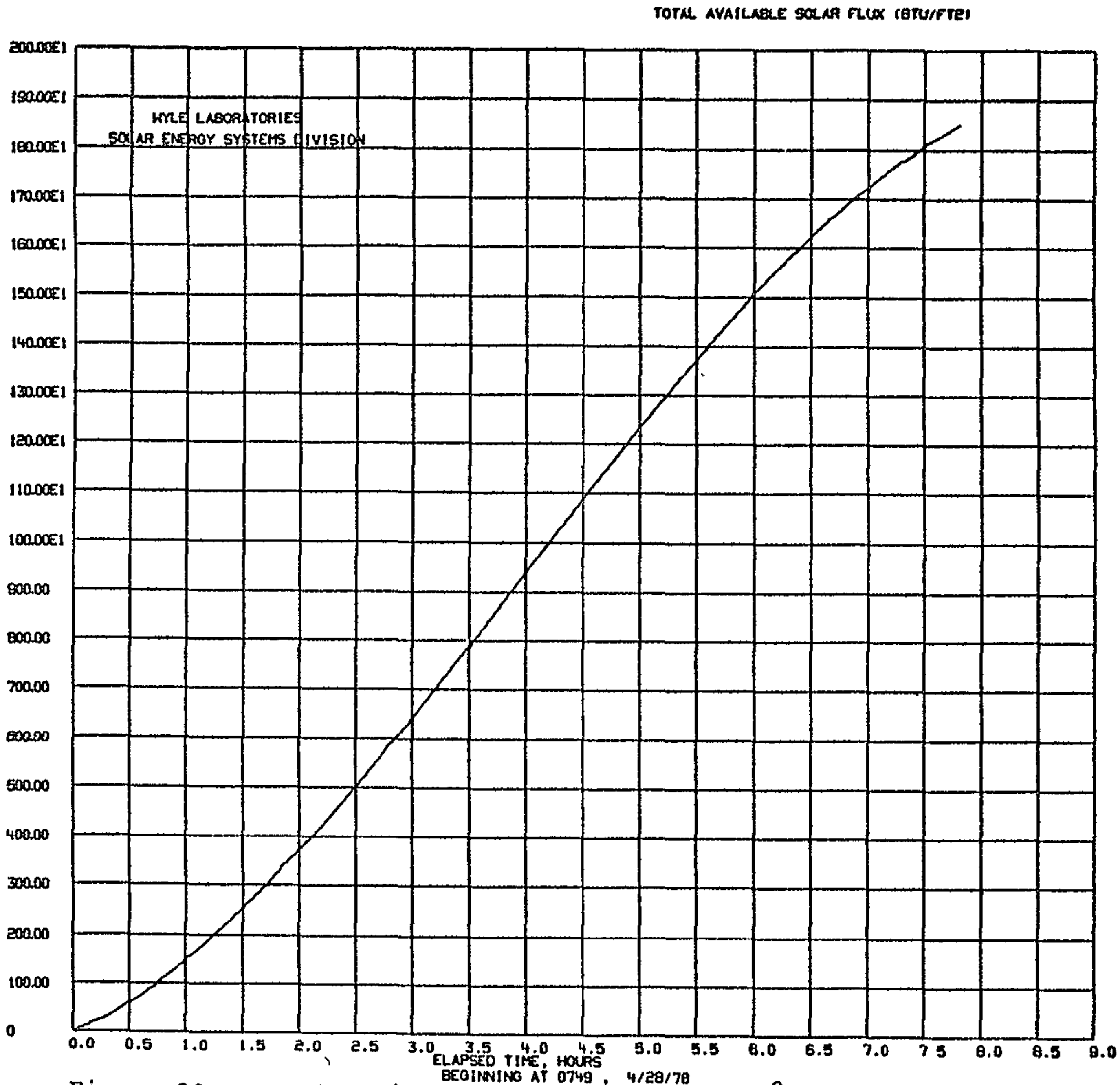

Figure 32. Total Available Solar Flux (BTU/Ft^2)

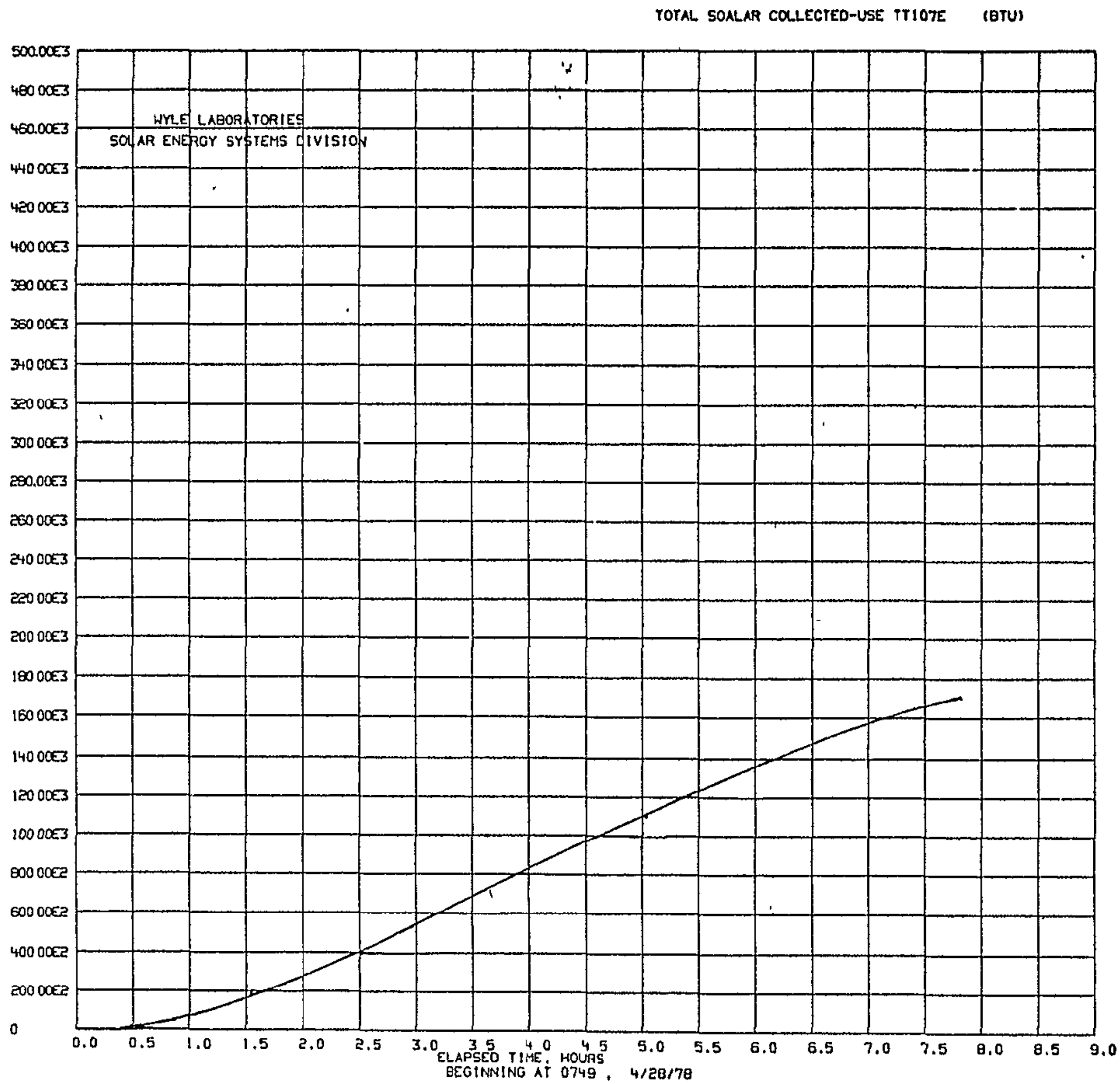

Figure 33. Total Solar Collected-Use, TT107E (BTU)

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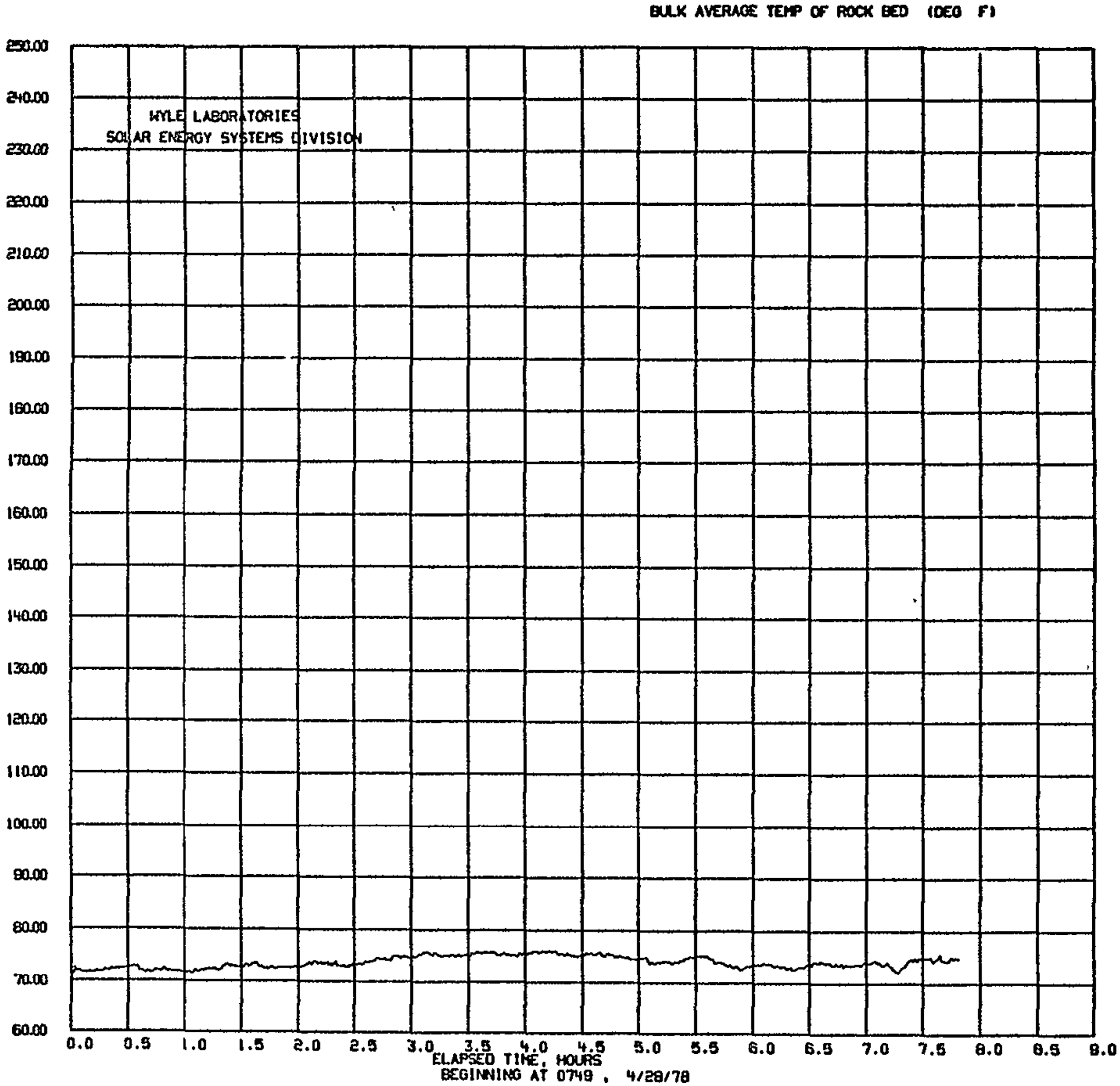


Figure 34. Bulk Average Temperature of Rock Bed, °F

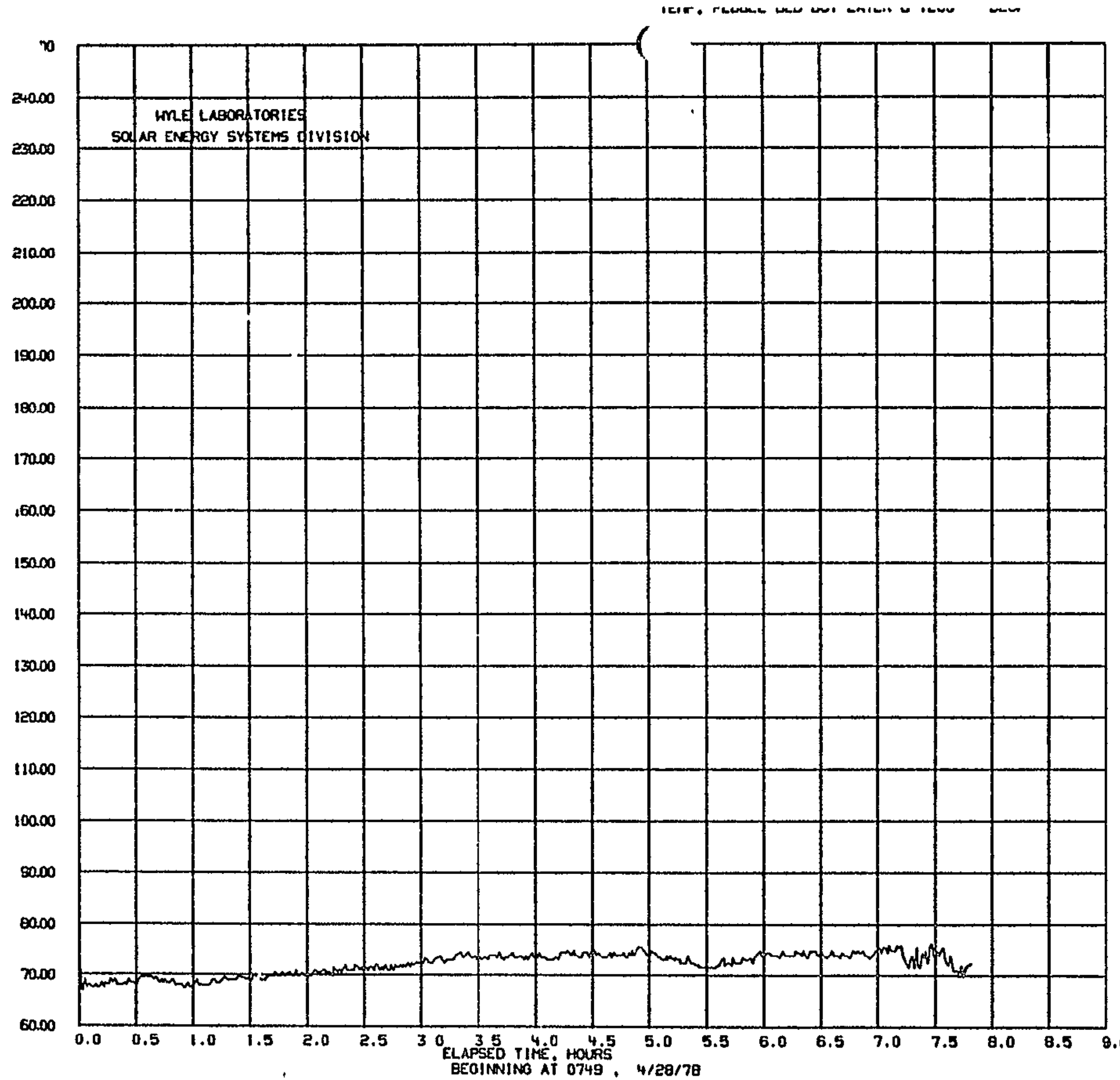


Figure 35. Temperature, Pebble Bed Bottom Layer 8, T206, °F

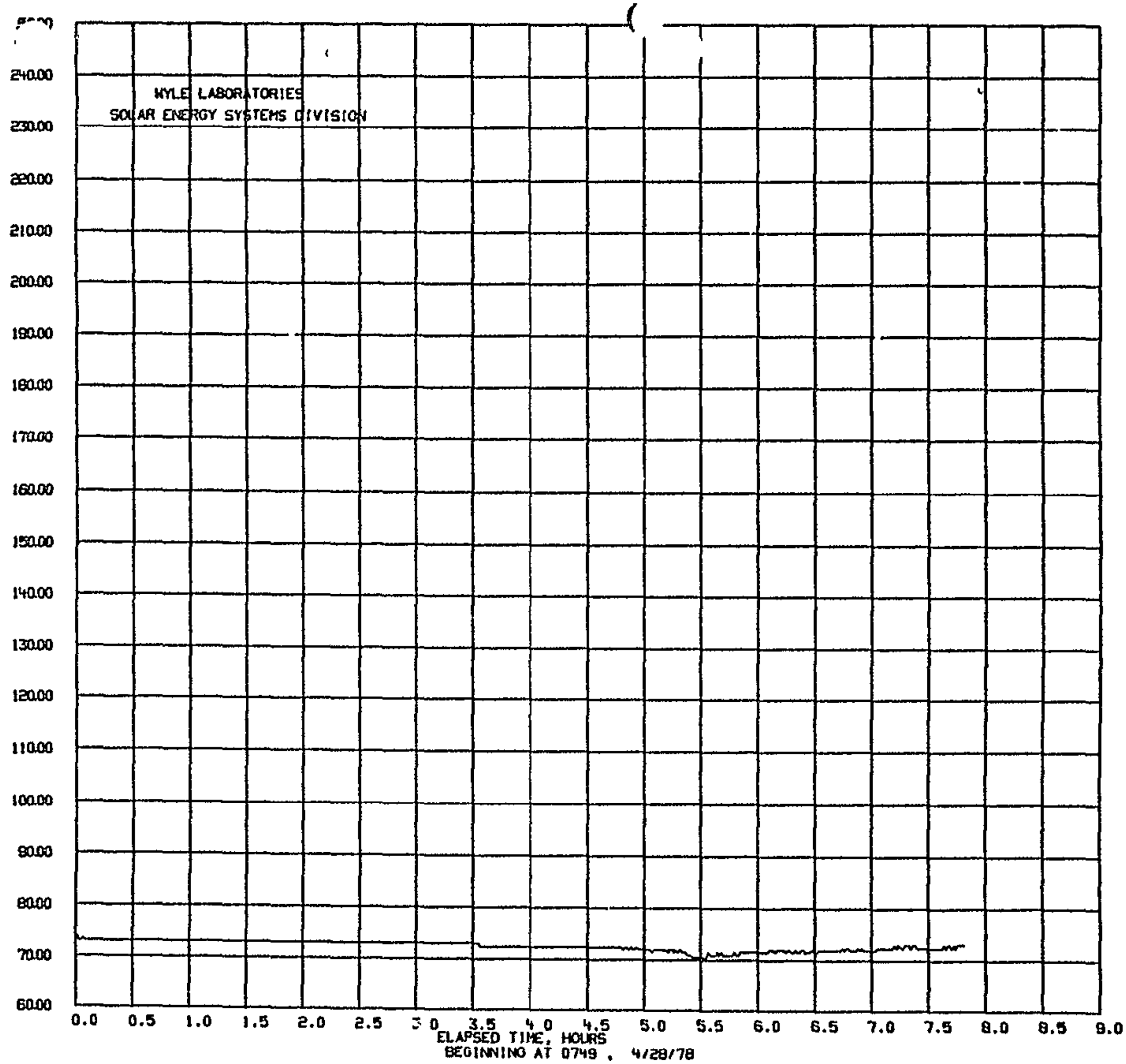


Figure 36. Temperature, Pebble Bed Middle Layer 8, T218, °F

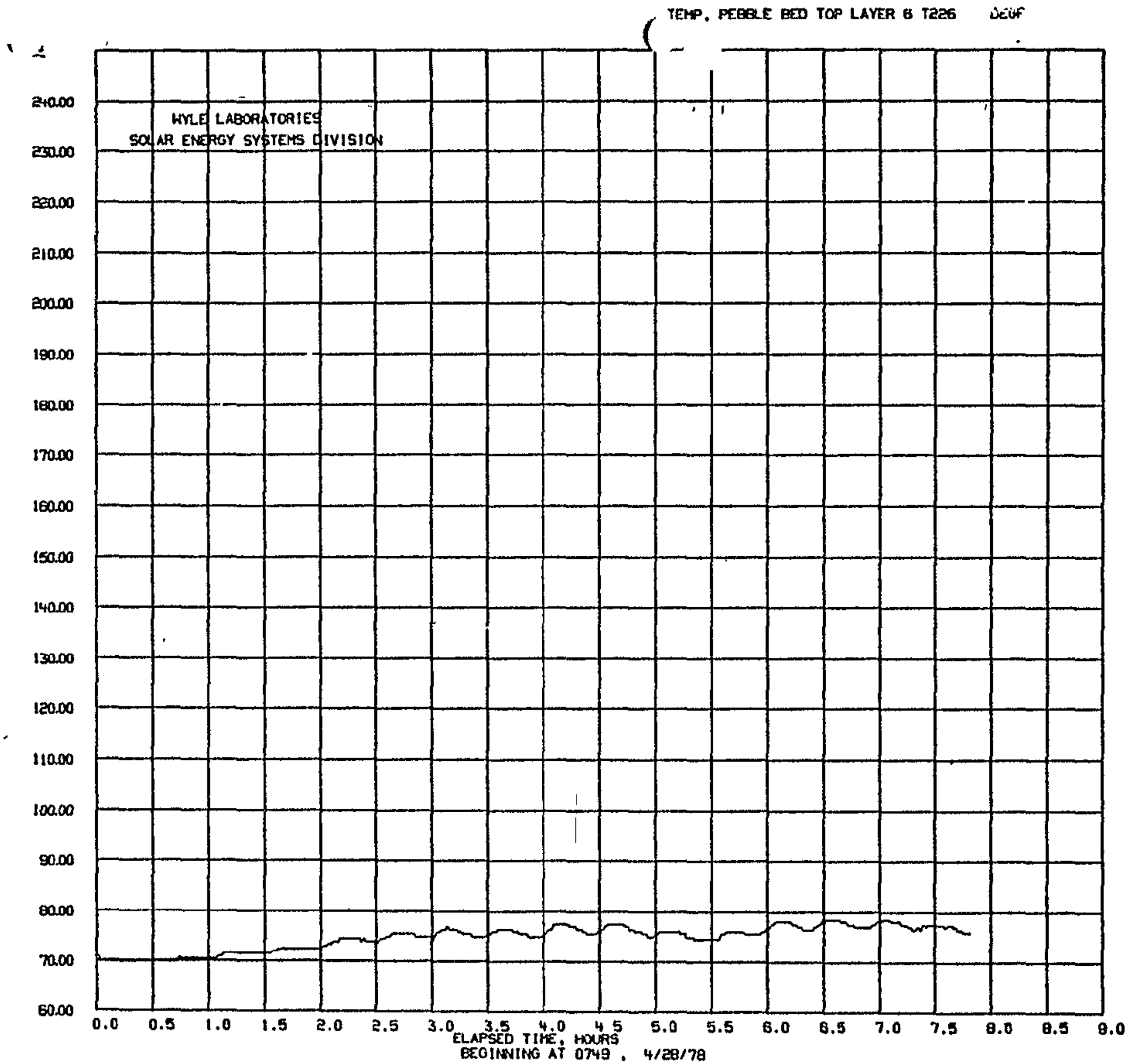


Figure 37. Temperature, Pebble Bed Top Layer 8, T226, °F

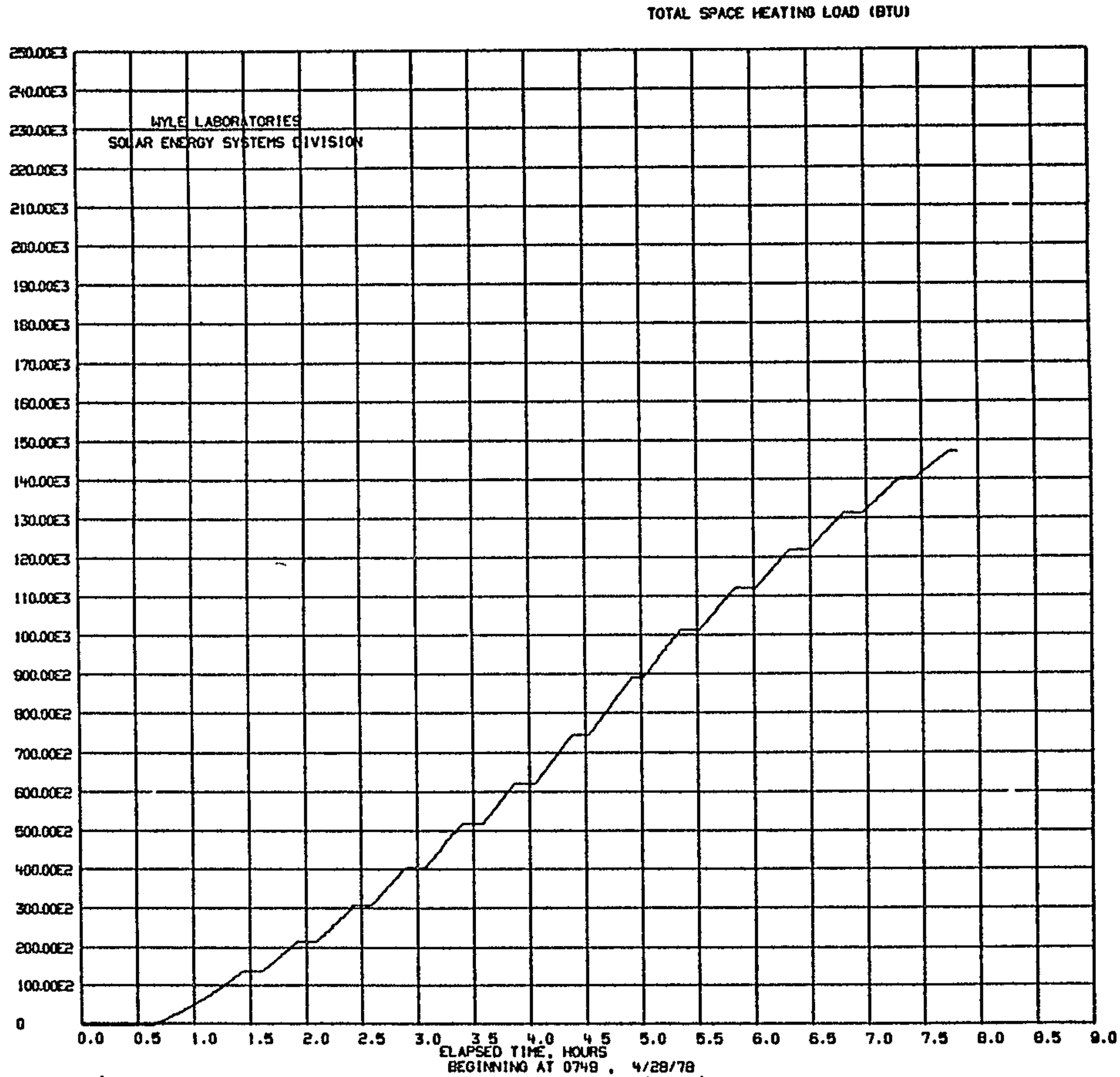


Figure 38. Total Space Heating Load (BTU)

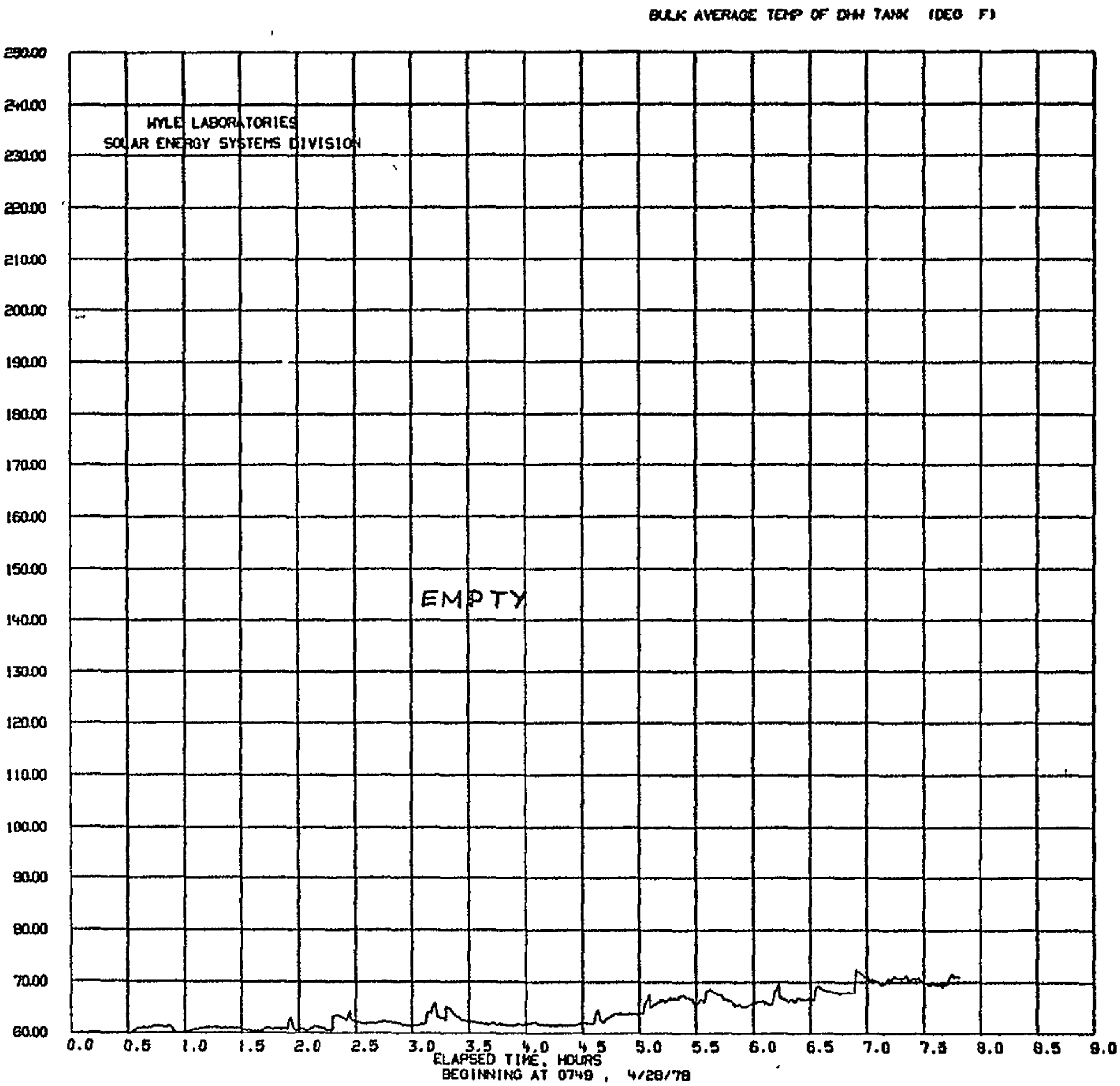


Figure 39. Bulk Average Temperature of DHW Tank, °F

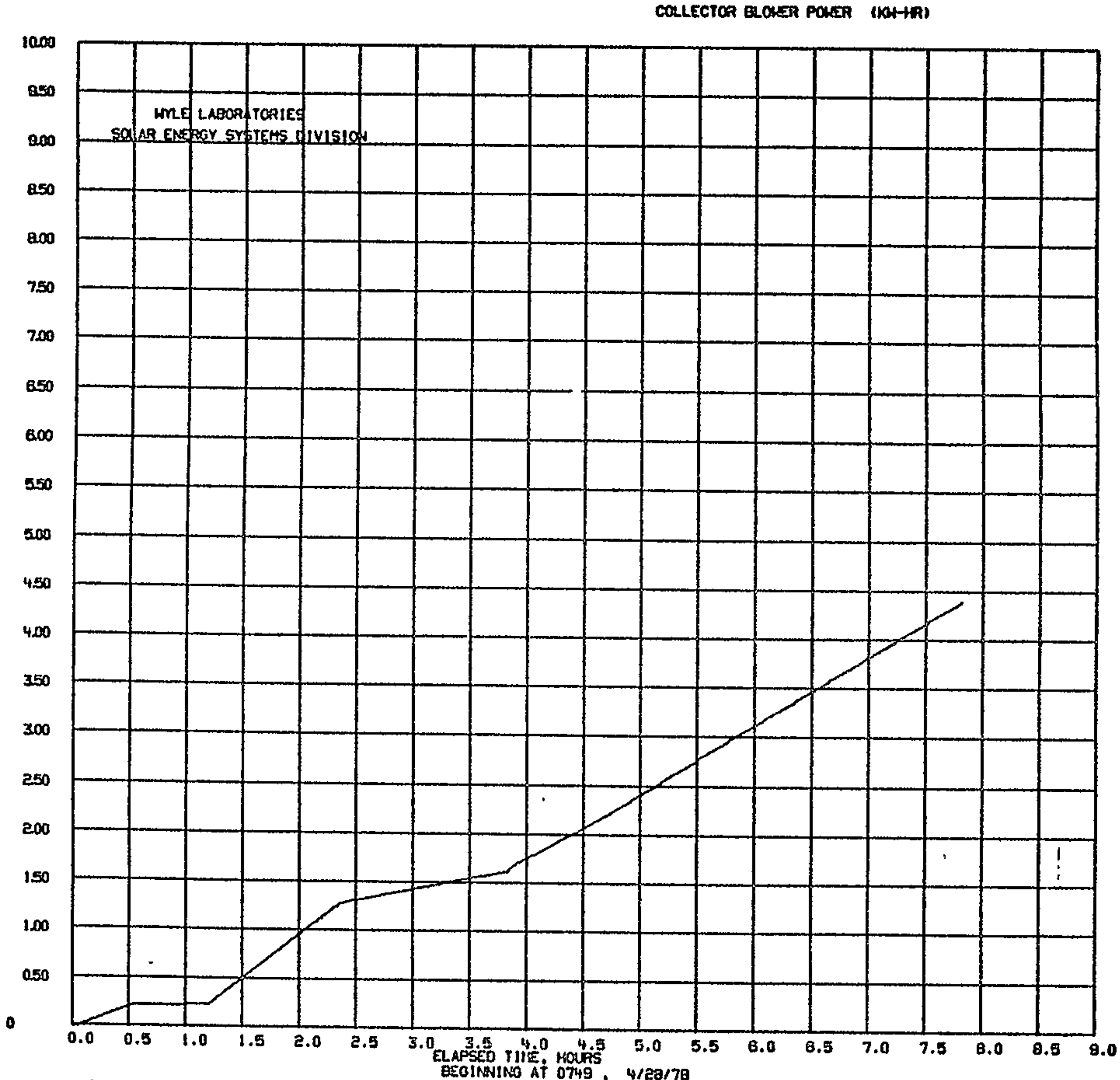


Figure 40. Collector Blower Power (Kw/Hr)

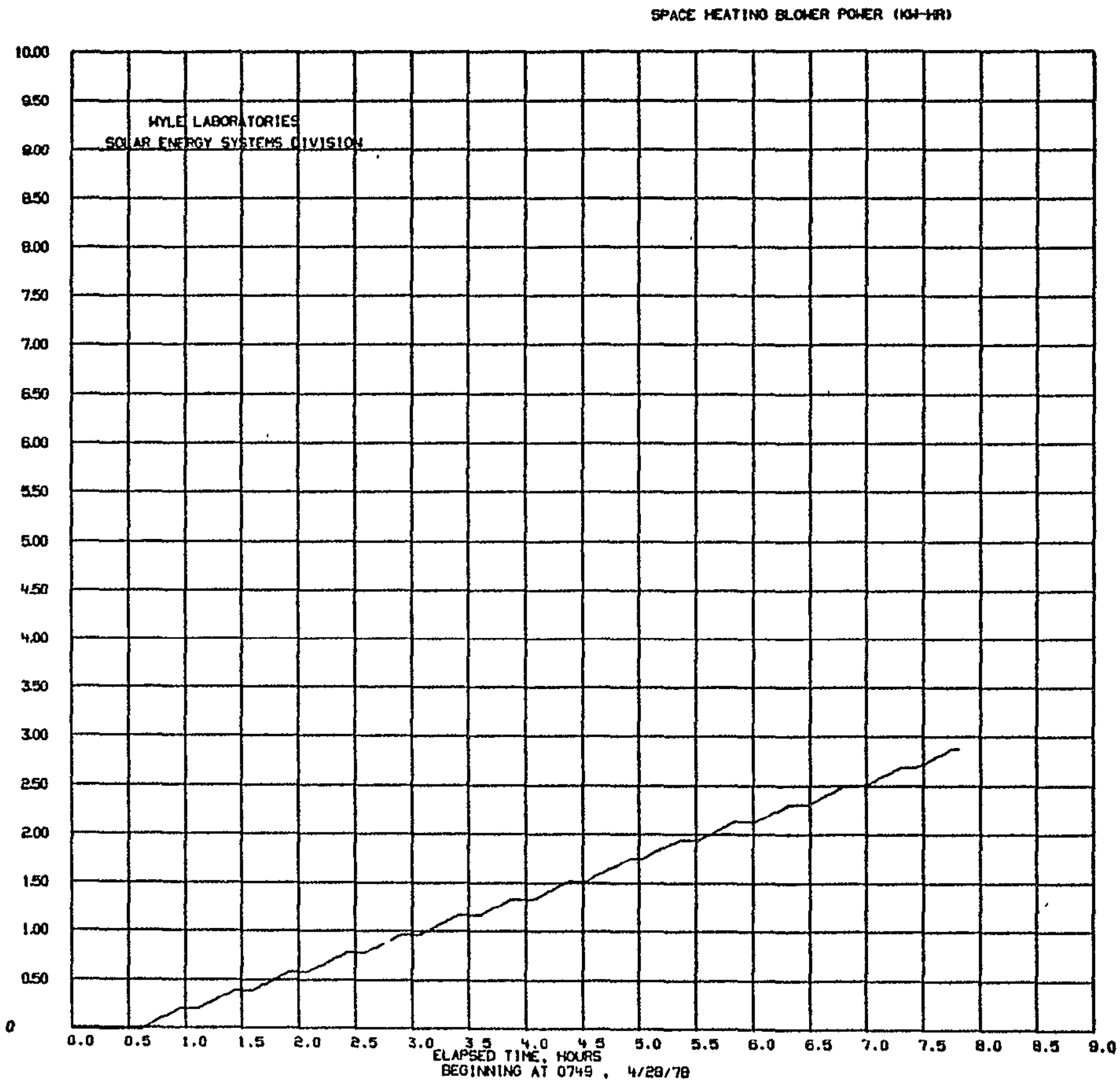


Figure 41. Space Heating Blower Power, Kw/Hr

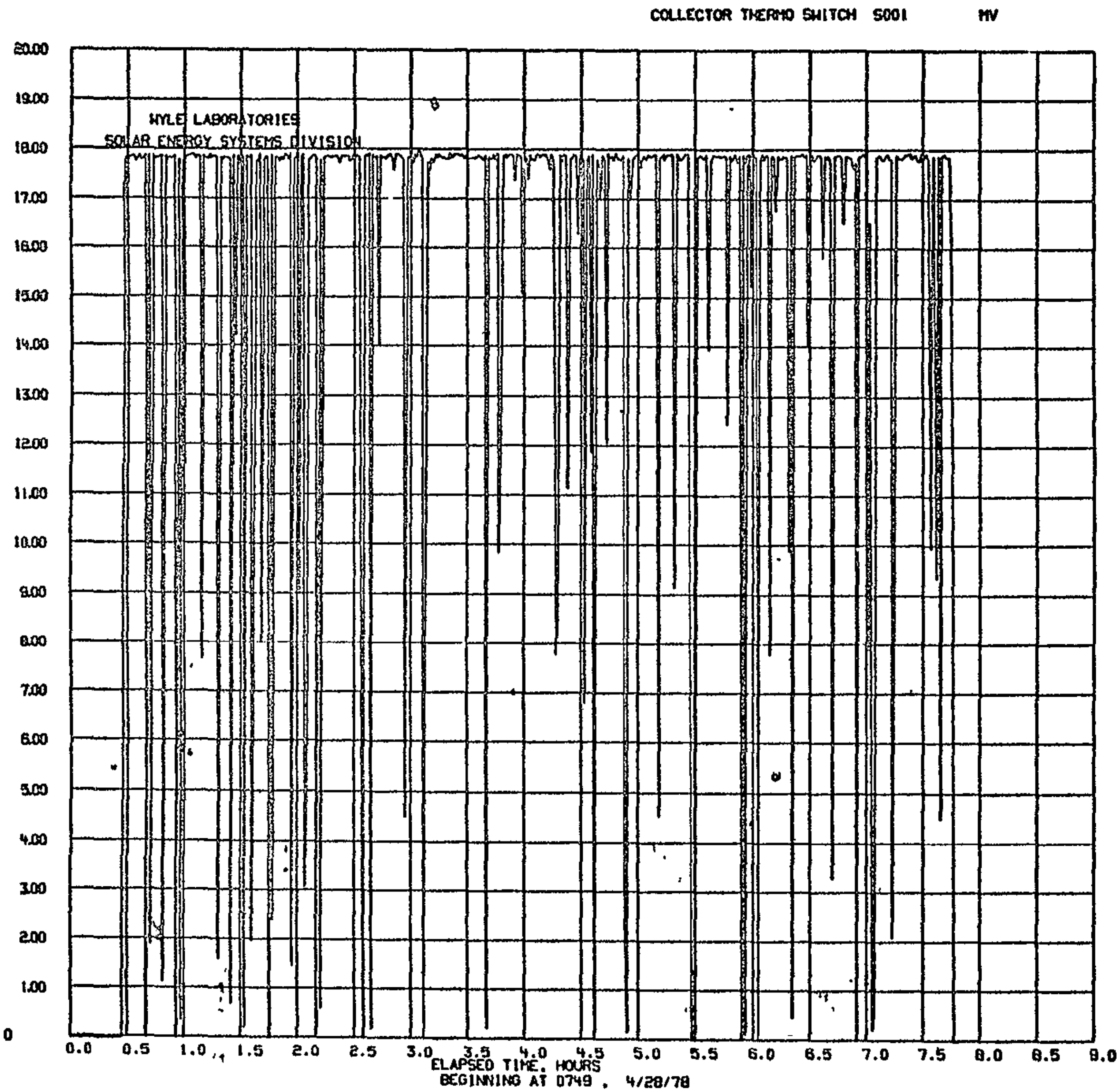


Figure 42. Collector Thermoswitch, S001, Mv

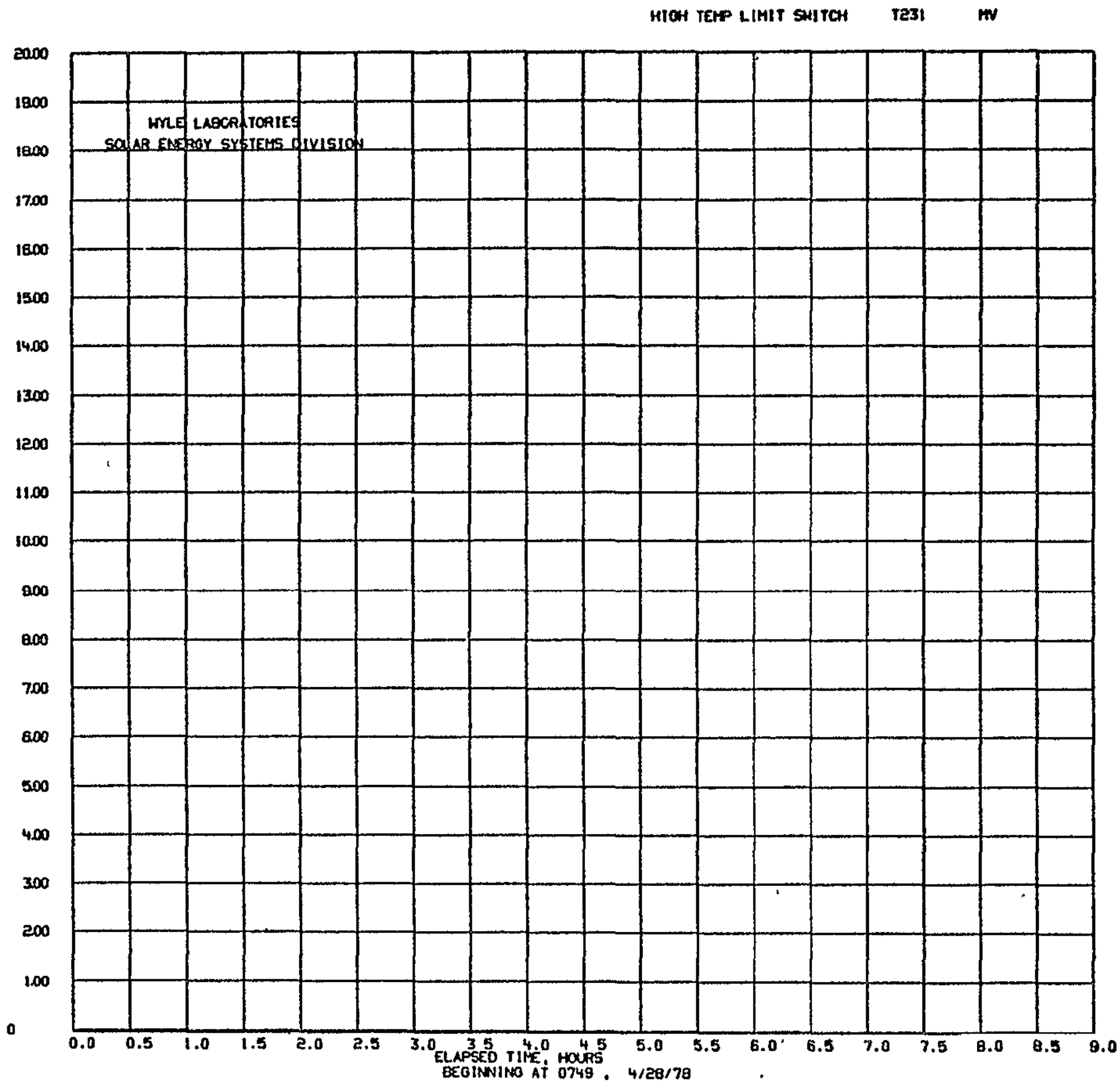


Figure 43. High Temperature Limit Switch, T231, Mv.

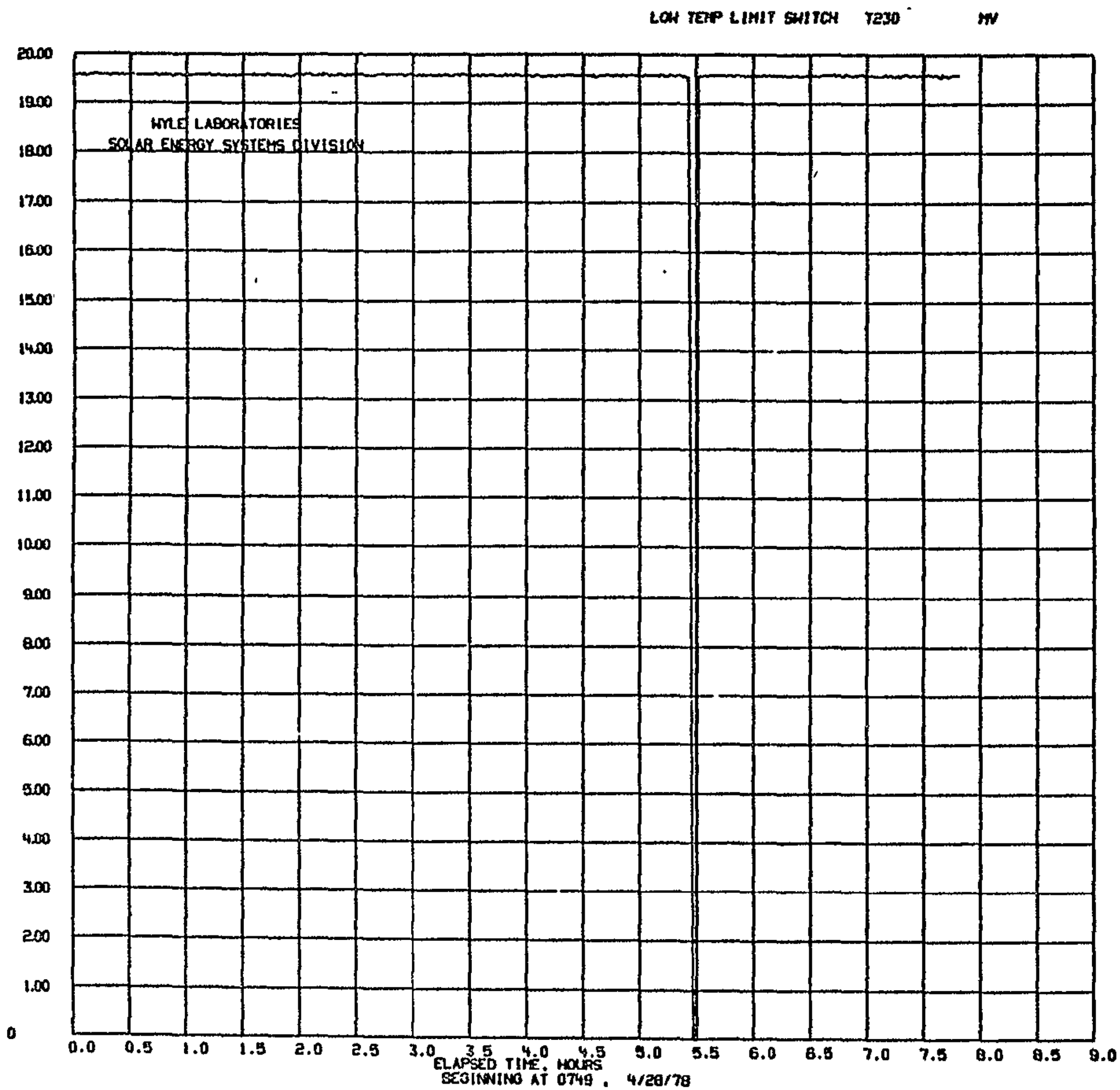
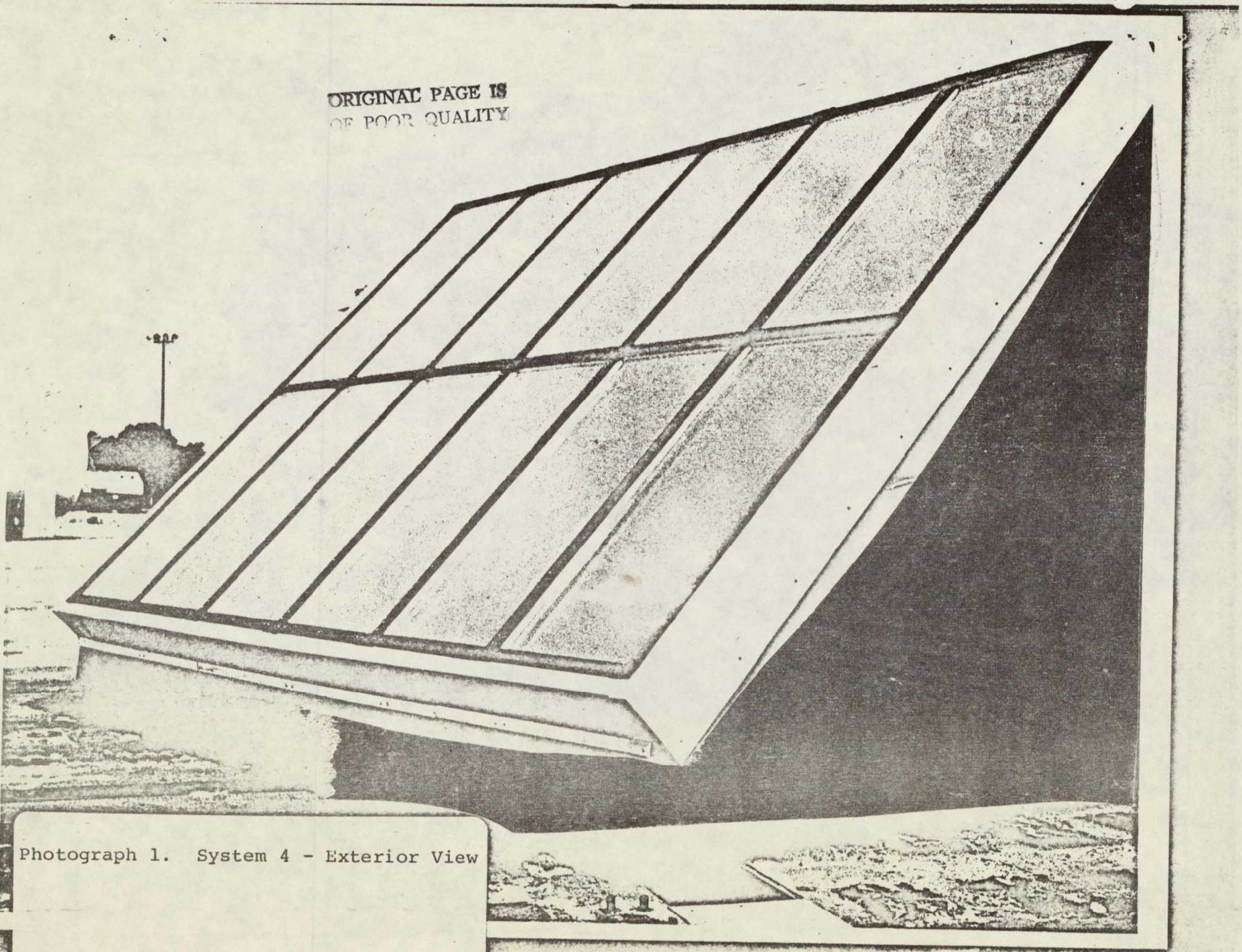
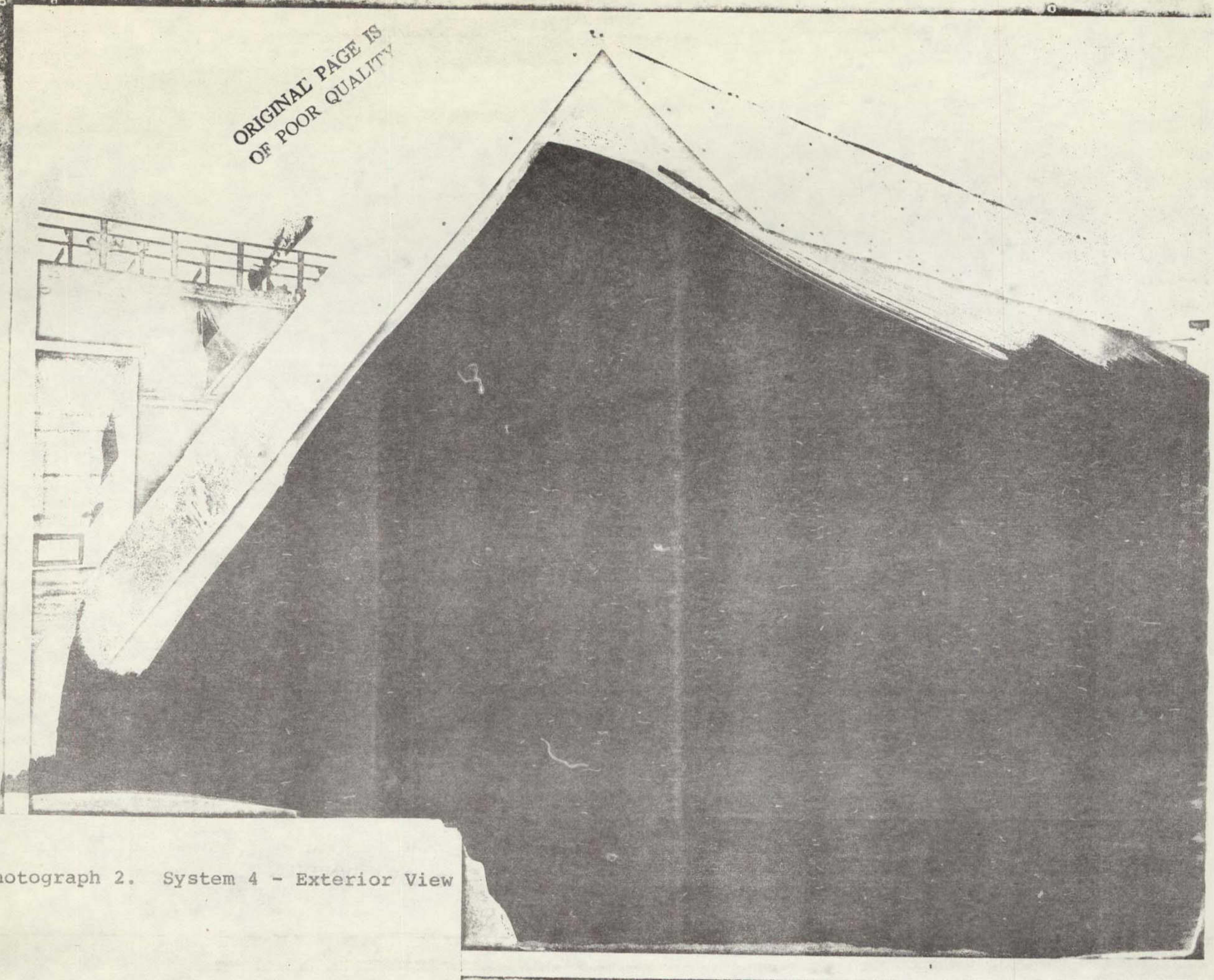


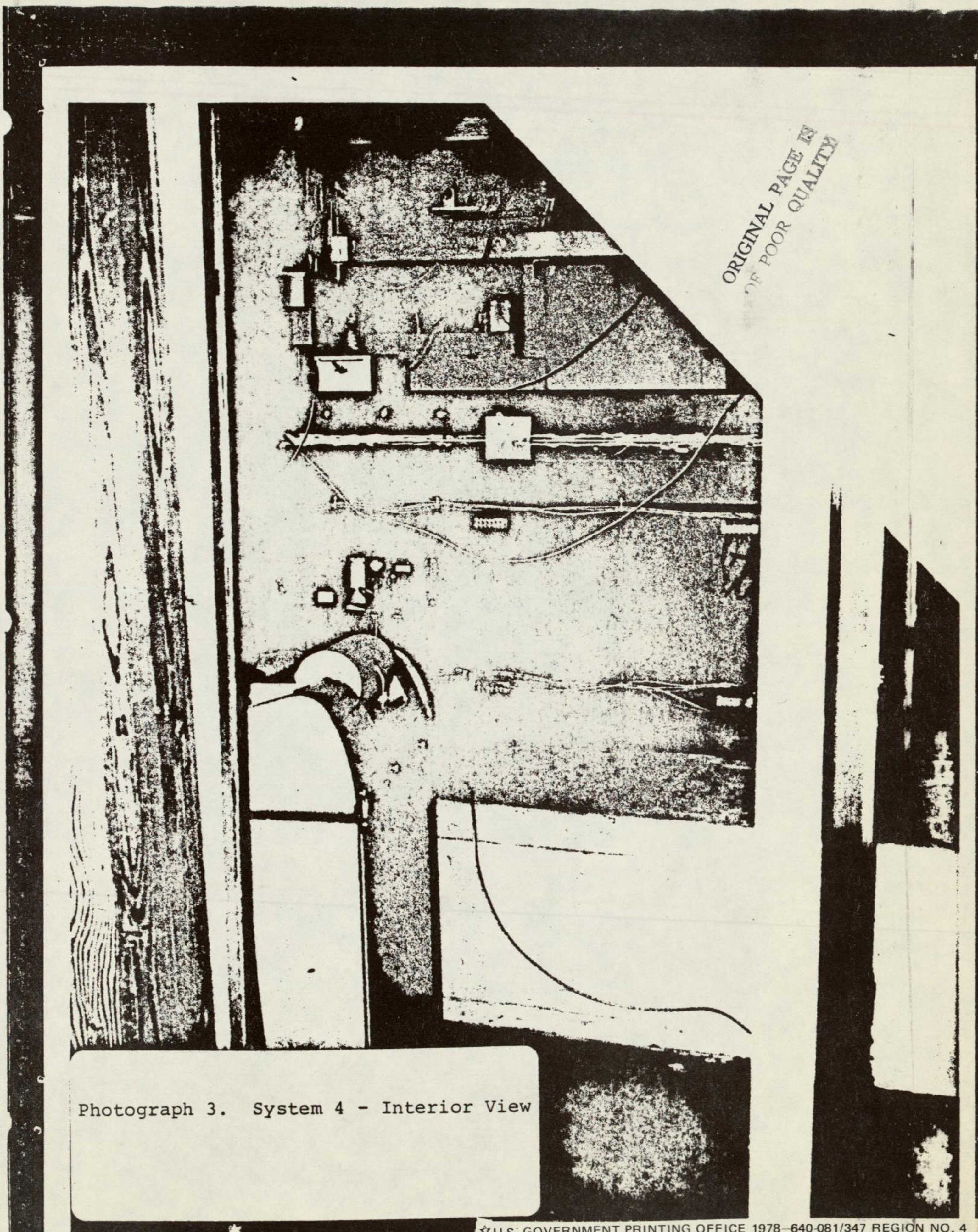
Figure 44. Low Temperature Switch, T230, Mv



Photograph 1. System 4 - Exterior View



Photograph 2. System 4 - Exterior View



Photograph 3. System 4 - Interior View

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