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DOE/NASA CONTRACTOR REPORT

DOE/NASA CR-150758

SIMS PROTOTYPE SYSTEM 3 TEST RESULTS - ENGINEERING ANALYSIS

Prepared by

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Under Contract NAS8-32036 with

National Aeronautics and Space Administration
George C. Marshall Space Flight Center, Alabama 35812

For the U. S. Department of Energy

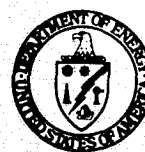
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16. ABSTRACT This document presents the results obtained during testing of a closed hydronic drain down solar system designed for space and hot water heating. Data analysis is included which documents the system performance and verifies the suitability of SIMS Prototype System 3 for field installation.			
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1.0 INTRODUCTION

The solar system tested was a space and hot water heater, assembled from currently marketed components, for solar heating a single family dwelling of approximately 1200 square feet floor area. The prototype system was designed by IBM under Contract NAS8-32036 to NASA Marshall Space Flight Center. The system utilizes: (1) Sunworks flat plate collectors to capture the solar radiation, (2) an Adamson 1,000 gallon hot water storage tank, (3) a Ford Products 65-gallon tank for domestic hot water and (4) Grundfos pumps to transfer solar energy on command from the (5) Solar Control Corporation controllers. The components are configured into the collector, storage, energy transport and control subsystems which make up the System 3 configuration. Section 4.0 describes subsystem operation and presents summarized test results. An illustration of System 3 is shown in Figure 1-1. All testing and data collection, to support this evaluation, were performed by the Solar Energy Systems Division of Wyle Laboratories, within the MSFC Solar Heating and Cooling Test Facility.

The major test objectives were:

- To verify that individual marketable subsystems performed to design requirements within a solar environment.
- To verify design concepts and to insure that the system performed to specification.
- To provide a performance data base for future comparison with the performance reported by the National Solar Data Network after the tested system is installed in the field.

Test data analysis performed by IBM evaluates the system performance and document the suitability of SIMS Prototype System 3 hardware for field installation. The design percent solar contribution and a similar prediction, based on measured test performance, is used as the overall comparison parameter.

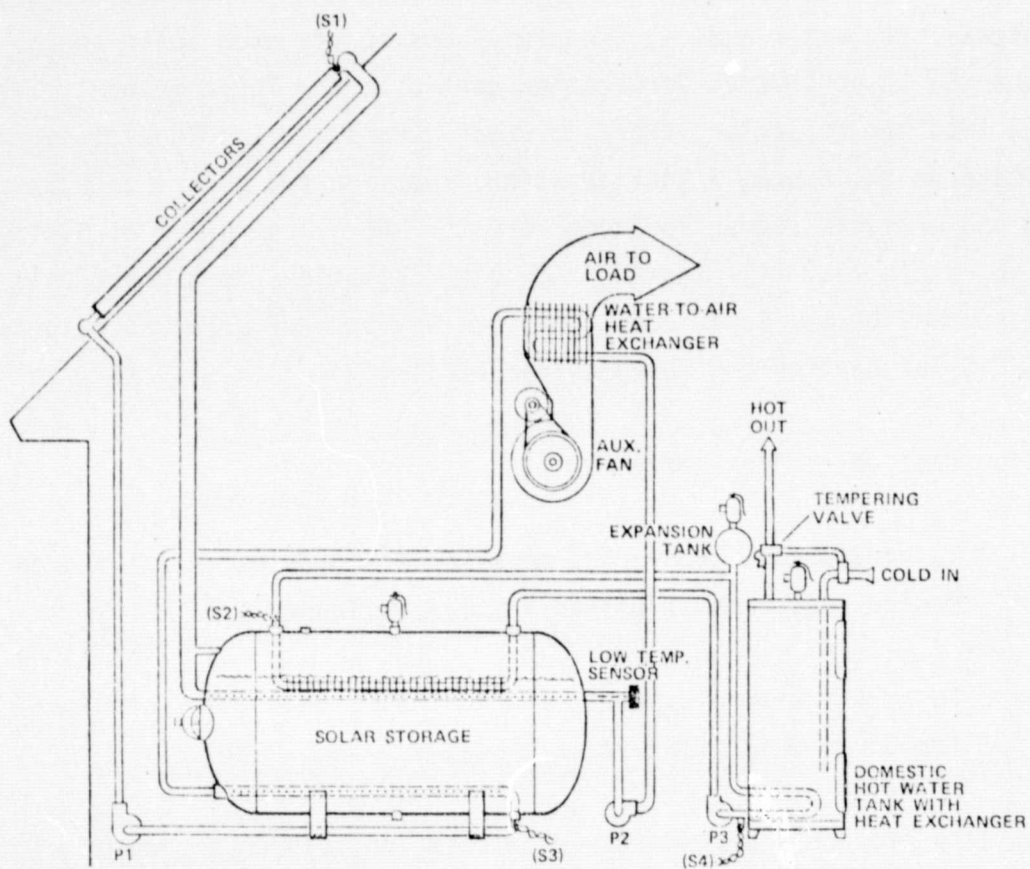


Figure 1-1 SYSTEM 3 DIAGRAM

2.0 SIGNIFICANT RESULTS

The performance testing of SIMS Prototype System 3, in the MSFC Solar Heating and Cooling Test Facility, resulted in the following significant findings:

- SIMS Prototype System 3, based on test data projected to Huntsville, Alabama weather data, will provide 53% of the 75.5×10^6 BTU/Yr design heating load.
- The normal electrical energy required to drive the solar portion of the system is approximately 2.5 percent of the collected energy.
- The flow distribution manifolds are effective in producing thermal stratification in solar storage. This stratification results in improved collector efficiency if space heat is not energized. If space heat is energized, space heating is enhanced; usually at the expense of collection efficiency.
- A single-tank solar domestic water heater was demonstrated to be a viable design option.
- SIMS Prototype System 3 was judged suitable for field installation.

3.0 TEST DESCRIPTION

Testing was conducted in two principle phases: (1) simulated energy function to determine the thermal dynamics of main storage and (2) normal operation to obtain actual operating data. The simulated energy phase consisted of controlled temperature inputs and loads on the liquid thermal storage and domestic hot water subsystem. Operation during phase (2) duplicates "as installed" operation. Detailed test procedures and test data may be found in Appendix A.

4.0 SUBSYSTEM TEST

The collector, storage, energy transport and control subsystems were each tested at the subsystem level. The following paragraphs describe the test experience and performance measurements.

4.1 COLLECTOR SUBSYSTEM

The basic collector module is a 7' x 3' rectangular unit housed in an aluminum frame and weighing 114 pounds. Each module has a single 3/16" thick tempered safety glass cover for the 18.7 Ft² selective surface absorber area. The liquid system has a flow pattern designed to provide uniform flow through all tubes and to drain without water entrapment. Inlet and outlet fluid connections are 1" diameter copper pipe.

Collector performance indicators calculated from System 3 test data are plotted relative to the vendor supplied collector efficiency curve in Figure 4-1. Vendor data was from Desert Sunshine using aperture area in the efficiency equation. Array test efficiency was calculated by using 15-30 minute time integrals of the performance variables during periods of relatively constant solar insolation. The array test derived efficiency agrees closely with ASHRAE 93-77 tests from the MSFC solar simulator.

4.2 STORAGE SUBSYSTEM

The storage subsystem consists of an Adamson ASME 1000 gallon hot water storage tank and two internal distribution manifolds. The hot (top) and cold (bottom) distribution manifolds are designed to enhance stratification within storage.

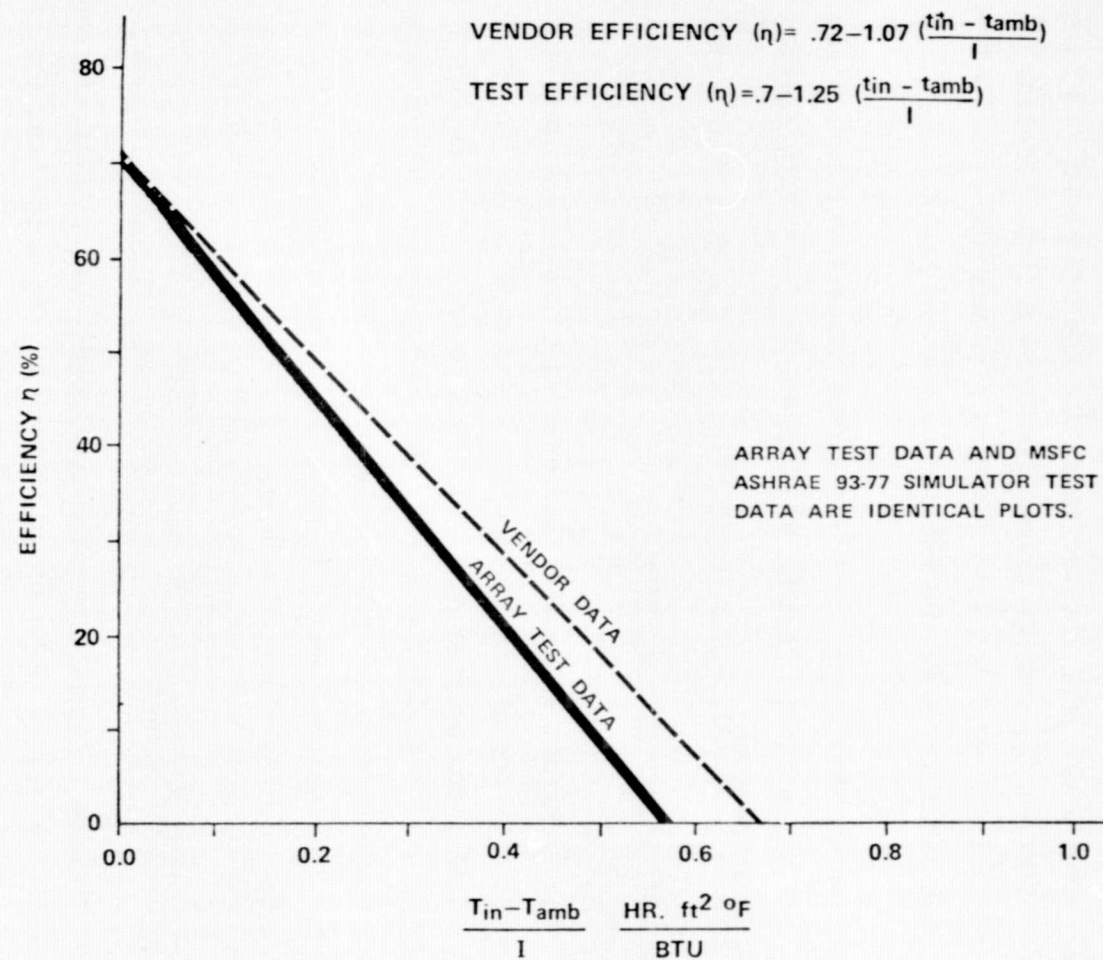


Figure 4-1 Collector Efficiency

(The finned tube heat exchanger which provides heat to DHW is installed near the hot manifold.) In operation, the tank will contain approximately 900 gallons of solar heated water with the remaining volume functioning as an expansion tank and air separator. To reduce corrosion problems, the system is air tight; therefore, the internal pressure will vary with storage temperature. Pressure relief is provided at 30 psig.

Typical temperature profiles for solar storage are shown in Figure 4-2 for several times during storage charging. Storage stratification approaching theoretical ideal resulted when charging flow was not disturbed by DHW or space heat flows (Pump P2 and P3 Off).

Interaction within storage during the simultaneous collection and delivery of energy are discussed in Section 5. Representative stratification data is contained in Appendix B.

4.3 ENERGY TRANSPORT SUBSYSTEM

The energy transport subsystem has three functional missions, with each function associated with one of the three circulating pumps. For residential hydronic solar systems, the average power expended to collect solar energy should not be greater than 1.5 percent of the collected energy. Pump energy requirements for the space heating and DHW subsystems should not exceed an additional three percent. The measured energy transport burden for System 3 varied from 1.1 to 4.5 percent of the collected energy.

Collector Heat Removal

Pump P1 transfers heat energy from the collectors to solar storage. See Figure 4-8. Grundfos Model UP 26-64F pumps lift water from the bottom of solar storage, through the collector array (where it is heated) and over the brink of the free fall return line. Solar heated water entering the free fall return line "drops" into storage.

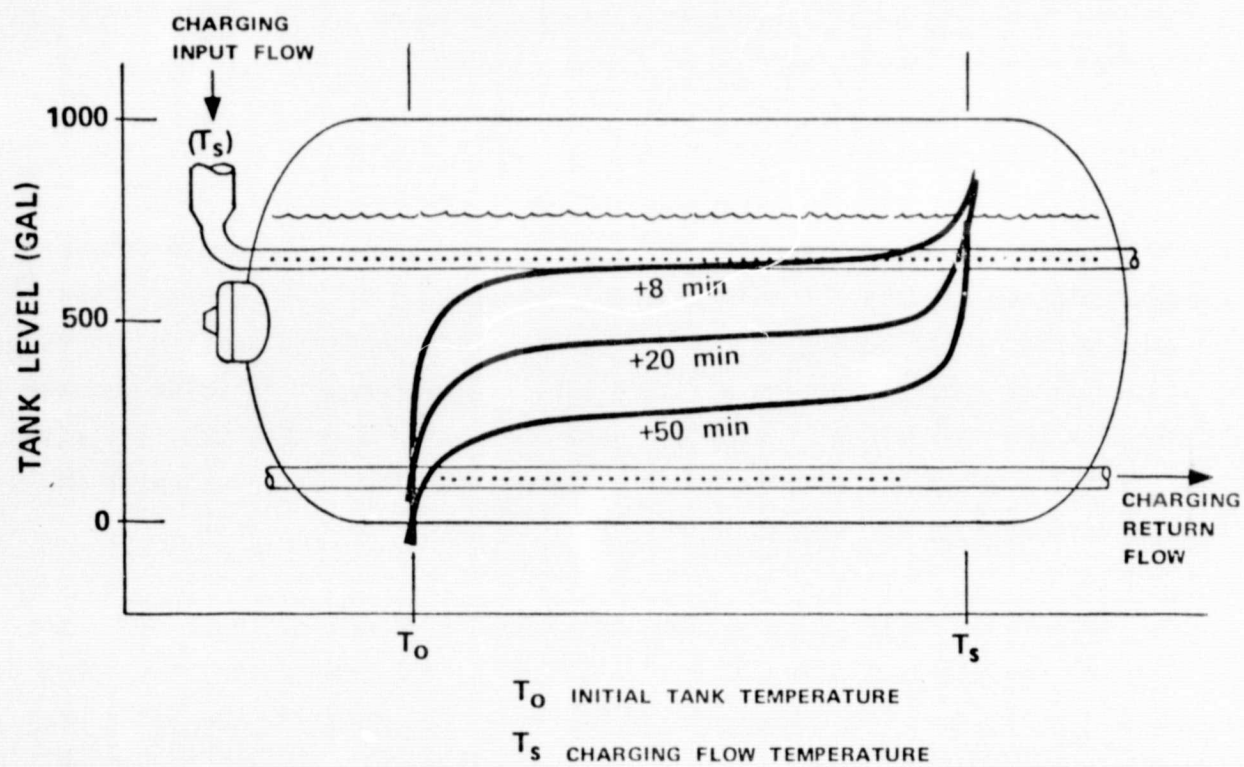


Figure 4-2 Storage Charging Stratification

The collector flow initiation transients are shown in Figure 4-3 for a day of high solar insolation. Within eight minutes after collector pump P1 is energized, the absorber temperature is cooled 55°F concurrent with establishing approximately 10°F thermal gain within the collector flow.

Space Heating

Pump P2 removes heat energy from solar storage and adds it to air being circulated from the heated space. A single Grundfos Model UP 26-64F pump delivered seven gpm design flow through the coils of an liquid-to-air heat exchanger against 14 Ft H₂O head. The heat exchanger delivers 30,000 BTU/Hr from solar storage water at 120°.

Domestic Water Heating

The DHW pump begins to transfer heat energy from solar storage to domestic hot water storage anytime the solar storage temperature is 20°F greater than the temperature at the bottom of the DHW tank. The transfer circuit consists of a water filled loop connecting a finned tube heat exchanger in solar storage to the DHW tank heat exchanger. This configuration provides double wall isolation between solar water and potable water. Energy transfer continues until the control differential is reduced to 4°F.

The performance of the single tank DHW system is shown in Figure 4-4. Note that the resistance heating element, located at the top of the tank, does not significantly heat DHW storage below its level. Contrarily the solar heat exchanger heats the entire tank in a uniform manner. The single tank thus functions similar to a dual tank. The data shows that stratification is so pronounced that less than 20% of the tank volume receives 95% of the electric element heat output (Figure 4-4). The remaining 5%, integrated over 24 hours, helps maintain recovery capacity when solar energy is not available. This is accomplished by reducing the temperature rise required when water from a lower strata move upward. Without this influence and for worse case solar conditions,

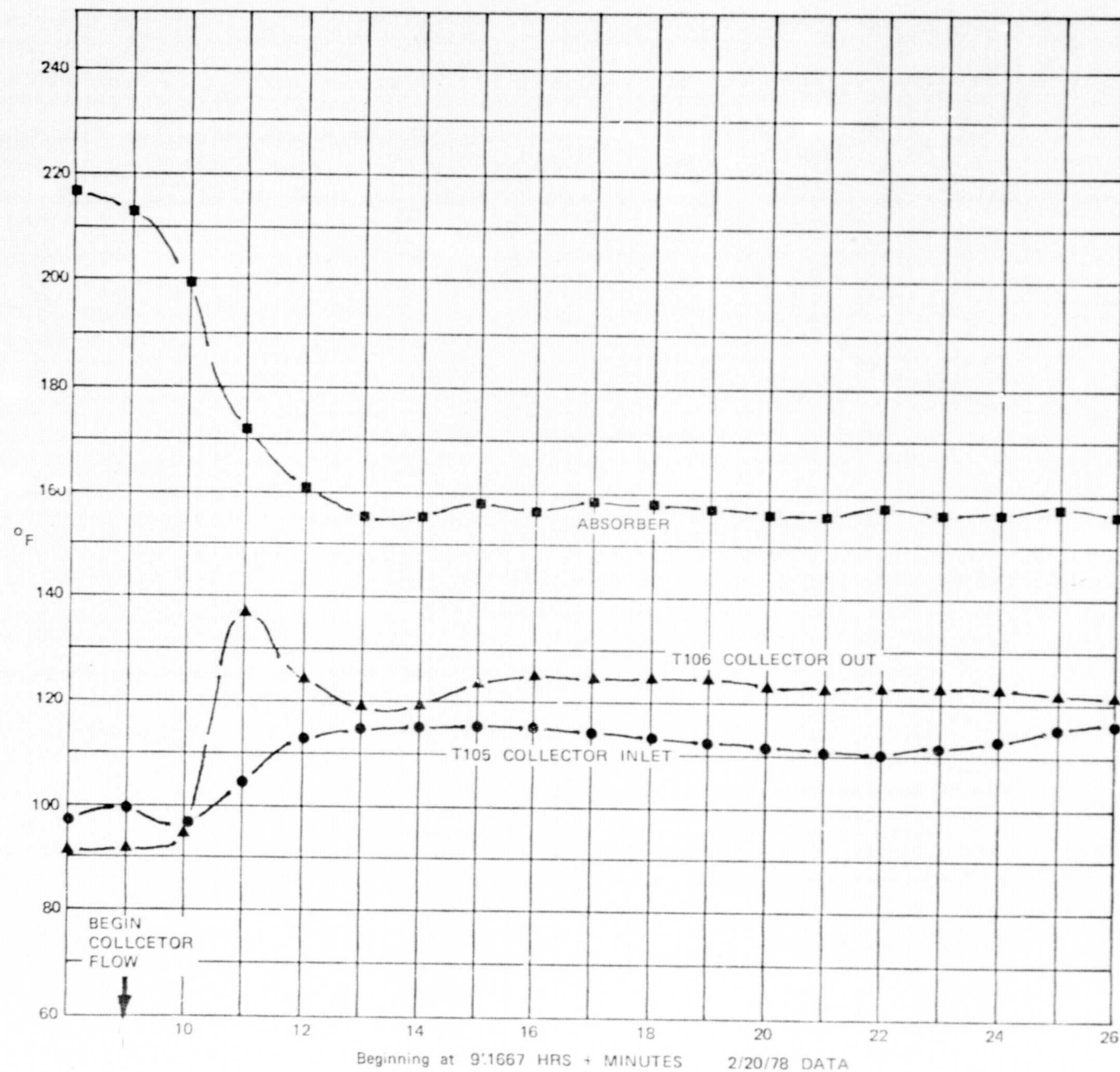


Figure 4-3 Collector Start Transient

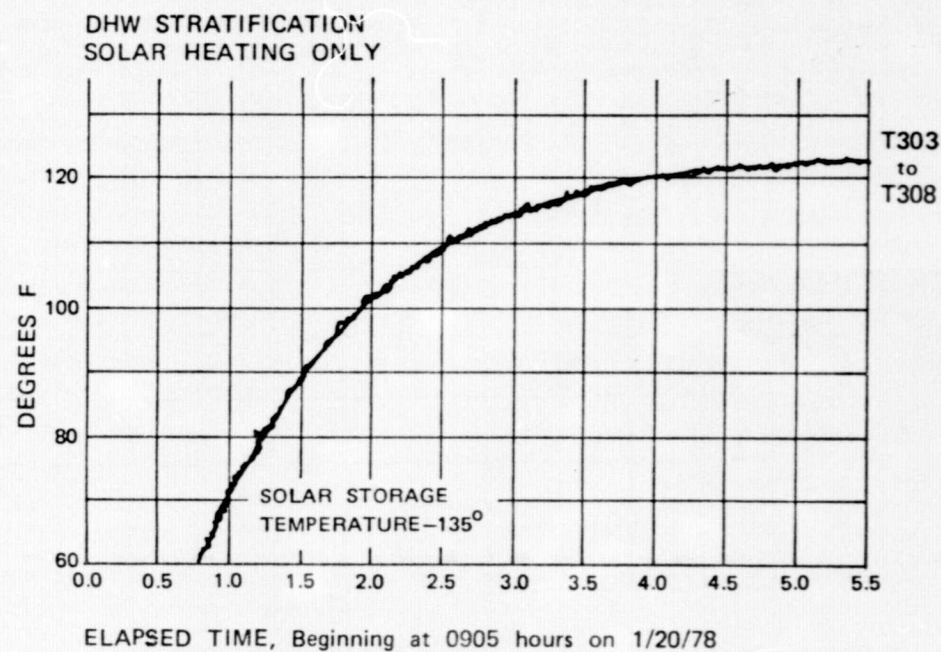
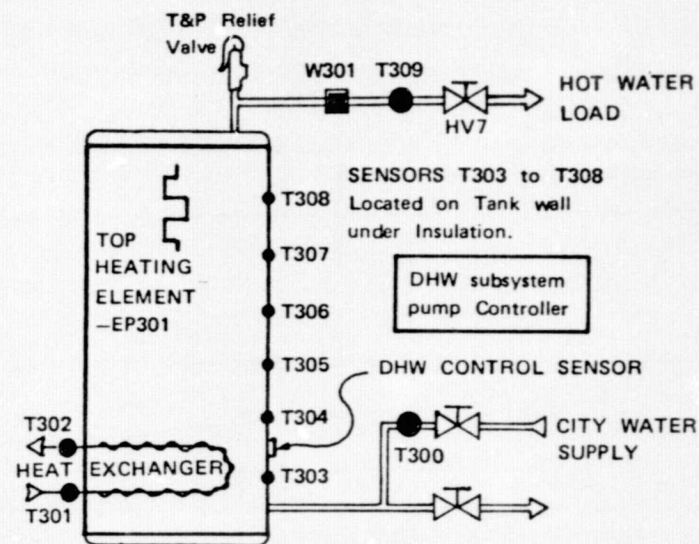
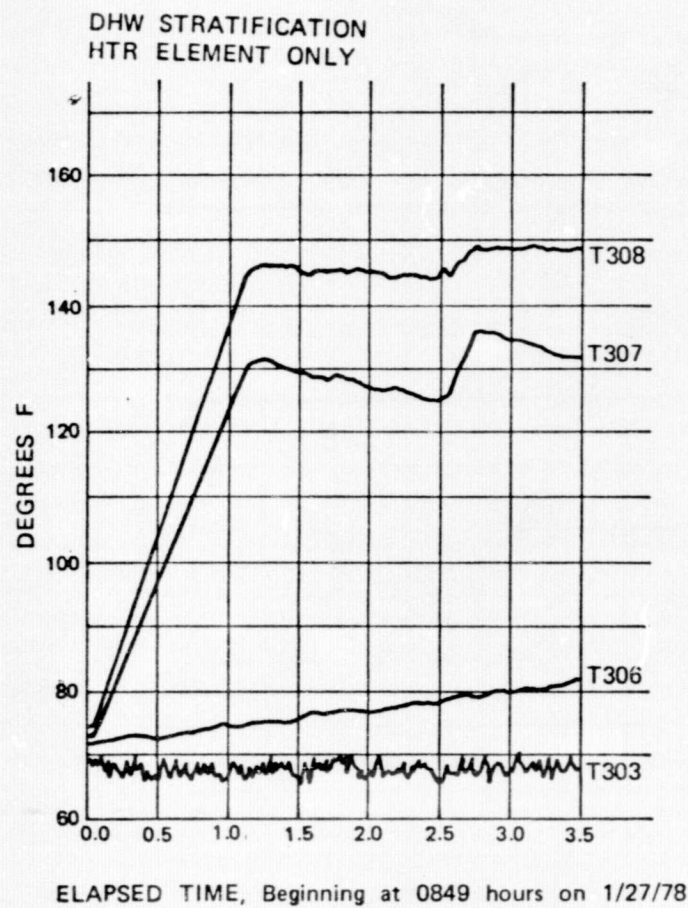


Figure 4-4 Single Tank DHW

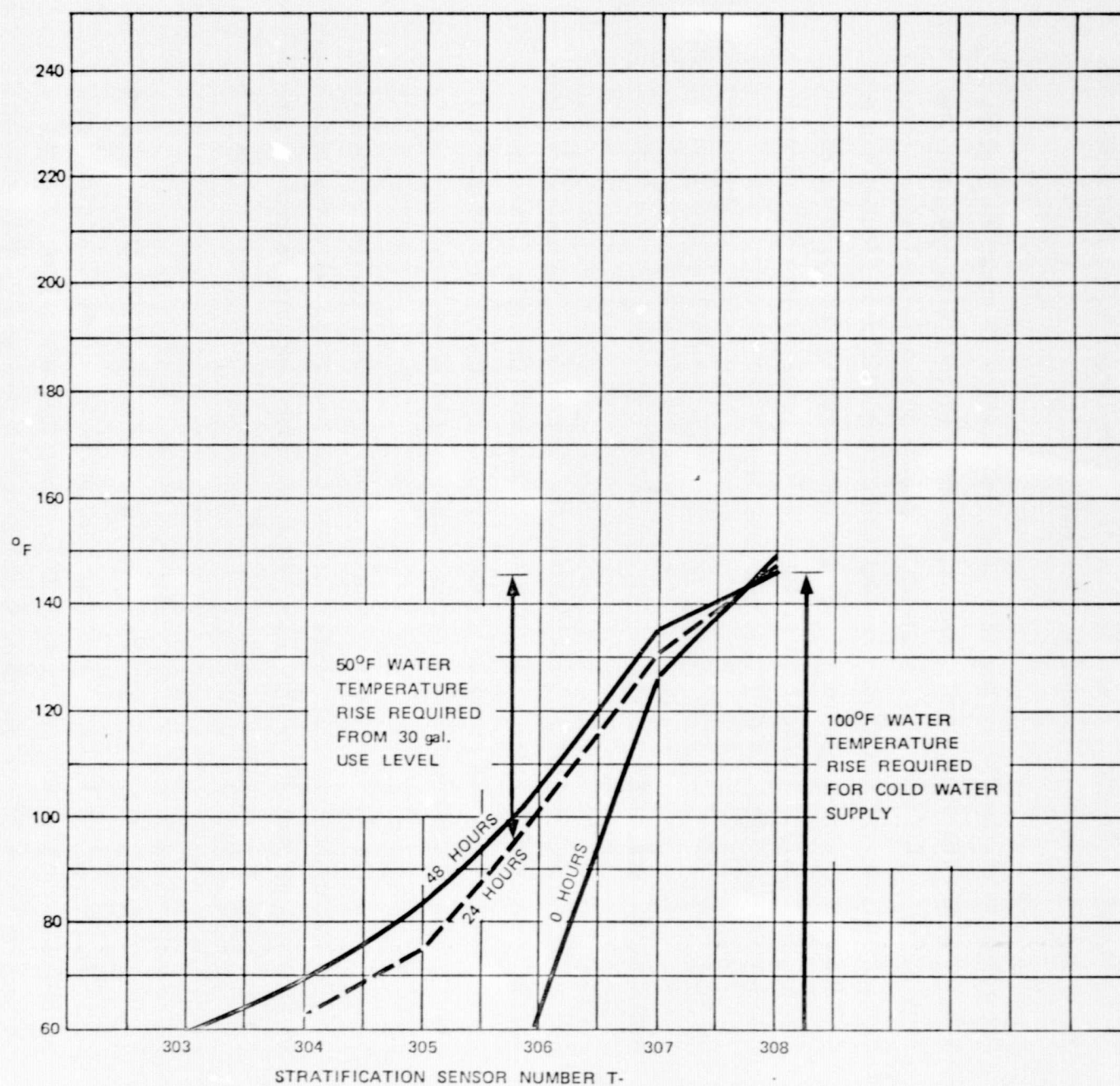


Figure 4-4C DHW Auxiliary Heat Soak

the draw capacity for the 65-gallon test tank is approximately 30 gallons based on 100°F water temperature rise. With the integrated 5% heat boost, only 50°F water temperature rise is required, therefore, the draw capacity is increased to 48 gph. (See Figure 4-4C.) The larger value meets HUD IMPS for a two bedroom house having 1 1/2 baths.

The response of the DHW system to a 30-gallon outflow is shown in Figures 4-5, 4-6 and 4-7. The short-term dynamics, shown in Figures 4-5, 4-6, and the longer-term response of Figure 4-7, are each sensitive to the initial stratification existing within the DHW tank. For design solar conditions, Figures 4-6 and 4-7 show the DHW response to a 5 GPM use rate existing for six minutes (30-gallon total). The full 30-gallon DHW load resulted in a 12°F drop in DHW delivery temperature and left the tank highly stratified.

4.4 CONTROL SUBSYSTEM

The solar control subsystem provides for the independent, non-exclusive operation of each of the three liquid pumps to accomplish its assigned heat transfer function. Two differential thermostats, a low temperature sensor and a standard two-stage room thermostat provide the controller input signals.

The relay in the differential thermostat used to control collector operation will energize when probe S1 is 20°F hotter than probe S3. When the temperature of probe S3 becomes 4°F \pm 2°F colder than the high temperature probe, the relay will open; then pump P1 will turn off. This decision logic is shown in Figure 4-8.

The relay in the differential thermostat used to control the DHW loop will energize when probe S2 is 20°F hotter than probe S4. Pump P3 controlled by the N-0 contacts will be turned "ON". When the temperature of probe S4 becomes 4°F \pm 2°F colder than the high temperature probe, the relay will open; then pump P3 will turn off. This decision logic is shown in Figure 4-9.

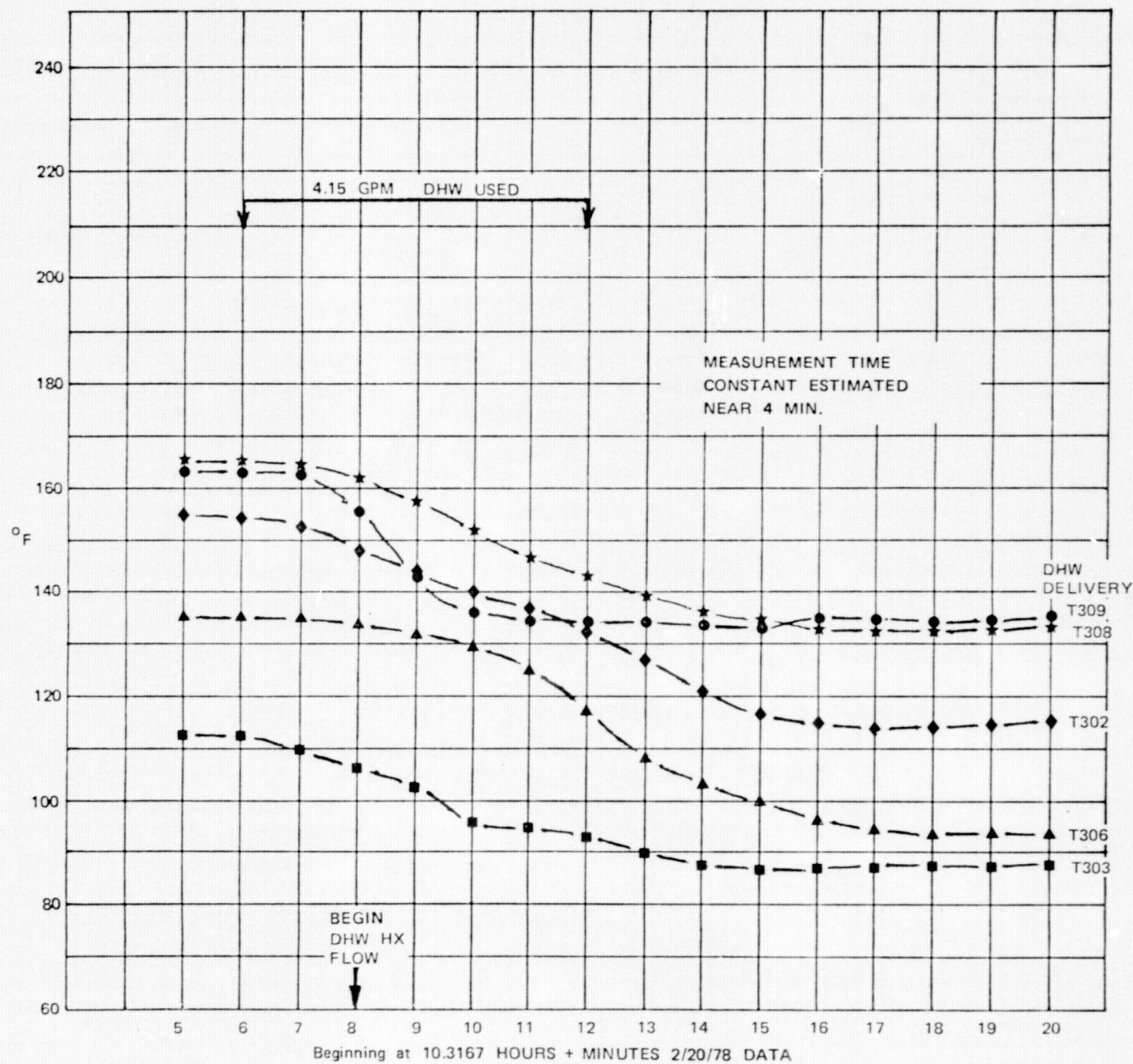


Figure 4-5 Short-Term DHW Dynamics

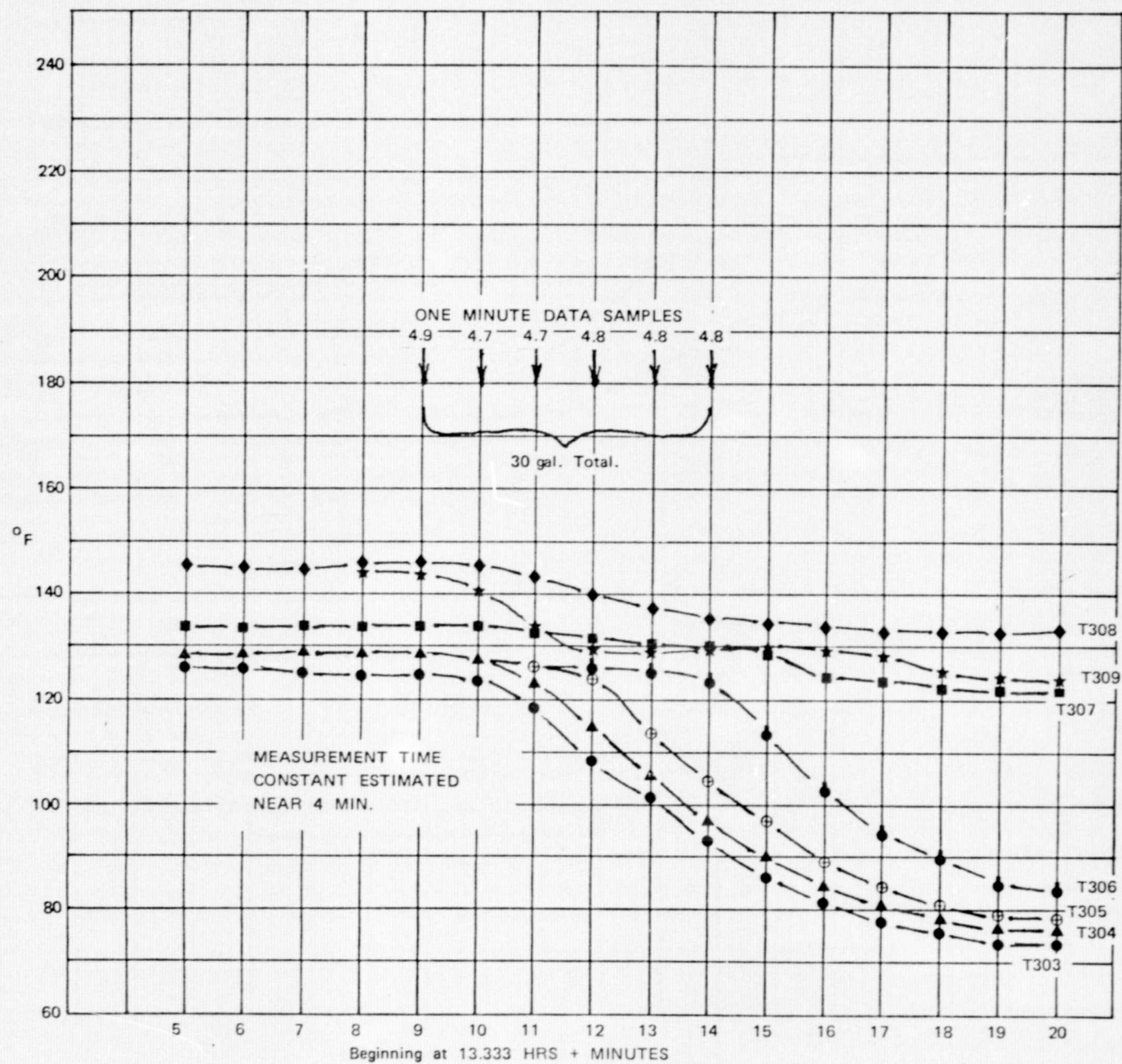


Figure 4-6 Short-Term DHW Dynamics

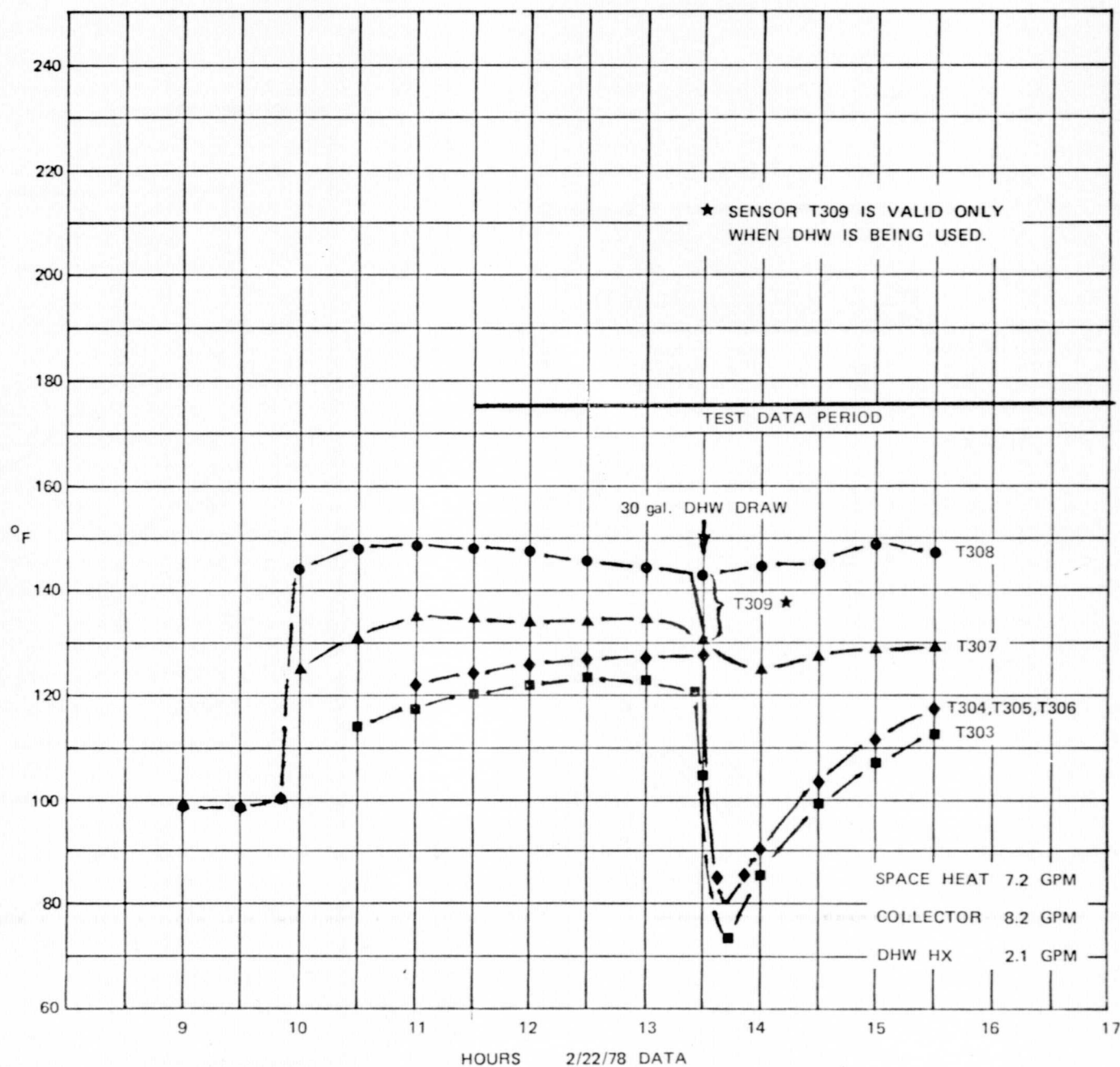
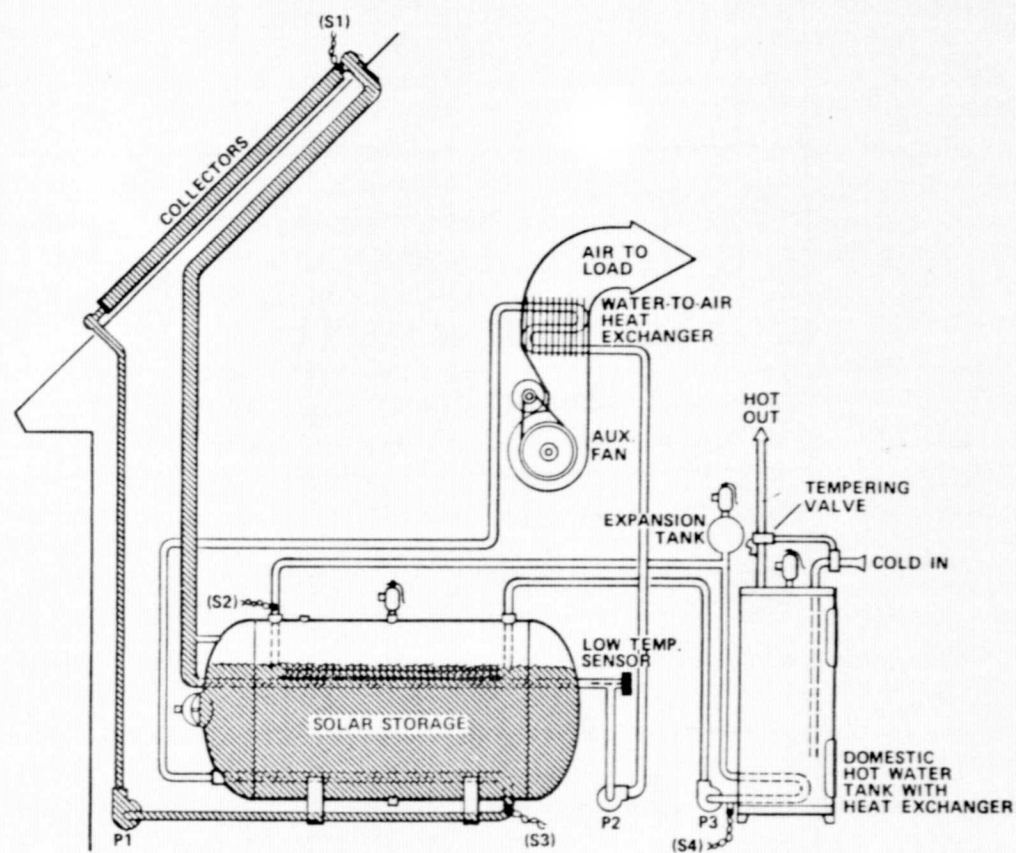
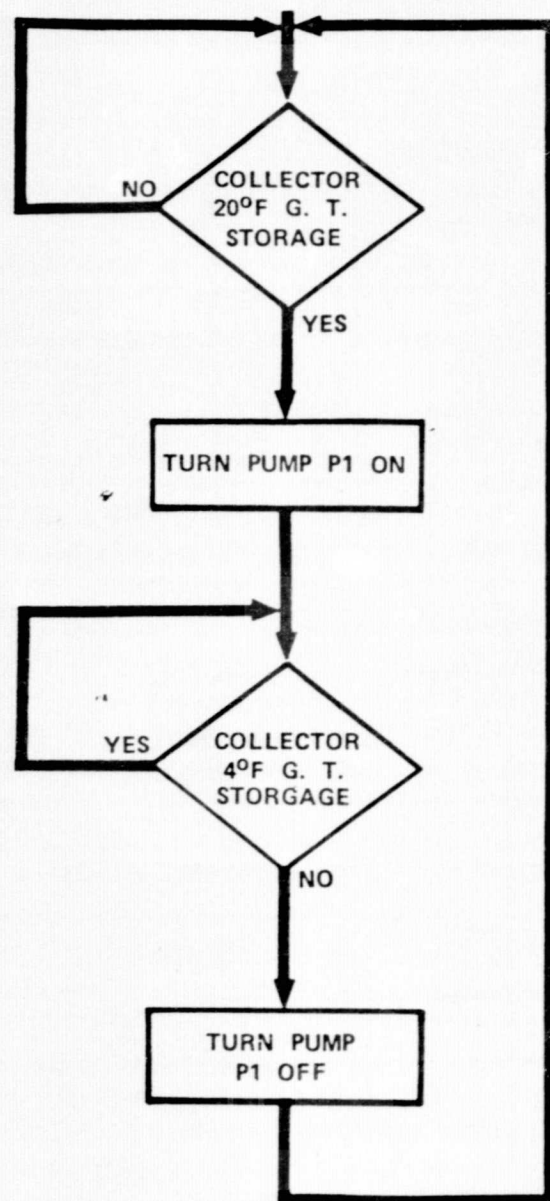
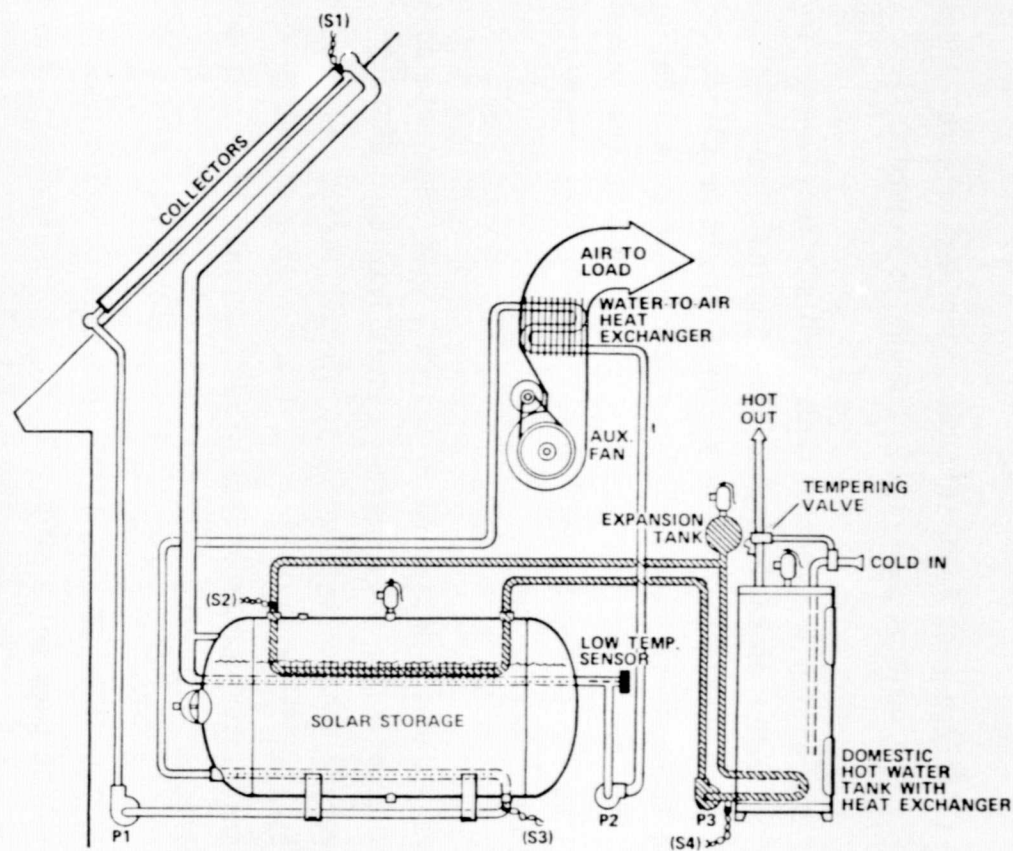
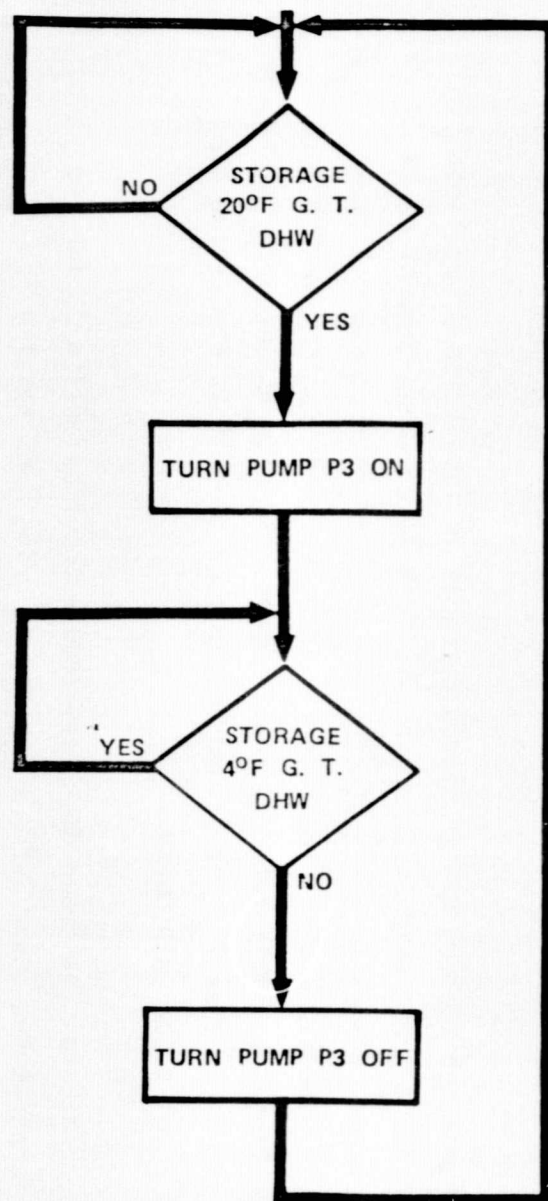


Figure 4-7 DHW Thermal Response



SYSTEM 3 DIAGRAM

Figure 4-8 Collect and Store



SYSTEM 3 DIAGRAM

Figure 4-9 Heat Domestic Hot Water

Figure 4-10 shows the decision logic for the Space Heat control modes. A wiring diagram for the control subsystem is shown in Figure 4-11.

The criteria for evaluating the control subsystem's effectiveness in initiating and terminating collector operation is developed using Figure 4-12. If ideal control hardware were available control sensor S1 would be placed on the absorber plate and the control ON-OFF differential set to zero. Collector flow would exist any time the solar insolation corresponding to the current (Ti-Ta) was higher than the 0°F collector gain curve. Contrariwise insolation below this line would be a no-flow case.

The actual control hardware installed in System 3 will terminate collector operation when the collector flow energy gain is less than $4^{\circ}\text{F} \pm 2^{\circ}$. (The 4°F minimum operating gain is determined by circuit design tolerances). If control ON-OFF cycling is to be avoided, collector flow should be initiated when the solar insolation corresponding to the current (Ti-Ta) is greater than the 4°F collector gain curve.

Values of (Ti-Ta) less than 30 have little practical heating season value. (Solar storage is not used below 90°F. Heating loads approach zero above Ta=60°F for solar sites. Therefore, Ti-Ta=30).

The System 3 controller will initiate collector operation when control sensor S1 detects a temperature 20°F greater than storage (sensor S3) temperature.

Ideal placement of control sensor S1 would result in initiation of collector flow along the 4°F collector gain curve of Figure 4-12. When control sensor S1 is mounted in the collector exit stub (external to collector), collector flow is initiated along the 8°F collector gain curve. The control switching states are listed in Table 4-1. Relocating sensor S1 near the absorber plate, as discussed in Section 7.2, caused collector flow to be initiated along the desired 4°F collector gain curve.

Freeze Protect: Passive drain down performed without exception during the freezing temperatures (near 10°F) encountered during MSFC testing.

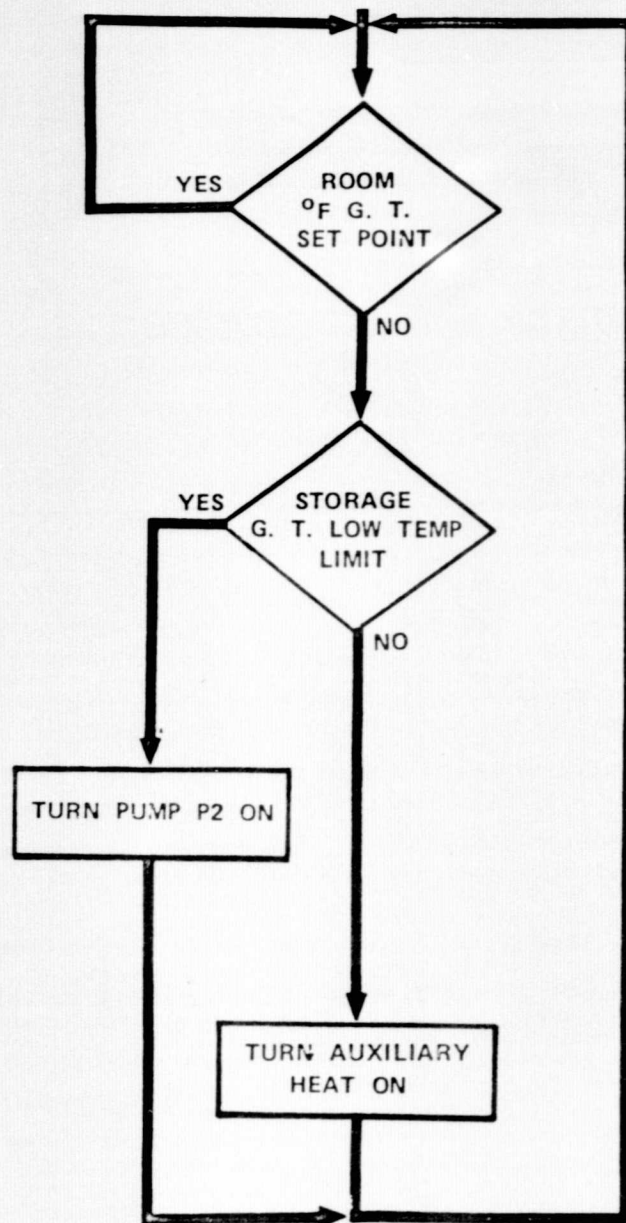
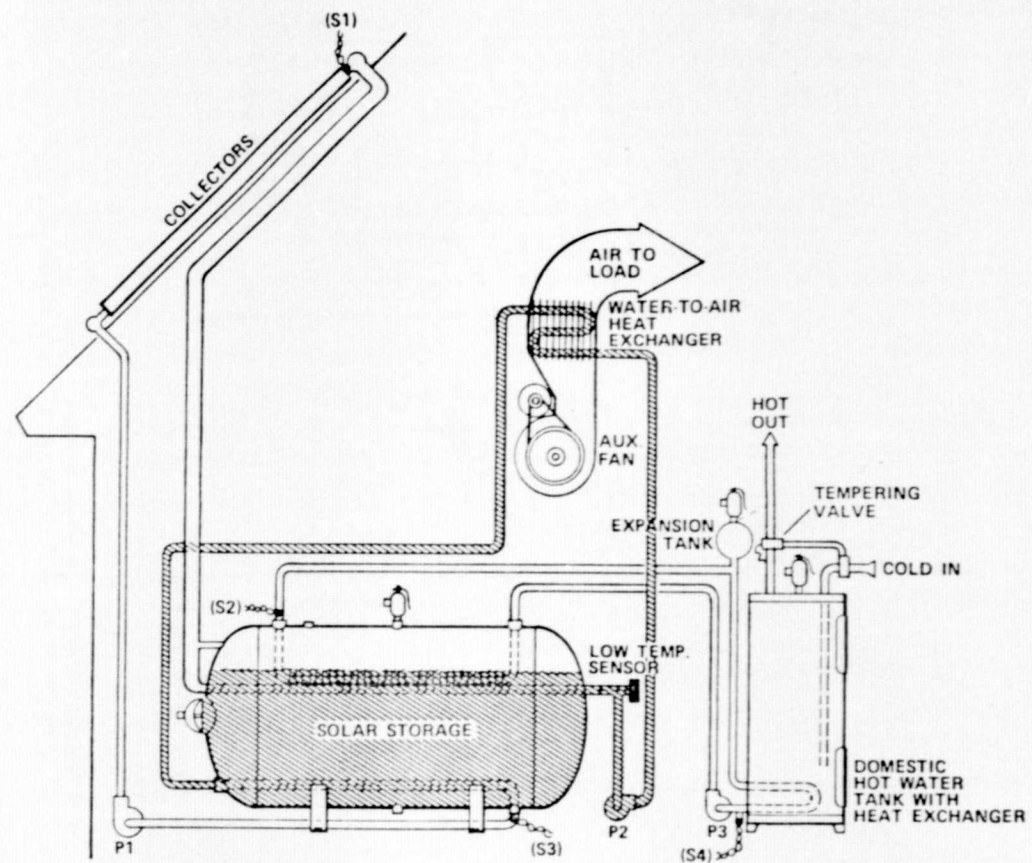
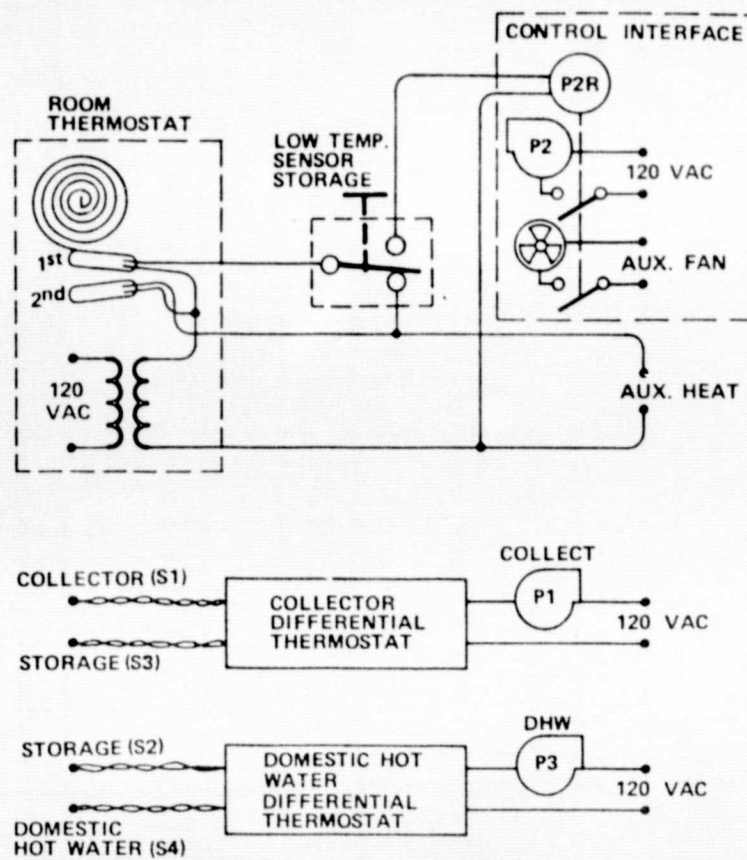


Figure 4-10 Space Heat



SYSTEM 3 DIAGRAM



CONTROL DIAGRAM

Figure 4-11 Control Wiring

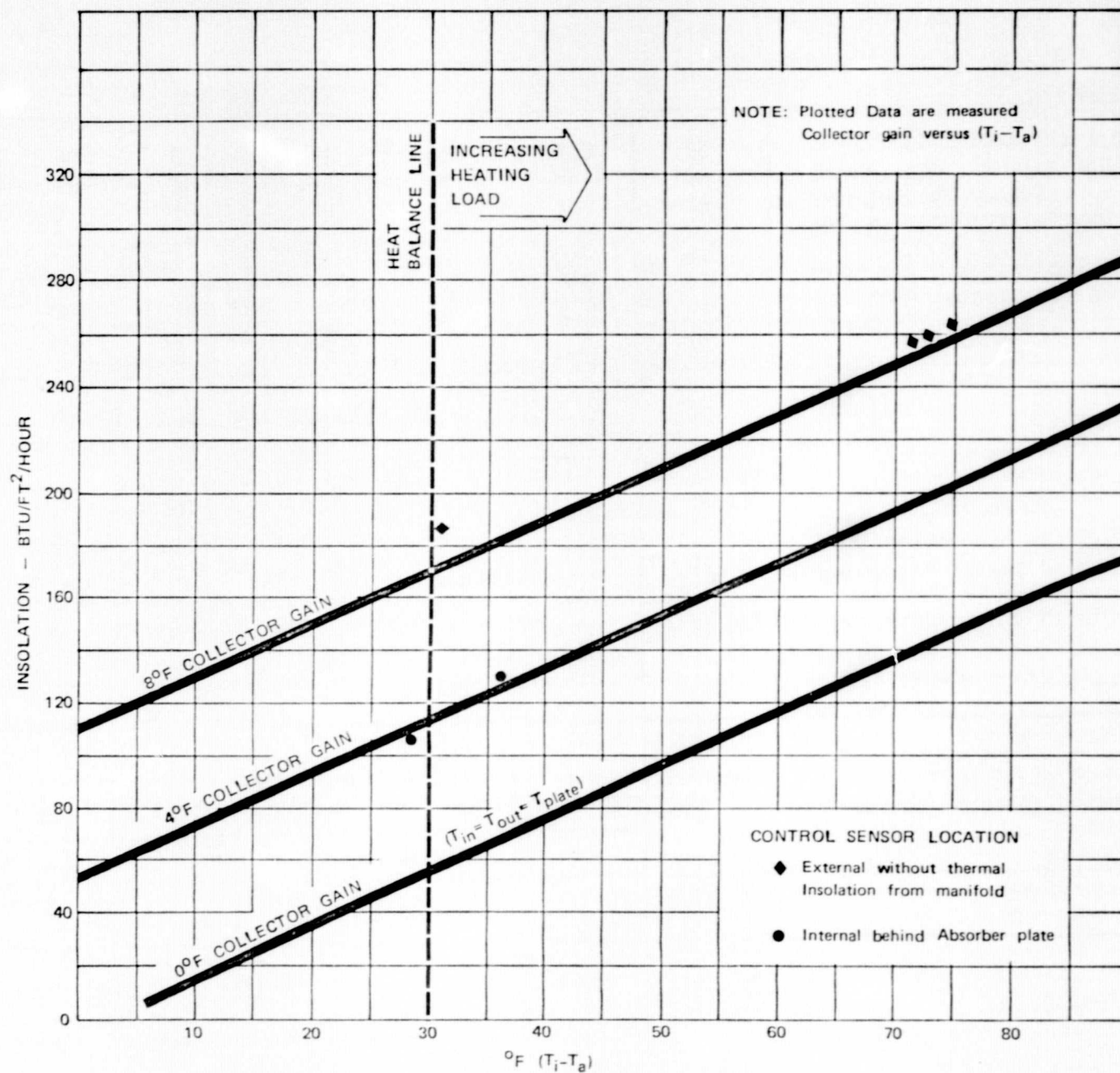


Figure 4-12 Collector Flow Initiate State

Table 4-1: System 3 Control Switching States

COLLECTOR FLOW INITIATION							
Date	Insolation	Collector				T AMB	Remarks: Control Sensor External to Collector
		T _{IN}	T _{OUT}	Absorber			
				Flow OFF	Flow ON		
2-7-78 *	280	99	111	245	-	30	Plate Sensor 3 reads 230 OFF, 155 ON
2-9-78	200	102	105	-	130	37	Manual ON
2-10-78	250	110	115	-	-	35	Two false starts prior to operation
2-17-78	175	70	79	175	107	40	
2-19-78	240	102	110	215	142	29	Two false starts prior to operation
2-20-78	270	112	120	220	150	37	Insolation Data Questionable
2-22-78†	295	120	130	-	165	28	Manual ON
2-24-78	265	112	120	-	150	40	Manual ON
COLLECTOR FLOW TERMINATION							
2-7-78	142	109	109	-	-	33	Plate Sensor 3 reads 132 ON, 138 OFF
2-9-78	80	118	115	125	125	46	Variable Insolation, poor data
2-10-78	140	135	140	160	205	46	Insolation valve questionable
2-17-78	200	112	117	140	-	54	
2-19-78	193	110	113	133	-	41	Manual flow termination
2-20-78	-	110	111	110	170	46	Bad Insolation Data
2-22-78	150	110	111	-	-	38	Manual flow termination
2-24-78	300	127	137	170	210	55	High temperature limit cutoff

5.0 SYSTEM MEASUREMENTS

A listing of the measured test variables and a description of the test equipment and procedures are contained in Appendix A and B. Representative data is also included. All test data were recorded on magnetic tape.

Operating Map

The following operating maps, derived from single shift (8 hours), short-term (daily) testing provide insight into design accomplishments; however, test initial conditions may not represent states closely correlating to realizeable long-term values.

The operating maps shown in Figures 5-1 and 5-2 show thermal interaction between the collector and space heating energy transport subsystems when concurrently operated. At the operating profile shown, space-heating performance is enhanced at the expense of collector efficiency. Figure 5-1 shows that, without interaction, storage water between 112°F and 124°F would have been available to the space heat exchanger; with interaction 136°F. This 12 to 24°F enhancement of the temperature to the space heater (water-to-air heat exchanger) resulted in a 10°F degradation (112° - 122°) in the collector inlet temperature. Similar, but somewhat less in magnitude, results are shown in Figure 5-2. Long-term test data is required to fully evaluate the net impact of the distribution manifolds, however, the cold distributor configuration was modified and tested. Figure 5-3 shows an operating thermal map for the modified system discussed in Section 7.3.

Figure 5-4 shows that heat removal from solar storage did not produce significant stratification.

Measurement T211, located above the hot manifold, is not within the manifold to manifold flow.

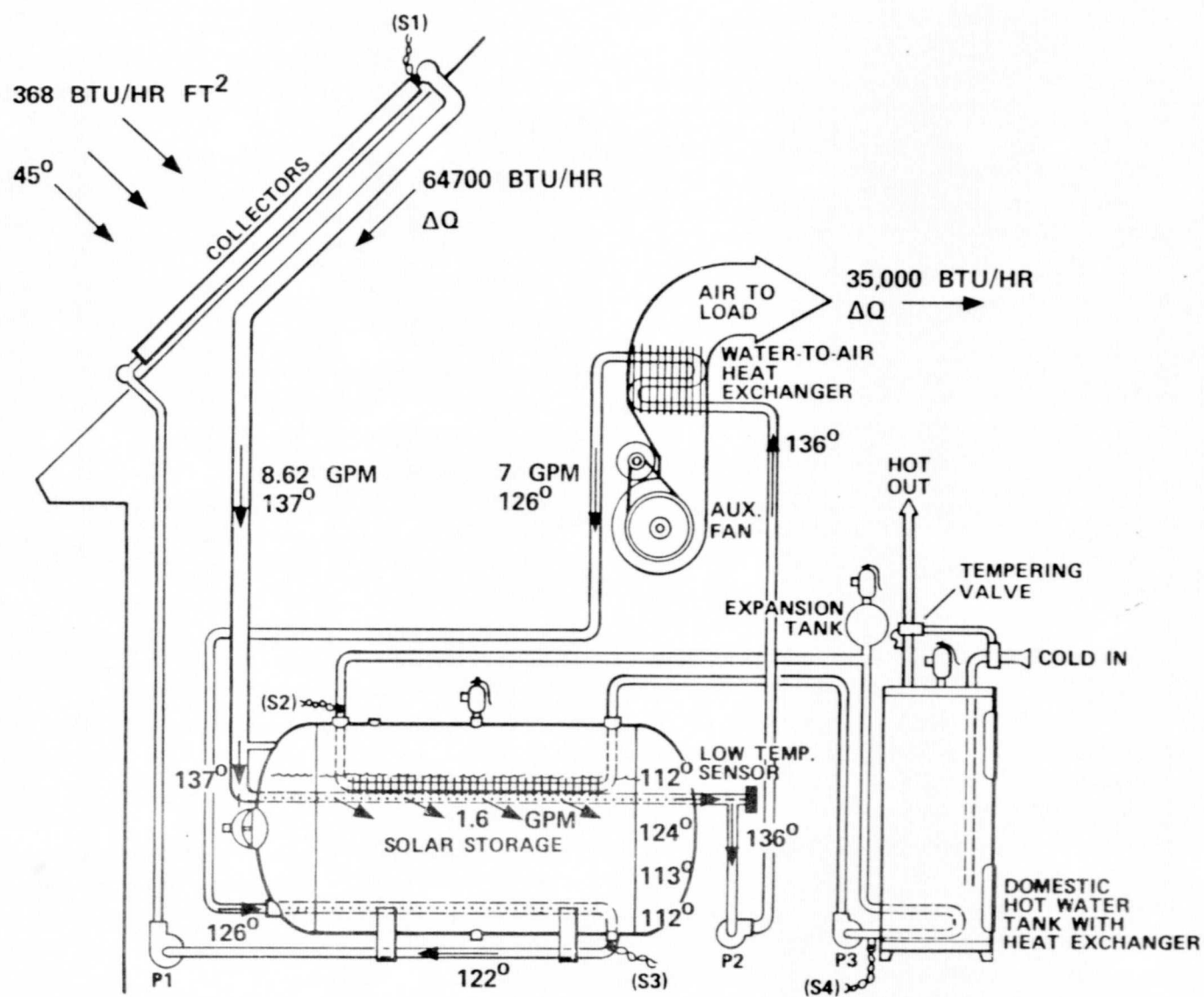


Figure 5-1 Operating Thermal Map

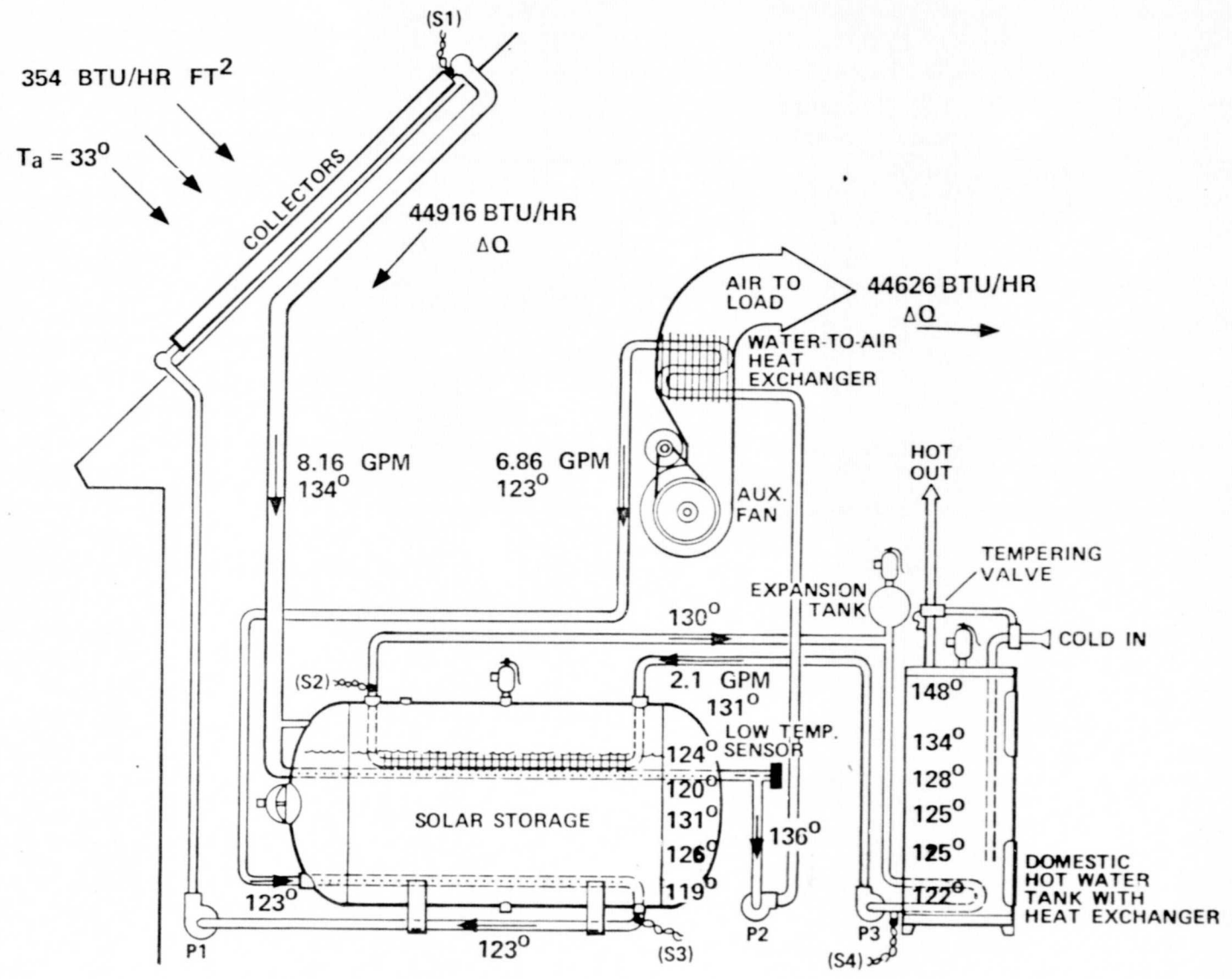


Figure 5-2 Operating Thermal Map

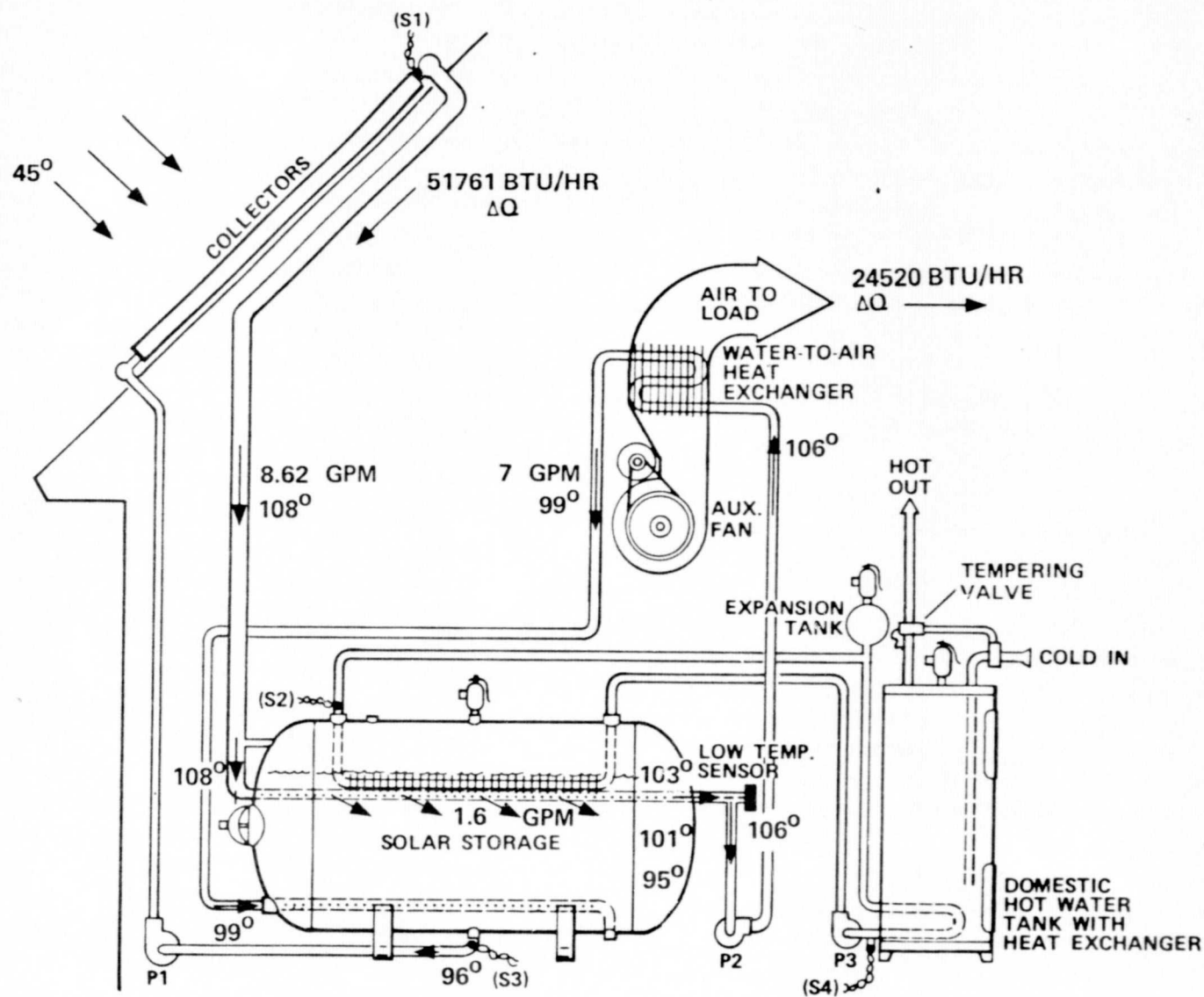


Figure 5-3 Operating Thermal Map (Modified)

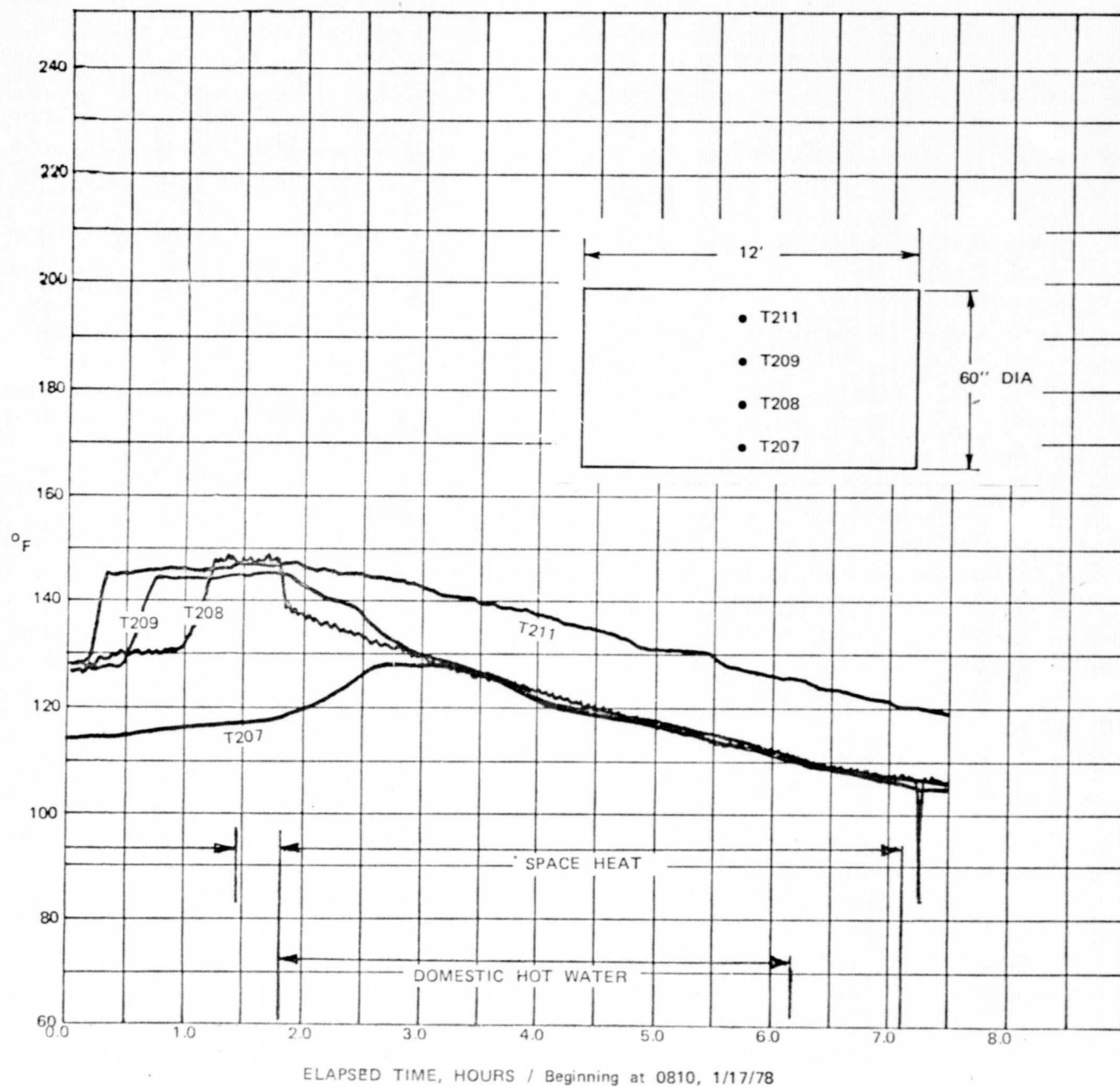


Figure 5-4 Storage Thermal Discharging

Electric Energy Required

Table 5-1 shows the amount of electric power used by the solar system during various operating modes. Also shown is a Coefficient of Performance (COP) defined as the ratio of solar energy collected to the electrical energy expended by the solar components. Pump energy P2 and P3 has been charged against the test COP. This causes low COP values for days of low insolation. Auxiliary energy utilization is not a part of the COP calculation.

6.0 SYSTEM PERFORMANCE

A daily summary of System 3 test performance is shown in Table 6-1 and 6-2.

Percent solar contribution, the primary measure of solar system performance, is weather and load profile dependent. Since the test data were recorded only during January and February, it was necessary to extrapolate short-term test data to yield equivalent year-around data. An FCHART computer program, obtained from the University of Wisconsin, was used to project test performance to the same base as System Performance Specification No. 7933451 Appendix A.

PERFORMANCE ANALYSIS SUMMARY FOR HUNTSVILLE, ALABAMA

A-0 SYSTEM IDENTIFICATION

This section defines the system performance for SIMS Prototype Heating and Hot Water System, Model Number 3 installed in Huntsville, Alabama at the MSFC Solar Heating and Cooling Test Facility. The design average insolation (typical winter mean) is 1062 BTU/Ft² Day and the heating degree days (typical winter mean °F) is 3270. Test configuration is:

Table 5-1 Electrical Requirements

Mode	Watts	COP
Collect	408	22-92
Space Heat	204	-
DHW	57	-

TABLE 6-1
PHASE I THERMAL PERFORMANCE DATA

DATE	1/10	1/11	1/13	1/16	1/17	1/20	1/23	1/27	2/7	2/9	2/10
AVAILABLE SOLAR FLUX DURING TEST (BTU)	566,924	315,781					487,280		176,791	441,504	407,82
ENERGY COLLECTED (BTU)	210,170	92,744					130,605		52,710	101,550	154,22
SIMULATED ENERGY INPUT TO STORAGE (BTU)			¹ 197,356		134,119						
TOTAL SPACE HEATING LOAD (BTU)			235,352		190,544						
ENERGY TRANSPORTED TO DHW SUBSYSTEM (BTU)	18,430	10,321	706	44,160	39,663	41,806			5,097	16,176	19,464
TOTAL DHW LOAD (BTU)	908										
ELECTRICAL ENERGY CONSUMPTION (BTU)	2,283	2,017	1,267	607	1,679	649	1,541		1,106	2,592	2,886
THERMAL LOSS COEFFICIENT (BTU/°F·HR)								² 42.95	³ 6.54		

1

Data from 1/12

2

Phase I Main Storage Tank

3

DHW Tank

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TABLE 6-2
PHASE II THERMAL PERFORMANCE DATA

ATE	2/16	2/17	2/19	2/20	2/22	2/23	2/24	2/27
AVAILABLE SOLAR LUX DURING TEST (BTU)	125,647	675,864	649,782	529,880	676,885		532,602	317,437
ENERGY COLLECTED (BTU)	21,262	317,427	288,595	177,752	256,584		218,844	87,148**
TOTAL SPACE HEATING LOAD (BTU)			231,088	134,423	292,480		169,824	117,536
ENERGY TRANSPORTED TO DHW SUBSYSTEM (BTU)		23,286	37,228	29,687	47,367		33,220	16,343
TOTAL DHW LOAD (BTU)		22,837	24,350	30,012	26,474		16,002	16,730
ELECTRICAL ENERGY CONSUMPTION (BTU)	828	2,173*	10,689	8,080	7,988		5,651	15,493
THERMAL LOSS COEFFICIENT (BTU/°F·HR)						130.42		

* The large increase in electrical energy consumption after this date is due to the use of an electrical heating element in the DHW tank that was rated at 4.5kw at 240 VAC.

** Collected energy on this date was estimated based on an energy balance on the storage tank.

1 Phase II main storage tank.

- 18 Sunworks liquid flat plate collectors
- 1 Adamson 1,000 gal. model K96 storage tank
- 3 Grundfos UP26-64 liquid pumps
- 1 Grundfos UP25-42SF liquid pump
- 1 Rome-Turney Liquid to Air Heat Exchanger
- 1 Ford Products Aqua Coil Domestic Water Tank
- 2 Solar Control Corp. Differential Thermostats

The test installation will not contain auxiliary space heat. Refer to IBM Drawing 7933647 for the system configuration description.

A-1 SYSTEM PERFORMANCE SHEETS

Space Heating Capacity

The system will provide solar energy for 44 percent of the total space heating load during the heating season based on an average annual heating load of 54.89×10^6 BTU and a peak space heating load of 33,600 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 35.5×10^6 BTU. This shall be no greater than 47 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

Seventy-five gallons per day of hot water shall be delivered at no less than 1.2 gal/min at temperatures no less than 140°F. Draw shall be 44 GPH. The average hot water heating load will be 20.6×10^6 BTU/year of which 25% is provided by auxiliary energy.

Operating Requirements

The maximum electrical power required to drive the solar portion of the system at its rated capacity was 0.7 K.W. The maximum electrical power required to drive the complete system shall be no greater than N/A K.W. The average yearly electrical energy required to drive the system shall be no greater than N/A. Water requirements for cooling condensers and/or air humidification shall be no greater than N/A gal/hr.

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 artificially 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 DOMESTIC HOT WATER SUBSYSTEM

A one-bedroom house with 1-1/2 baths requires 30 gph draw capacity for direct fired water heaters. Any combination of storage capacity (gal.) and recovery (gph) to produce the one-hour draw is acceptable (MPS Table 6-15.2). The 65-gallon single tank DHW configuration baselined for System 3 meets the 30-gallon requirement by combining a 14 gph recovery rate (based on 100°F temperatures rise by the electric heat element) with 16-gallon DHW storage (volumetric capacity above electric heat element). For a two-bedroom house with 1-1/2 baths, the 44 gph draw capacity requirement is met by accepting the 50°F temperature rise as justified in Section 4.3.

The above worse case discussion assumes total absence of solar. For higher draw capacity requirements, a larger capacity single tank is recommended.

The third option would use the solar DHW tank as a preheat tank in series with a standard DHW tank. In this concept, thermal loss from the standard DHW tank can only be made up by the expenditure of auxiliary energy.

7.2 CONTROL SUBSYSTEM

The location and mounting detail for collector control sensor S1 has a major impact on the state variables required to initiate collector flow. The major test procedures were conducted with control sensor S1 mounted in the collector exit stub (external to collector) as close as practical to the collector housing. With this configuration, collector flow was initiated when a 8°F collector gain could be maintained. The 8°F turn on gain being higher than the 4°F design goal is attributed to the absence of the collector fluid thermal energy transfer path in this drain down configuration.

Additional testing was conducted to define more optimum mounting specifications for collector control sensor S1. Based on the results of these additional tests, the control sensor should be placed between the absorber plate and the back side insulation near the collector exit. This location will initiate collector flow along the 4°F collector gain curve shown in Figure 4-12.

7.3 COLD DISTRIBUTOR MANIFOLD

The collector flow circuit was modified by moving the storage exit point from the cold distributor manifold to the bottom center of storage as shown in Figure 5-3. A horizontal deflector plate, mounted on the distributor manifold directly over the exit point, prevents the collector drain back flow from disturbing storage stratification. The modification was successful in that the cold distributor manifold no longer enhances flow ducting between the space heat return flow and the collector inlet flow during dual mode operation. This modification is recommended for incorporation in the prototype 3 system design.

APPENDIX A
TEST PROCEDURE

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1.0 SCOPE

This appendix describes the test procedure used to test SIMS Prototype Solar Energy Heating and Hot Water System 3A in the MSFC Solar Heating and Cooling Test Facility. 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-7933452 | Verification Plan/Procedure for Prototype Solar Energy Heating and Hot Water System Model No. 3 |
| 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 | NAS8-32036 | NASA/IBM Contract |

3.0 MANUFACTURER

<u>Equipment</u>	<u>Manufacturer</u>	<u>Model No.</u>
Collectors	Sunworks New Haven, CT 06508	
Collector Pumps (2)	Grundfos Pump Corp. Clovis, CA 93612	UP26-64
Collector Differential Thermostat	Solar Control Corp. Boulder, COLO	77-171
Storage Tank (Phase 1 Test)	Best Products Company Birmingham, AL 35222	Manufacturers Prototype
Storage Tank (Phase 2 Test)	Adamson Co., Inc. Richmond, VA	K-96H

3.0 MANUFACTURER (Continued)

<u>Equipment</u>	<u>Manufacturer</u>	<u>Model No.</u>
Storage Tank Internal Heat Exchanger (Phase 1 Test)	Wolverine Tube Decatur, AL	Manufacturers Prototype
Storage Tank Internal Heat Exchanger (Phase 2 Test)	Rome-Turney Radiator Co. Rome, NY	Manufacturers Prototype
Space Heating Pump	Grundfos Pump Corp. Clovis, CA 93612	UP26-64
Low Temperature Switch	Automatic Switch Co. Florham, NJ	ASCO Tri-Point SB10A/QF10A1
Room Thermostat	Honeywell Minneapolis, MN 55408	T42H
DHW Pump	Grundfos Pump Corp. Clovis, CA 93612	UP25-42SF
DHW Tank	Ford Products Corp. Valley Cottage, NY 10989	Aqua Coil
DHW Differential Thermostat	Solar Control Corp. Boulder, COLO	77-171

4.0 TEST CONFIGURATION

Presented in Figure 1 is a schematic of Prototype Solar Energy Heating and Hot Water System No. 3 installed at the Solar Test Facility Test Bed #2. An array of Sunworks liquid collectors with an accumulative collector area of 378 ft² provided the primary heating for the system. Water was the heat transfer medium which was circulated by pumps Nos. 1A and 1B through the collectors and back to the main storage tank. A closed loop heat exchanger and pump No. 3 coupled the heat transfer between the main storage unit and the domestic hot water tank. On demand, pump No. 2 circulated water to the water to air heat exchanger which accomplished the heat transfer used for space heating. System controllers were provided to automatically control pump operation.

5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

Unless otherwise specified herein, all tests were performed in the existing natural environment.

5.2 Instrumentation and Equipment

All transducers with the exception of the Eppley PSP pyranometer used in recording test data were calibrated by either NASA or AMC calibration laboratories as required by MSFC MMI 5300.4C. The PSP pyranometer was 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 was not done, confidence in printout accuracies was established by installing calibrated "parallel" transducers and direct read-outs 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 indicated that the data presented is suitable for the purpose intended.

A listing of the equipment to be used in the system test is as follows:

<u>Apparatus</u>	<u>Manufacturer/Model</u>	<u>Range/Accuracy</u>
Digital Thermometer	Fluke/2175A	-99 to 999°F ±1%
Volt Ammeter/Ohmmeter	Amprobe/RS3A	0-300A, 0-300V/±5%
Digital Multimeter	Hewlett-Packard/3465A	4-1/2 digits/0.05% ±1 count
Pressure Gauge	Weksler Instruments	0-300 psi/±1%FS
Pyranometer	Eppley/PSP	0-400 BTU/Hr·Ft ² ±3%
Platinum Resistance	Hy-Cal/4135 Hy-Cal/4175 Minco	60-250°F ±2.5°F 60-250°F ±2.5°F -50 - 400°F ±2.5°F
Flowmeter - Collector Flowmeter - DHW Flowmeter - Space Heating	Potter Aero Co.	4 - 50 GPM
Watt Transducer	Customer Supplied	
Relative Humidity Sensor	Thunder Scientific/SC-4021L	0-100%/±1%

5.0 TEST CONDITIONS AND TEST EQUIPMENT (Continued)

5.2 Instrumentation and Equipment (Continued)

<u>Apparatus</u>	<u>Manufacturer/Model</u>	<u>Range/Accuracy</u>
Watt Transducer	Customer Supplied	
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%
Air Velocity Sensor	Sierra/440	0-2000 FPM ±3% FS

5.2.1 Instrumentation Designation

The System 3 instrumentation designations and locations are depicted in Figures 1 and 2 corresponding to the Phase 1 tests. Instrumentation designations on the thermal storage tank which are peculiar to the Phase 2 tests are shown in Figure 3. A detailed description of the instrumentation is contained in the Instrumentation Program and Component List (IP&CL Rev. A-16).

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 System Operational Functional Test

Tested By: Robert Tourville
Started: 4 January 1978
Completed: 6 January 1978

6.1.1 Performance Criteria Requirements

A system operational functional test was conducted on prototype System 3. The test was conducted to insure that the major components of the system were operating properly after installation on Test Bed No. 2. The operational functional test consisted of the following individual tests:

- . A system pressurization/leakage test.
- . An operational test of the system controllers.
- . An operational test of the system pumps.
- . The measurement of the flow rate across the collector array.

6.1.2 Test Procedure

The primary objective of this portion of the test was to verify that the system equipment was operating properly. Two of the three system controllers were found to be defective when they were tested. This is discussed in further detail in Section 6.3.2. The remainder of the equipment, however, was found to be operating properly.

The system pumps were also set at design flowrates at this time. The space heating pump and the DHW pump flowrates were set by throttling the pump pressure with a hand valve. The collector pump flowrate was set by adjusting the pump pressure by limiting the electrical power to the pumps. It should be noted that two 1/12 horsepower pumps were joined in series to obtain enough head pressure to operate the collector subsystem.

The voltage and current drawn by each of the pumps and the DHW heating element were also measured and are listed in the test results.

1. Install the prototype System 3 on Test Bed No. 2. The system should be installed as prescribed by IBM in order to duplicate the actual site installation as closely as possible. Figure 1 depicts the required system layout.
2. Install the space heating heat exchanger in the temporary structure enclosing the system storage tank. The heat exchanger should be installed in such a manner that the

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1.2 Test Procedure (Continued)

warm air generated from the space heating tests can be used to heat the enclosure.

3. Charge the DHW transfer loop by slowly filling the flow volume by adding water through a fitting near the lowest elevation point while concurrently venting air at the expansion tank inlet fitting. After venting is completed, tighten the expansion tank inlet fitting and add water to attain a five (5) PSI loop pressure. At this pressure level, the expansion tank shall be approximately 1/4 full of water. Seal the system and check for leaks. If any leaks are found, drain the system, repair the leaks and recharge the system.
4. Charge the storage system by filling the storage tank to approximately the 925 gallons level with filtered water at 50 to 80°F.

NOTE: The storage tank used in phase 1 tests is rated at 5 PSI maximum internal pressure. A vented stand pipe shall be installed of sufficient length to allow the water to rise to a height compatible with an internal tank pressure equal to 5 PSI.

5. Turn on the system pumps and verify that they operate properly.
6. Turn on the system controller and verify that it operates properly.
7. Activate the system pumps. The nominal flow rate should be 8 GPM thru the collector loop.
8. Measure the flow rate through DHW Heat Exchange subsystem. The nominal flowrate should be 2 GPM.
9. Measure the flowrate through the heat exchanger used for space heating. The flowrate in this liquid loop will be unrestricted by the test conductor.

6.1.3 Test Observations

- One of the differential thermostats was inoperative on initial check out. Both of that vendors thermostats were replaced by control hardware developed under a previous MSFC contract.
- The DHW tank capacity was measured at 59 gallons exclusive of the capacity within the internal heat exchanger.
- The pump flowrates were set at design flowrates as follows:

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1.3 Test Procedure (Continued)

Collector Loop - 8 GPM ± 0.2 GPM
DHW Loop - 2 GPM ± 0.1 GPM
Space Heating Lamp - Unrestricted

- The measured electrical parameters of the equipment was as follows:

Collector pumps - 1.8A ea. @ 113.5 VAC

DHW pump - 0.5A @ 113.7 VAC

Space Heating Pump - 1.5A @ 113.6 VAC

DHW Heating Element - 18.7A @ 208 VAC

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 System Test, Simulated Energy Input

Started: 12 January 1978

Completed: 20 January 1978

6.2.1 Performance Criteria Requirements

The primary objective of this test was to determine the operating characteristics of the storage unit using simulated energy inputs. This test was also used to evaluate the performance of the space heating and the domestic hot water DHW subsystems.

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

In addition, the prototype System 3 was monitored to provide the following calculated parameters on a daily basis:

- . Total energy supplied to the storage tank from the simulated energy input.
- . Temperature stratification profiles in the DHW tank and the storage tank.
- . 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 tank as a function of time.
- . Ambient average temperature of the storage tank and the collectors.
- . Total combined electrical power of the
 - Collector pumps
 - Space heating pump
 - DHW subsystem pump
 - DHW tank auxiliary heater element

6.2.2

Test Procedure

The primary objective of this portion of the test was to determine the operating characteristics of the storage tank and the various subsystems using simulated energy inputs.

1. Set up System 3 to isolate the collector array from the rest of the system.
2. Connect the storage tank to the simulated energy input.
3. Energize the auxiliary facility pump. Set the flow to meet the design requirements of 8 GPM using the facility liquid flow controller. Verify that all temperature stratification has been eliminated in the storage tank before proceeding to the next stop.
4. Maintain the inlet temperature to the storage tank at 140°F using the facility temperature indicating controller, TIC-35.
5. Flow shall continue until the water at the bottom of the tank reaches 110°F at which time the simulated energy input will be discontinued.
6. The storage tank will be thermally discharged by energizing the DHW pump P3 and leaving the load pump P2 off. Before this test, potable water will be flowed through the domestic hot water tank until the bulk average temperature is equal to the city water temperature. The electrical heating element in the hot water tank will be inhibited from energizing in this portion of the test. This test will be run until the storage tank water temperature has reached 100°F or at the end of the day if this temperature has not been reached.
7. Steps 1 through 6 will be repeated for each of the following additional pump configurations:
 - . DHW pump P3 off, load pump P2 on.

During this test, a consistent load will be applied to the space heating heat exchanger with the use of a fan or blower.
 - . DHW pump P3 on, load pump P2 on.

During this test the domestic hot water tank bulk average temperature shall equal the city water temperature with the electrical heating element deenergized. A consistent load shall be applied to the space heating heat exchanger.

8. Stratification and heat transfer data shall be collected throughout the system operation in each pump configuration. Data collection shall continue for two hours after flow termination. Data shall be collected on the data system located in Building 4646. Performance parameters shall be computed by past test data analyses on the UNIVAC 1108 computer/the DDP-224 computer.

6.2.3 Test Observations

The original intent was to charge the storage tank with a uniform input temperature of approximately 140°F and then to discharge the thermal energy in the main storage using the DHW subsystem and/or the space heating subsystem. Attempts were made to obtain adequate charge data. The data from January 12 and February 21 reflect these attempts. However, because of faulty facility control equipment a uniform charging of the storage unit with a constant temperature water was not possible.

It should be noted that the Phase I storage tank was initially filled to the level of 850 gallons. On January 23, 75 additional gallons were added to make certain the upper level of temperature sensors were submerged. The Phase II tank was filled and maintained at the 830 gallon level through the testing activities.

Parameters which were measured and recorded during this evaluation are shown in Table I. Computer plots were prepared from data contained on the magnetic tapes, by post-test processing.

6.3 System Test, Outside Weather Conditions

Started: February 16, 1978
Completed: February 27, 1978

6.3.1 Performance Criteria Requirements

The prototype System 3 was operated in the normal operating mode. The normal operating mode is defined as conditions where the collector pump controller and the DHW pump controller are at automatic settings. The room thermostat was overridden to maintain a continuous space heating load condition. While operating in this mode, periodic domestic hot water demand loads were imposed.

The primary objective of this test was to obtain as much actual operating data as possible from prototype System 3 prior to its installation at the demonstration site.

During the system test, complete weather records were kept. These included total solar radiation, ambient temperatures, wind speed and direction.

The following parameter was calculated in addition to the performance parameters as detailed in Section 6.2.1.

- . Total energy collected
- . Total available solar flux

6.3.2 Test Procedure

The primary objective of this portion of the test was to determine the operating characteristics of the system under automatic control.

The DHW pump was controlled manually until 27 January 1978 after which the automatic mode was used.

1. Apply power to prototype System 3 and allow the system to operate in accordance with the system controller's normal mode of operation.
2. The system shall be turned on daily, Monday through Friday, by 8:00 A.M., and operated continuously until 4:00 P.M., when the system shall be shut down. The system shall be allowed to operate in its normal control mode.
3. The heating load shall be maintained continuously during each day's testing by setting the room thermostat at a point that will energize the fan and pump P3. The load shall be dependent upon the prevailing transient storage tank liquid temperature and the ambient air temperature at the test site.
4. Daily hot water will be drained from the system according to the following schedule:

<u>Time</u>	<u>Quantity</u>	<u>Rate</u>
30 min. \pm 10 min. after system start up	31 Gal. \pm 1.0 Gal.	2 GPM \pm 0.2 GPM
1300 hours \pm 30 min.	31 Gal. \pm 1.0 Gal.	2 GPM \pm 0.2 GPM

A container will be used to collect and measure the volume of hot water removed from the system. The container will be clearly marked to indicate the volume of 31 gallons.

5. Visually determine that drain-down of fluid from the collector array has occurred upon deactivation of collector loop pumps. This activity will be performed at the end of each day's test.
6. Monitor system operation and check for malfunctions or leaks throughout the test duration.
7. Throughout the system's operation, data will be collected on the data system located in Building 4646.
8. At the test conductor's discretion, simulated energy will be provided to recharge the storage tank. This decision will be made on a daily basis and is subject to the prevailing weather conditions.

6.3.3 Test Observations

The system was instrumented to determine storage stratification heat transfer to the space heating load and heat transfer to the domestic hot water tank. The behavior of the collector loop fluid drain-down when pumps 1A and 1B are deactivated was observed. The collector fluid drain-down is a freeze protection feature of the system design.

Efforts were made to verify that the drain-down freeze protection system drained completely when the collector pumps deactivated. Also, tests were made to investigate the possibility that the water vapor might freeze in the collectors and eventually close off the flow passages during non-operational periods. Hand valves were positioned such that when these valves were closed they would isolate all the water that might have frozen in the collectors and subsequently melted in the morning. This check was performed on several days with no evidence of freezing being apparent.

7.0 DATA PROCESSING

7.1 Simulated Energy Input

Post test data processing were performed to determine the amount of energy transferred to the various subsystems. Methods and equations used to process the test data are described in the following paragraphs.

7.1.1 Total Energy Supplied to the Storage Tank From the Simulated Energy Input

The total energy supplied to the storage tank from the simulated energy input per day was computed as follows

$$Q_{SEI} = \int_{t_1}^{t_2} W_{101} \cdot C_p \cdot (T_{111} - T_{112}) dt$$

where

W_{101} = Simulated energy input flowrate

C_p = Specific heat of water

T_{111} = Inlet water temperature to storage

T_{112} = Outlet water temperature from storage

7.1.2 Energy Transported to DHW Subsystem

Computations performed to determine the energy supplied to the DHW subsystem were based on the following equation

$$Q_{DHW} = 8.33 \int_{t_1}^{t_2} W_{300} \cdot C_p \cdot (T_{301} - T_{302}) dt$$

where

W_{300} = Liquid flowrate

C_p = Specific heat of water

T_{301} = Inlet water temperature to DHW HX

T_{302} = Outlet water temperature from DHW HX

7.1.3 Total DHW Subsystem Load

Computations to determine the total energy removed from the DHW subsystem were based on the following equation.

7.1.3 Total DHW Subsystem Load (Continued)

$$Q_L = 8.33 \sum V \cdot C_p \cdot (\bar{T}_{DHW_i} - \bar{T}_{DHW_f})$$

where

V = Volume of the DHW tank

C_p = Specific heat of water

\bar{T}_{DHW_i} = Initial average temperature of the DHW tank sensors
T303 through T308

\bar{T}_{DHW_f} = Final average temperature of the DHW tank sensors
T303 through T308

7.1.4 Space Heating Load

Computations performed to determine the thermal load on the space heating subsystem were based on the following equations

$$Q_L = 8.33 \int_{t_1}^{t_2} W_{400} (T_{401} - T_{402}) dt$$

where

W₄₀₀ = Liquid flow rate

C_p = Specific heat of water

T₄₀₁ - Inlet water temperature

T₄₀₂ - Outlet water temperature

7.1.5 Bulk Average Temperature of the Thermal Storage Tank

Computations performed to determine the bulk average temperature of the Phase I thermal storage tank were based on the following equation.

$$\bar{T}_s = \frac{1}{12} [T_{203} + T_{204} + T_{205} + 2(T_{208} + T_{209} + T_{210}) + T_{213} + T_{214} + T_{215}]$$

where

T₂₀₃-T₂₁₅ = Internal storage tank temperature (These sensors were positioned at the center of gravity of respective equal sectional areas of the container.)

The storage tank used in Phase II tests utilized temperature sensors T202 through T207 as shown in Figure 3, and the bulk average temperature was calculated by

$$\bar{T}_s = \frac{1}{6} (T_{202} + T_{203} + T_{204} + T_{205} + T_{206} + T_{207})$$

Bulk Average Temperature of the Main Storage Tank (Phase II)

Computations performed to determine the bulk average temperature of the Phase II main storage tank were based on the following equation

$$\bar{T}_s = 1/6 (T_{202}+T_{203}+T_{204}+T_{205}+T_{206}+T_{207})$$

where

T203-T207-internal storage tank temperature. The sensors were positioned at the center of gravity of respective equal sectional areas.

7.1.6 Bulk Average Temperature of the DHW Tank

Computations performed to determine the bulk average temperature of the DHW tank were based on the following equation

$$\bar{T}_{DHW} = \frac{1}{6} [T_{303}+T_{304}+T_{305}+T_{306}+T_{307}+T_{308}]$$

where

T303-T308 = DHW tank surface temperatures

7.1.7 Loss Coefficient of a Storage Tank

Computations performed to determine the thermal loss coefficient of a storage tank were based on the following equation

$$UL = \frac{MC_p(\bar{T}_i - \bar{T}_f)}{(\bar{T}_T - \bar{T}_A) \Delta t}$$

where

M = Mass of stored water

C_p = Specific heat of water

\bar{T}_i = Initial bulk average storage tank water temperature

\bar{T}_f = Final bulk average storage tank water temperature

\bar{T}_T = Bulk average storage tank temperature over Δt

\bar{T}_A = Average ambient temperature in the vicinity of the storage tank over Δt

Δt = Elapsed time data sampled

7.2 Outside Weather Conditions

Post test data analyses were performed to evaluate data obtained from the system automatic mode operational tests at outside weather conditions. The method of evaluation for each performance parameter is presented in the subsequent paragraphs.

7.2.1 Total Energy Collected

The total energy collected per day was determined as follows,

$$Q_c = 8.33 \int_{t_1}^{t_2} W_{100} \cdot C_p \cdot (T_{200} - T_{105}) \Delta t$$

where

W_{100} = Collector water flowrate

C_p = Specific heat of water

T_{200} = Outlet water temperature (This sensor was used since its accuracy was greater than sensor T_{106})

T_{105} = Inlet water temperature

7.2.2 Available Solar Flux

The total solar radiation available per day was determined as follows

$$I_T = \int_{t_1}^{t_2} (I_{001}) A \, dt$$

where

I_{001} = Solar radiation measured at Test Bed #2

A = Area of the collector array

TABLE I

PARAMETERS MEASURED DURING SYSTEM TESTING

<u>Measurement</u>	<u>Parameter</u>
Solar radiation	BTU/Hr·Ft ² vs. hours
Ambient temperature	°F vs. hours
Wind speed/direction	MPH/direction vs. hours
Relative humidity	% vs. hours
Collector inlet temperature	°F vs. hours
Collector outlet temperature	°F vs. hours
Collector absorber temperature	°F vs. hours
Collector delta temperature	°F vs. hours
Main storage water temperature	°F vs. hours
DHW heat exchanger inlet temp. (water)	°F vs. hours
DHW heat exchanger outlet temp. (water)	°F vs. hours
DHW heat exchanger delta temp. (water)	°F vs. hours
Space heater heat exchanger air inlet temp.	°F vs. hours
Space heater heat exchanger air outlet temp.	°F vs. hours
Space heater heat exchanger air delta temp.	°F vs. hours
Space heater heat exchanger outlet temperature	°F vs. hours
Space heater heat exchanger inlet temperature	°F vs. hours
Space heater heat exchanger delta temperature	°F vs. hours
City water supply temperature	°F vs. hours
Hot water system outlet temp. (to load)	°F vs. hours
DHW load delta temperature	°F vs. hours
System temporary shelter temperature	°F vs. hours
Liquid flow through collectors	GPM vs. hours
DHW heat exchanger flow (water)	GPM vs. hours
Space heater heat exchanger flow	GPM vs. hours
Hot water flow to load	GPM vs. hours
Collector pump power	Watts vs. hours
DHW subsystem pump power	Watts vs. hours
Heating loop pump power	Watts vs. hours
Domestic hot water heating element power	Watts vs. hours
Solar pump outlet pressure	PSI vs. hours
Collector outlet pressure	PSI vs. hours
Heat exchanger outlet pressure (oil side)	PSI vs. hours

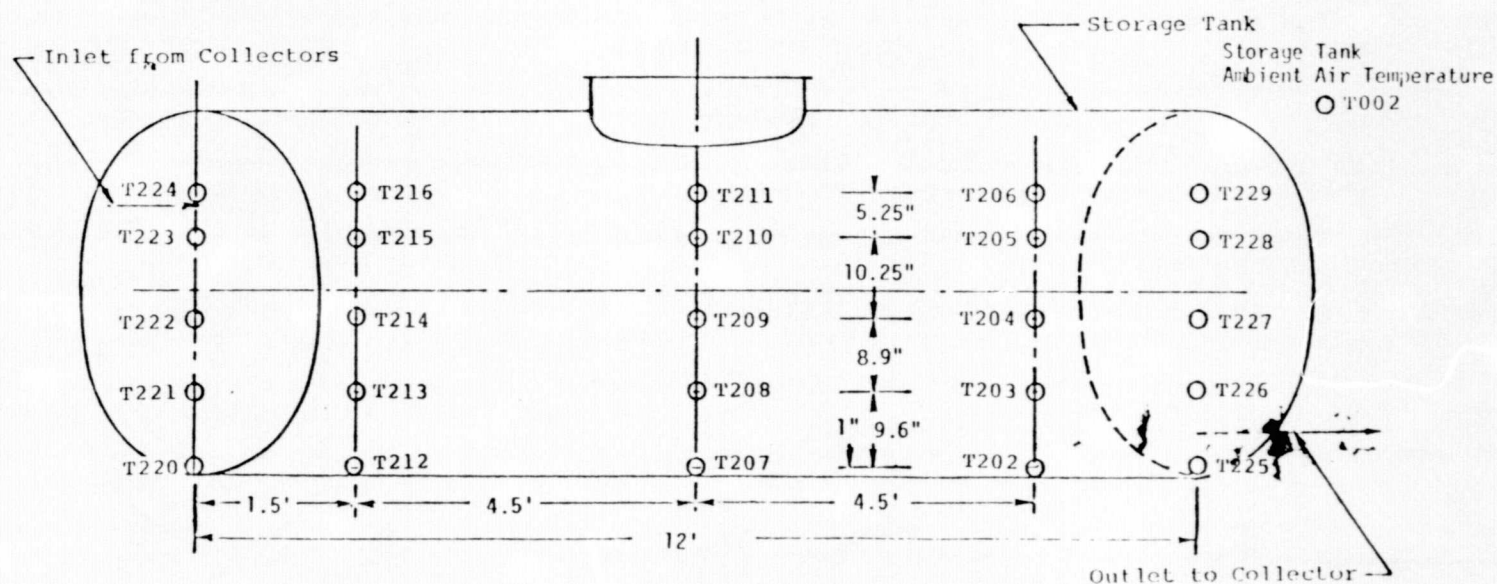
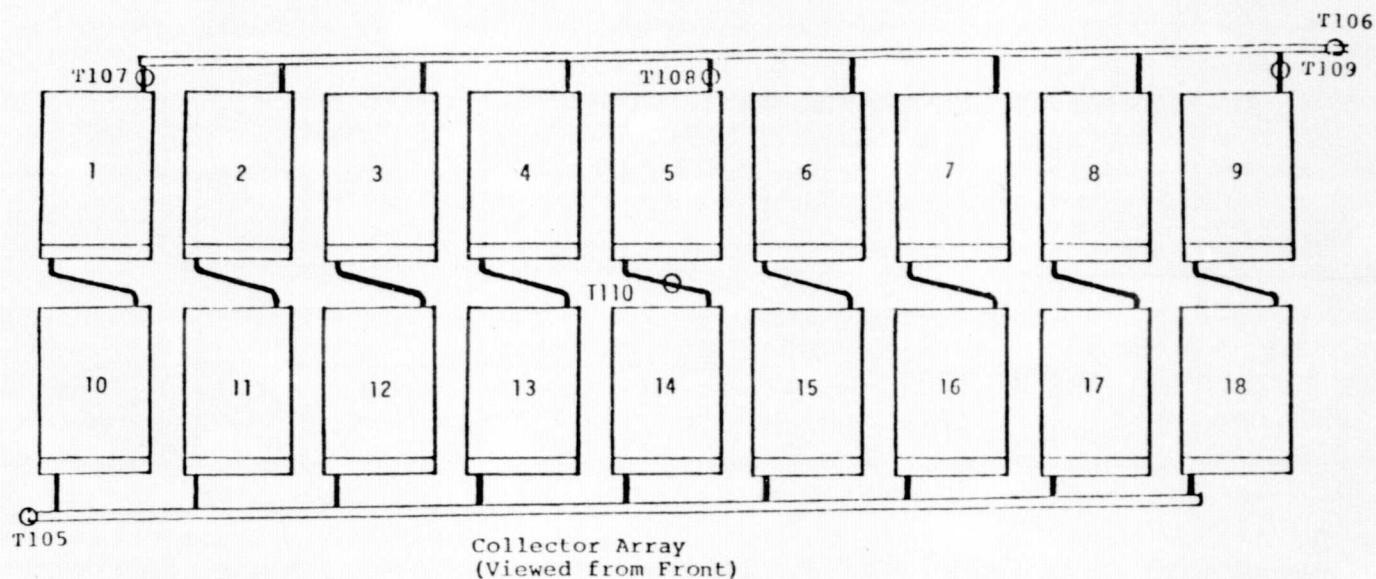


FIGURE 2. DETAILS OF INSTRUMENTATION LOCATIONS ON COLLECTOR ARRAY AND STORAGE TANK

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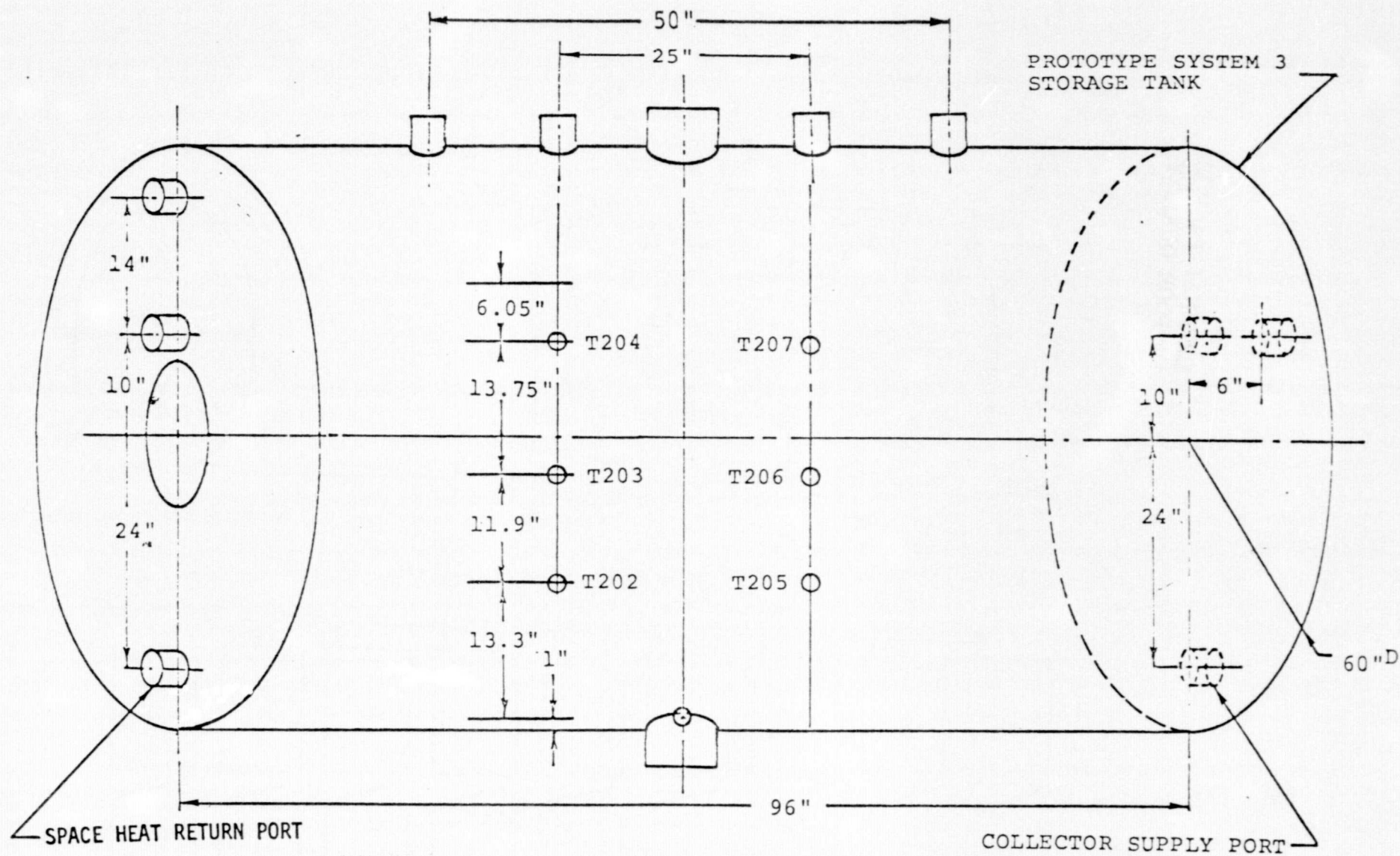


FIGURE 3. THERMAL INSTRUMENTATION LOCATIONS
ON PROTOTYPE SYSTEM 3 STORAGE TANK

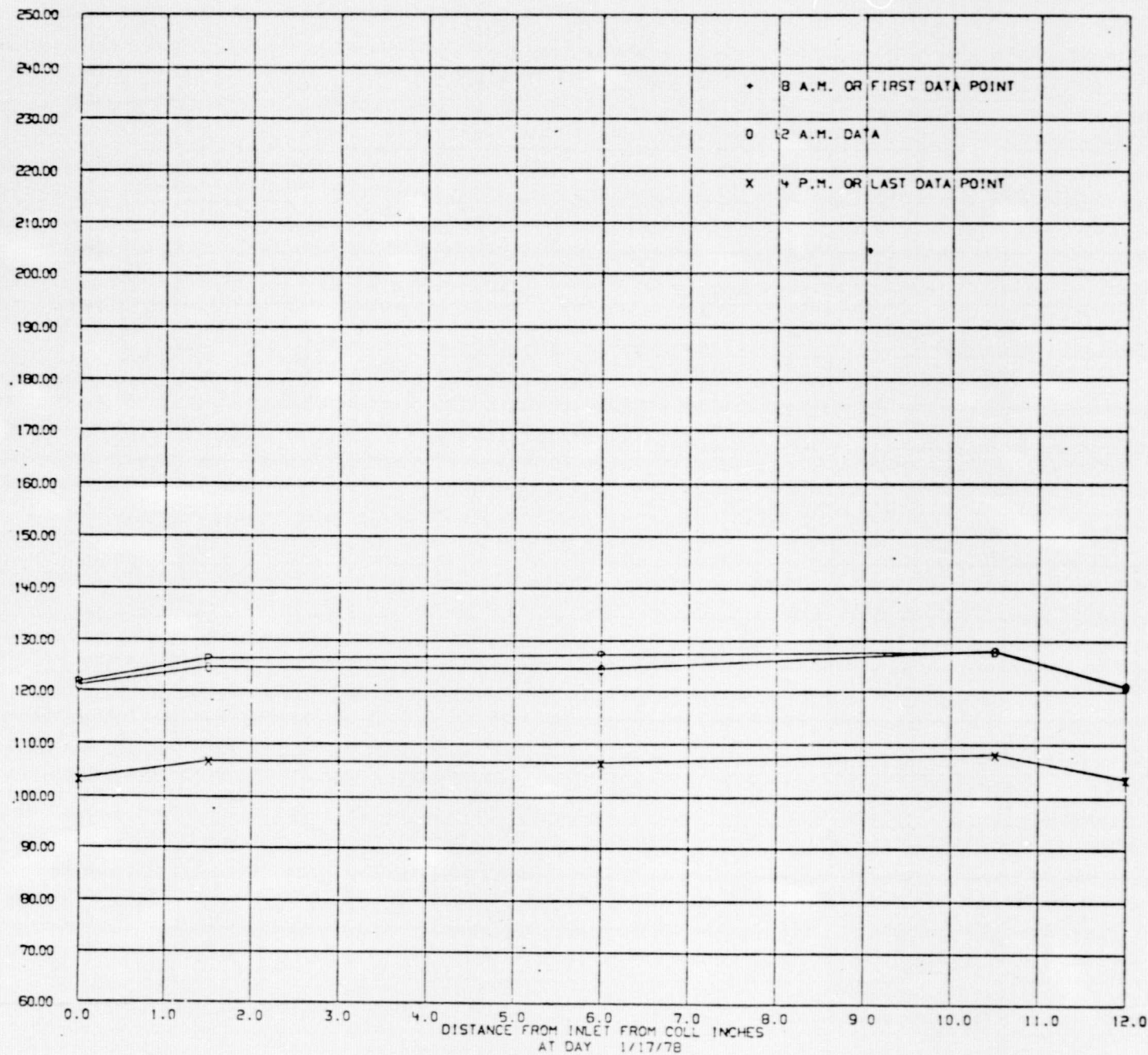
APPENDIX B
STRATIFICATION PLOTS

- Foreword -

The main storage tank was specially instrumented to allow a more in depth evaluation of temperature stratification effects. A total of twenty-five temperature sensors were employed, fifteen internal to the tank, the other ten mounted externally. Three trees of five vertically mounted sensors were spaced horizontally in the tank. The external sensors were mounted in vertical rows of five on each end of the tank as shown in Figure 2. The DHW tank was also instrumented to supply temperature stratification data. Six sensors were bonded vertically to the surface of the tank. Representative stratification data, presented in graphical form, are contained in this appendix.

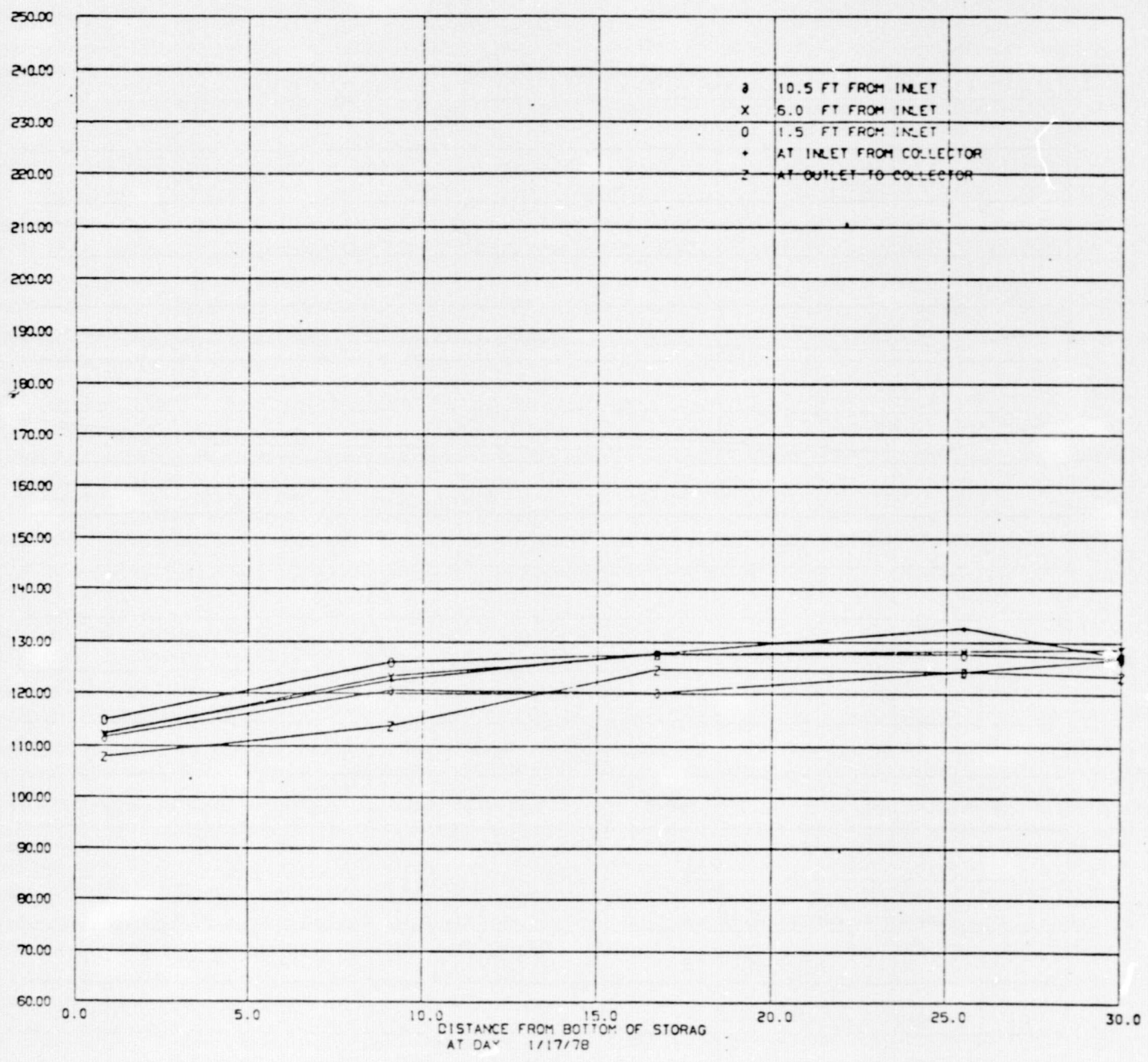
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LONGITUDINAL BULK TEMP IN STORAGE DEG F



Storage Discharging to DHW and Space Heat Subsystems

STORAGE TANK TEMP AT 8 A.M. OR 1ST SET DATA DEGF

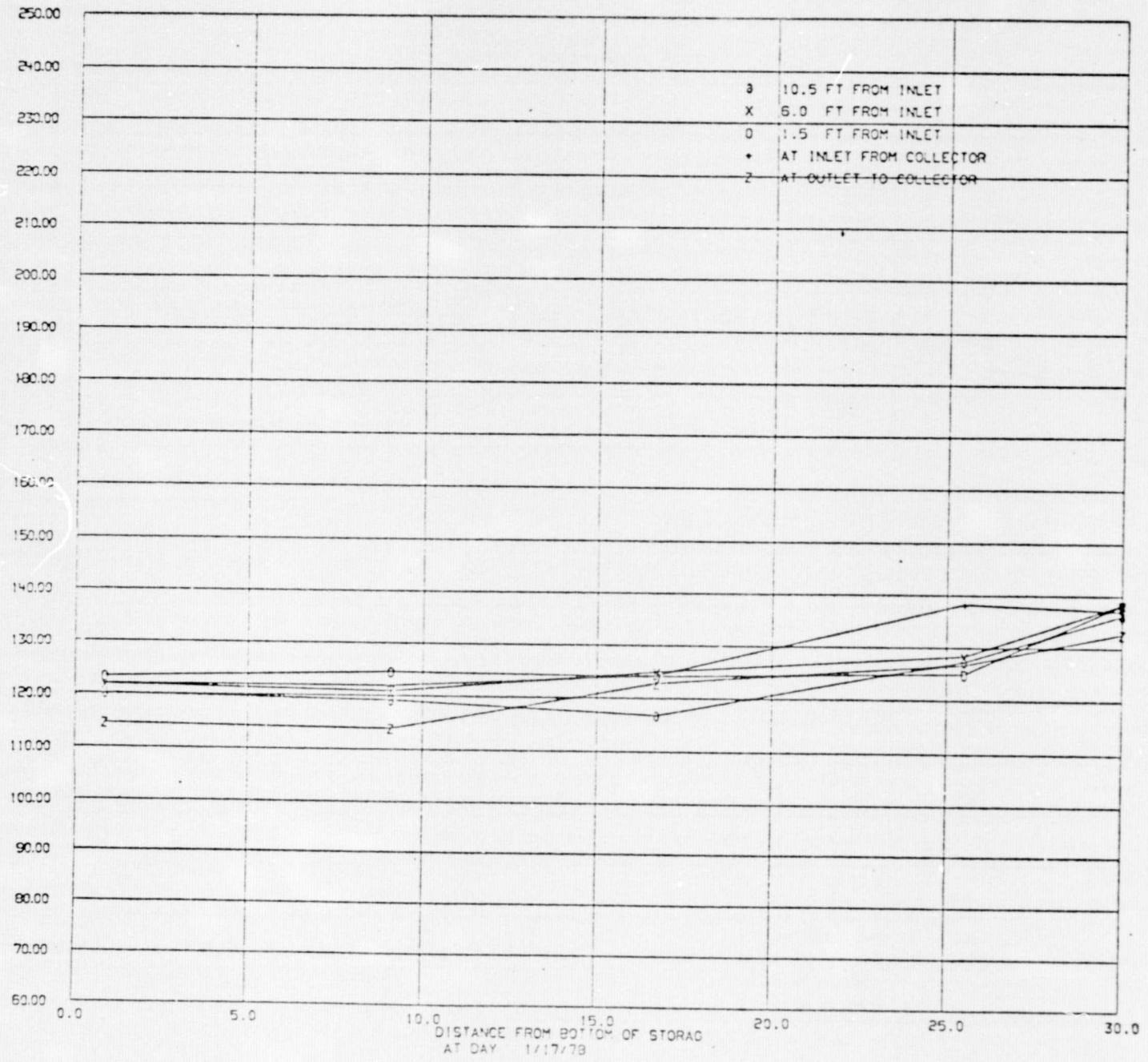


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Discharging Storage to DHW and Space Heat Subsystems

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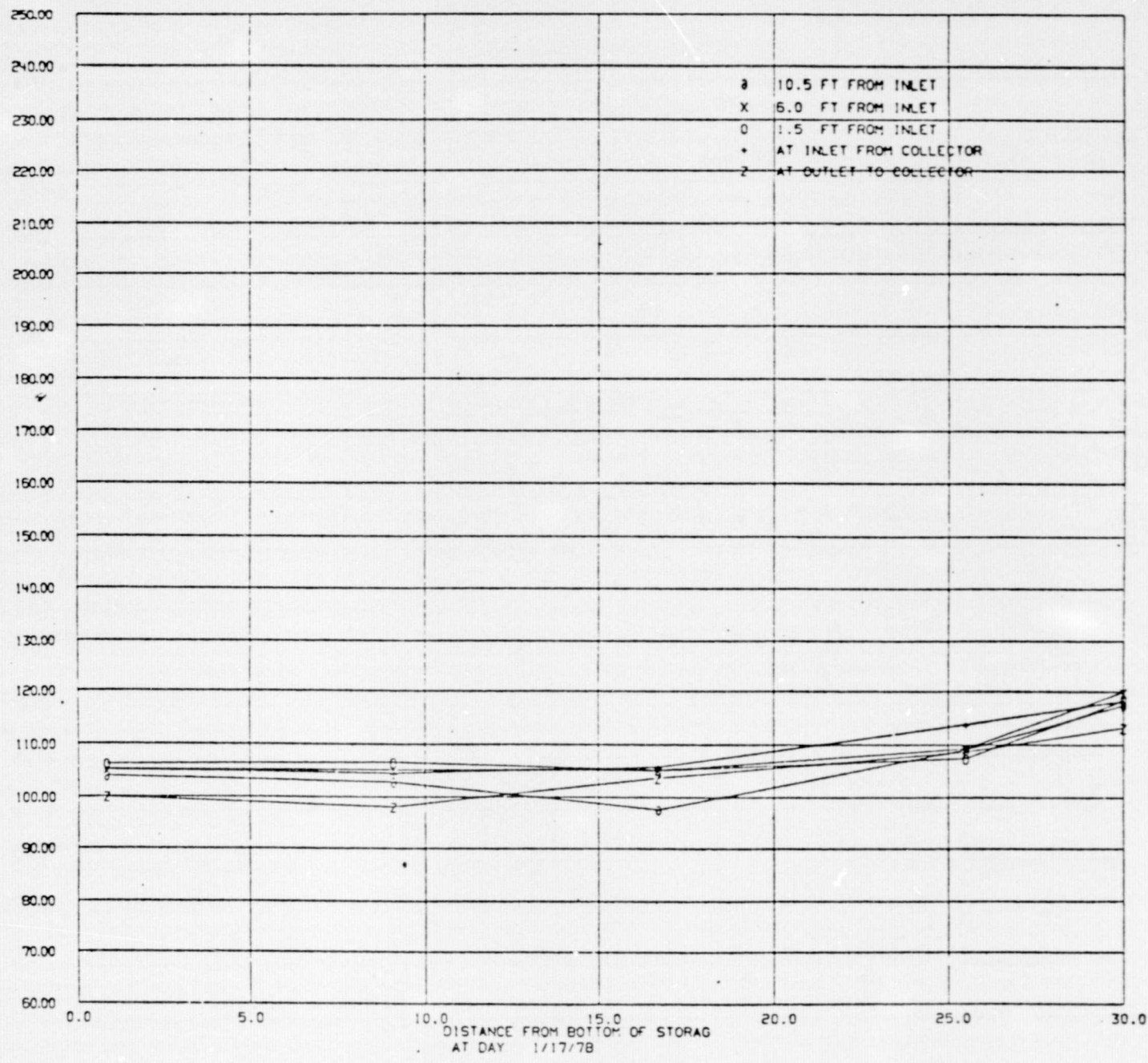
STORAGE TANK TEMP AT 12 NOON



B-5

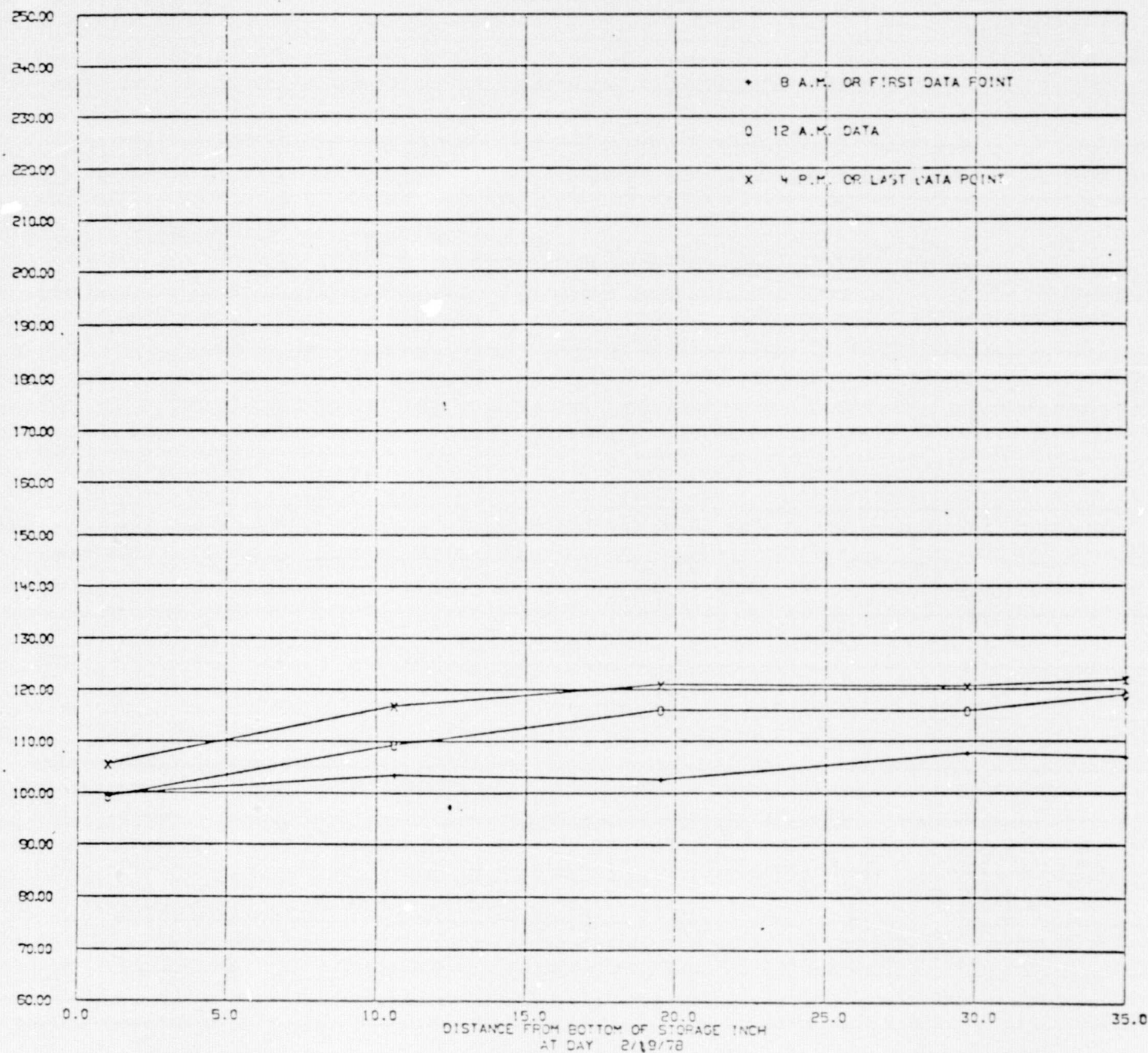
Discharging Storage to DHW and Space Heat Subsystems

STORAGE TANK TEMP AT 4 P.M. OR LAST DATA DEGF



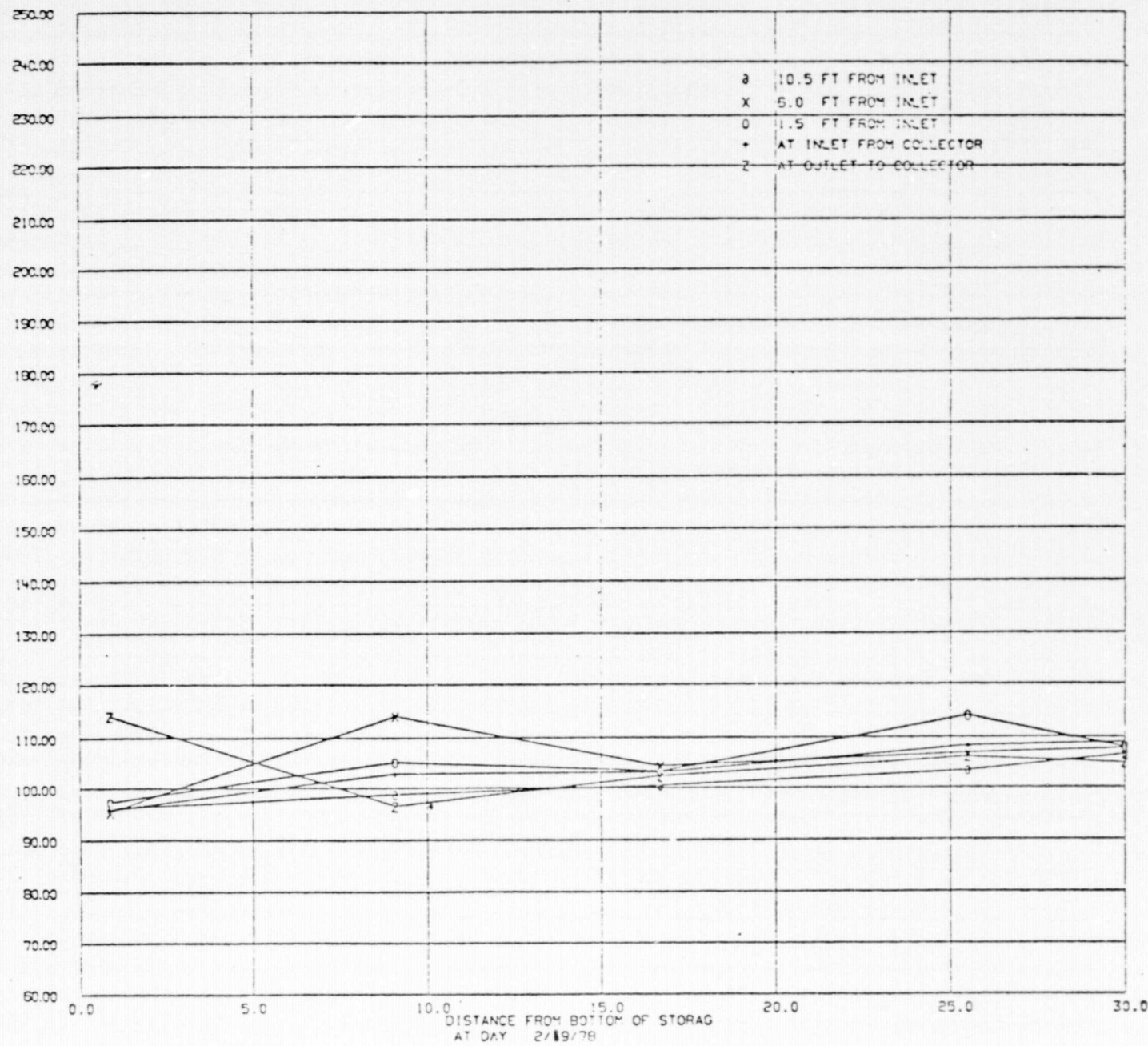
Discharging Storage to DHW and Space Heat Subsystems

RADIAL AVE TEMP IN STORAGE TANK DEGF


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Charging Storage from Test Facility Energy Source

STORAGE TANK TEMP AT 8 A.M. OR 1ST SET DATA DEGF

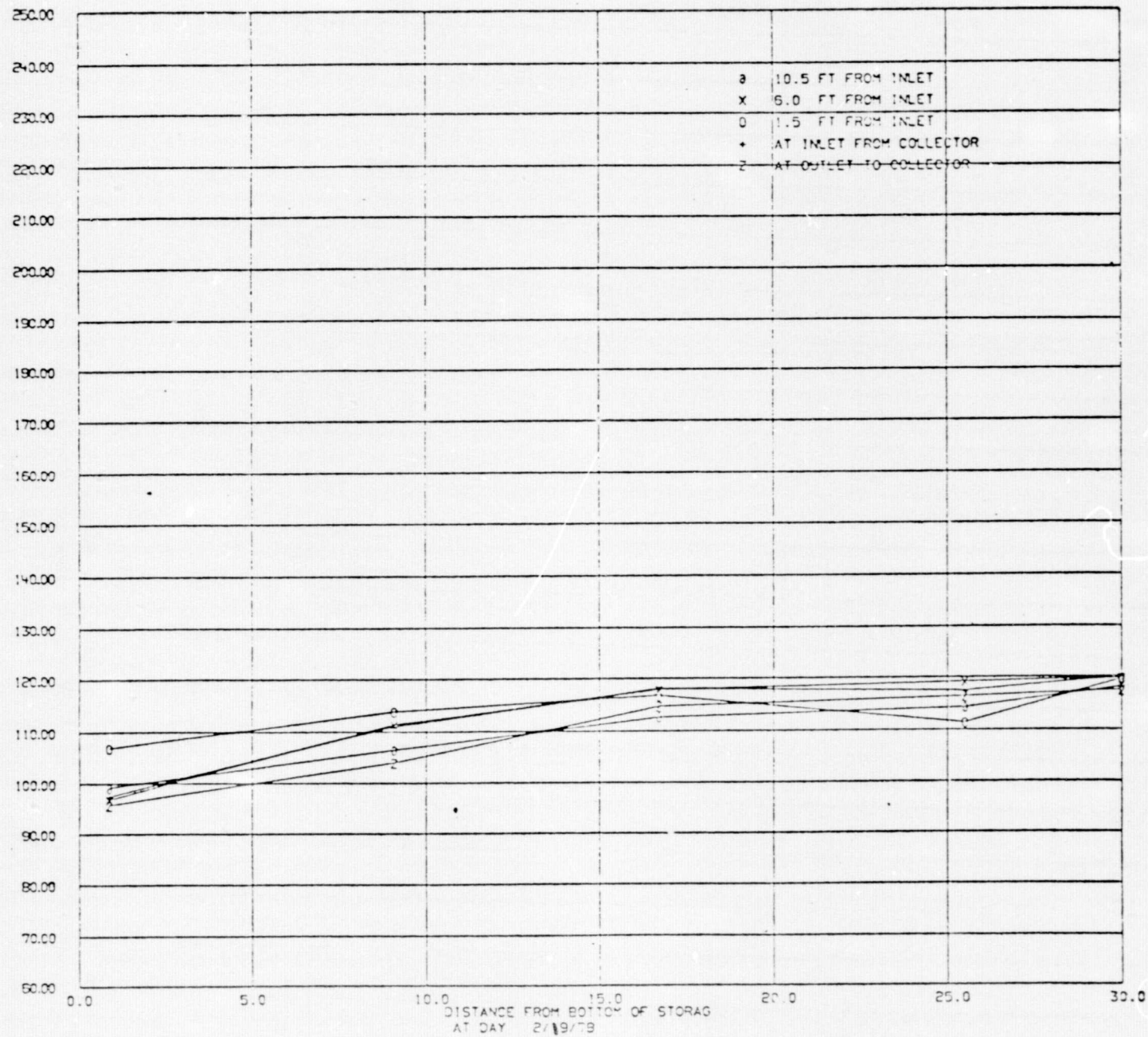


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Charging Storage from Test Facility Energy Source

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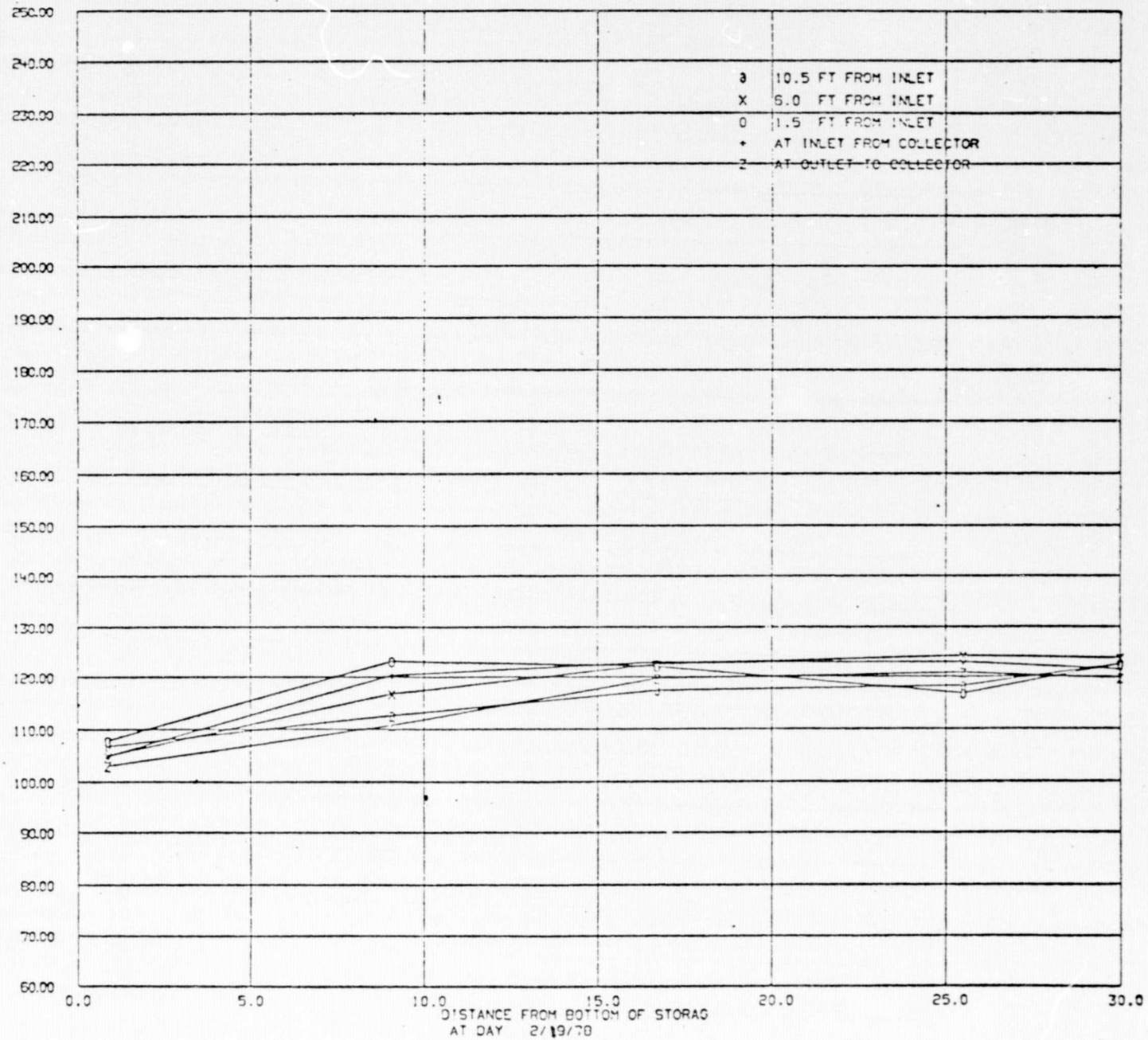
STORAGE TANK TEMP AT 12 NOON



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Charging Storage from Test Facility Energy Source

STORAGE TANK TEMP AT 4 P.M. OR LAST DATA DEG F



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