DOE/NASA CONTRACTOR REPORT

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THERMAL PERFORMANCE OF HONEYWELL DOUBLE COVERED LIQUID SOLAR COLLECTOR

Prepared by

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Under sub-contract to

IBM Corporation, Federal Systems Division, Huntsville, Alabama 35805

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This work was accomplished under the technical supervision of Charles N. Thompson, Marshall Space Flight Center.

16. ABSTRACT

This report presents the test procedures and results obtained during an evaluation test program to determine the outdoor performance characteristics of the Honeywell liquid solar collector. The program was based on the thermal evaluation of a Honeywell double covered liquid solar collection. Initial plans included the simultaneous testing of a single covered Honeywell collector. During the initial testing, the single covered collector failed due to leakage: thus, testing continued on the double covered collector only (as per test requirements). To define better the operating characteristics of the collector, several additional data points were obtained beyond those requested.

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1.0 PURPOSE

The purpose of this report is to present the test procedures used and the test results obtained during performance of an evaluation test program. The test program was conducted to determine the outdoor performance characteristics of the Honeywell liquid solar collector in accordance with the test requirements specified in Reference 2.1. Indoor evaluation of the same collectors will be reported upon completion of the indoor test program.

2.0 REFERENCES

2.1	EP45(76-82)	Outdoor/Indoor Test Comparison for Solar Collectors
2.2	MTCP-FA-SHAC-401	Procedure for Operating MSFC Subscale Facility
2.3	MTCP-DC-SHAC-402	Procedure for Thermal Performance Evaluation of the Honeywell Solar Collectors
2.4	AHSRAE-93-P	Method of Testing Solar Collectors Based on Thermal Performance
2.5	NBS-899	Development of Proposed Standards for Testing Solar Collectors and Thermal Storage Devices

3.0 MANUFACTURER

Honeywell
Minneapolis, Minnesota

4.0 SUMMARY

This test program was based on the thermal evaluation of a Honeywell double covered liquid solar collector. Initial plans included the simultaneous testing of a single covered Honeywell collector (not included in test request). During the initial testing, the single covered collector failed due to leakage; thus testing continued on the double covered collector only (as per test requirements). To better define the operating characteristics of the collector, several additional data points were obtained beyond those requested.

The results of this test are tabulated in Tables 1 through 4.

Analysis of these results are shown in Figure 3.

5.0 TEST CONDITIONS AND TEST REQUIREMENTS

5.1 Ambient Conditions

Tests were performed under the following ambient conditions.

Temperature	-	42.5 to 60.9°F
Wind Velocity	-	0.0 to 15.7 mph
Solar flux	-	152 to 303 BTU/Hr-Ft^2

5.2 Instrumentation and Equipment

All test equipment and instrumentation used for the performance of this test program complied with the requirements of MSFC MMI-5300.4C, Metrology and Calibration. A listing of the equipment used for each test is as follows:

Apparatus	Manufacturer/Model	Range and Accuracy
150°F Reference Junction	Pace/Model 150	150°F ± 1°F
Thermocouple	Copper/Constantan	-300 to +700°F ± 1°F
Resistance Thermometer	Thermal Systems, Inc./ T200	0 to 500°F ± 0.05°F
Pyronometer	Eppley/8-48	0-400 ± 10% BTU/Hr·Ft^2
Anemometer	MSFC Supplied	
Flowmeter	Foxboro/Model 81	0.1 to 2.5 GPM ± 1%

6.0 REQUIREMENTS, PROCEDURES AND RESULTS

6.1 Test Title

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Thermal Performance Evaluation

6.1.1 Requirements

The requirements of this test were to obtain performance information at 100, 150 and 200°F inlet temperatures with the flow rate controlled at 120 pounds per hour. While the solar flux was between 190 and 360 BTU/Hr-Ft^2, the following data were recorded for the the test.

1) Collector side wall temperature (°F)
2) Absorber surface temperature - west side (°F)
3) Absorber surface temperature - south side (°F)
4) Absorber surface temperature - north side (°F)

5) Outer cover temperature (°F)

6) Inner cover temperature (°F)

7) Absorber surface temperature - Center (°F)

8) Ambient temperature (°F)

9) Fluid inlet temperature (°F)

10) Fluid inlet temperature (°F)

11) Fluid differential temperature (°F)

12) Fluid flow rate (Lbm/Hr)

13) Total solar flux ($BTU/Hr\text{-}Ft^2$)

14) Wind velocity (MPH)

15) Wind direction (degrees from north)

6.1.2 Procedure

The procedure followed for each of the three test conditions indicated in section 6.1.1 may be found in Appendix A of this report. For the stagnation data point, the facility fluid loop was secured and the collector drained. All valves and controls referred to in Appendix A are identified in Figures 1 and 2.

6.1.3 Results

The results of this test are shown in Tables 1 through 4. Each test result cell is determined by averaging that cell over a period of time in which the test requirements are continuously met. The number in parentheses with each result cell indicates the standard deviation about the mean for the data represented by the cell.

7.0 ANALYSIS

The analysis of data contained in this report is in accordance with the National Bureau of Standards recommended approach. This approach is outlined below.

The efficiency of a collector is stated as:

$$\eta = \frac{q_u/A}{I} = \frac{\dot{m}\, C_{tf}\left(t_{f,e} - t_{f,i}\right)}{I} \qquad (1)$$

where:

q_u = rate of useful energy extracted from the Solar Collector (BTU)

A = Cross-sectional area (ft^2)

I = Total solar energy incident upon the plane of the solar collector per unit time per unit area ($BTU/Hr\text{-}Ft^2$)

$\dot{m}$ = Mass flow rate of the transfer fluid through the collector per unit cross-sectional area of the collector ($Lbm/Ft^2.Hr$)

$C_{t,f}$ = Specific heat of the transfer fluid ($BTU/Lb \cdot °F$)

$t_{f,e}$ = Temperature of the transfer fluid leaving the collector (°F)

$t_{f,i}$ = Temperature of the transfer fluid entering the collector (°F)

Rewriting Equation (1) in terms of the total collector area we get:

$$\eta = \frac{(\dot{m}A)\ C_{tf} \left(t_{fe} - t_{fi}\right)}{(IA)} = \frac{\dot{M}\ C_{tf} \left(t_{fe} - t_{fi}\right)}{P_i} \qquad (2)$$

Notice that:

P_i = IA = Total Power Incident on the Collector

$\dot{m}A = \dot{M}$ = Total Mass flow rate through the Collector

Since $\dot{M}\ C_{tf} \left(t_{f,e} - t_{f,i}\right)$ = Total Power Collected by the Collector

Substitution in Equation (2) results in:

$$\eta = \frac{P_{abs}}{P_{inc}} \qquad (3)$$

where:

P_{abs} = Total collected power

P_{inc} = Total incident power

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This value of efficiency is expressed as a percentage by multiplying by 100. This expression for percent efficiency is:

$$\text{Collector Efficiency} = \frac{P_{abs}}{P_{inc}} \times 100 \qquad (4)$$

or from Equation (2), collector efficiency is defined by the equation:

$$\%\ \text{Eff.} = \frac{\dot{M}\ C_{tf}\ \left(t_{f,e} - t_{f,i}\right)}{P_i} \times 100 \qquad (5)$$

Each term in Equation (5) was measured and recorded independently during the test. The calculated values of efficiency were determined at two-minute intervals. The mean value of efficiency was determined over a fifteen-minute period during which the test conditions remained in a quasi-steady state. Each fifteen-minute period constitutes one "data point" as is graphically depicted on a plot of percent efficiency versus ($(t_{fi}-t_a)$ /I).
Where:

$t_{f,i}$ = Fluid inlet temperature (°F)

t_a = Ambient temperature (°F)

I = Incident flux per unit area (BTU/Hr-Ft^2)

The abscissa term ($(t_{fi}-t_a)/I$) was used to normalize the effect of operating at different values of I, $t_{f,i}$ and t_a. The results are found in Figure 3.

The result of second order polynomial analysis is shown in Figure 3. The second order polynomial to best describe the test results is:

$$\text{Efficiency} = -\Gamma^2 * .10842 - \Gamma * .54263 + .72921$$

where:

$$\Gamma = (t_i - t_a)/I$$

The mean deviation of the prediction error based on the second order fit is .025.

TABLE 1. HONEYWELL TEST RESULTS

10/18/76		1	2	3
Collector Side	°F	84.3(0.5)*	89.7(0.7)	90.3(0.6)
West Surface	°F	199.6(0)	207.3(0.2)	200.8(0.1)
South Surface	°F	196.9(0.2)	202.6(0.2)	203.1(0.1)
North Surface	°F	210.5(0.3)	213.2(0.2)	212.6(0.1)
Out-Cover	°F	95.8(0.8)	92.9(1.1)	98.9(1.3)
Collector Back	°F	71.9(0.2)	75.7(0.2)	76.9(0.2)
Center Surface	°F	205.1(0.3)	209.1(0.3)	209. (0.1)
Inner Cover	°F	188.3(0.2)	188.1(0.1)	187.2(0.2)
Amb	°F	86.8(0.1)	60.5(0.3)	60.9(0.4)
WV	MPH		10.6(3.4)	7.5(3.5)
WD	Degree		86.7(36.7)	169.5([illegible].6)
Solar Flux	BTU/Ft^2 Hr	269.5(1.9)	235.6(2.7)	202.7(9.6)
Flow	Lbm/Hr	119.8(0.1)	120.2(0.2)	123.3(0.2)
Tin	°F	193.9(0.2)	200.3(0.1)	201.4(0.1)
ΔT	°F	11.3(0.2)	8.1(0.1)	6.9(0.2)
Efficiency	%	42.0(0.9)	34.9(0.9)	35.1(2.1)
$(T_i-T_a)/I$	°F Ft^2 Hr/BTU	.397	.593	.693

*Standard Deviation

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TABLE 2. HONEYWELL TEST RESULTS

10/21/76	1	2	3	4
Collector Side °F	72.9(0.6)*	79.6(0.2)	85.1(0.8)	84.2(0.4)
West Surface °F	207.5(0.9)	205.9(0.2)	201.8(0.1)	199.2(0.6)
South Surface °F	203.3(1.2)	201.6(0.1)	200.8(0.2)	201.0(0.3)
North Surface °F	213.4(0.5)	213.4(0.2)	211.4(0.2)	209.3(0.5)
Out-Cover °F	85.0(0.6)	86.5(0.4)	87.9(1.6)	85.9(1.0)
Collector Back °F	59.2(0.3)	65.2(0.2)	71.7(0.1)	72.9(0.1)
Center Surface °F	209.7(0.9)	208.8(0.1)	207.3(0.2)	206.1(0.4)
Inner Cover °F	187.2(0.2)	189.1(0.3)	187.0(0.4)	182.6(0.7)
Ambient °F	49.0(0.6)	52.2(0.4)	55.1(0.5)	55.9(0.5)
WV MPH	0 (0)	8.4(10.4)	15.7(8.3)	11.7(0.6)
WD Degree	305.8(39.0)	314.6(14.0)	293.9(18.1)	302.7(10.7)
Solar Flux $\frac{BTU}{Ft^2\,Hr}$	255.8(2.0)	250.3(3.9)	254.0(11.1)	221.9(1.8)
Flow Lbm/Hr	118.4(2.0)	119.3(0.7)	119.6(0.3)	120.0(0.4)
Tin °F	200.7(0.4)	199.0(0.2)	198.6(0.6)	199.8(0.3)
Δ T °F	9.3(0.4)	10.6(0.3)	9.2(0.7)	6.1(0.1)
Efficiency %	36.1(1.6)	42.5(1.0)	36.2(1.0)	27.7(0.3)
$(T_i-T_a)/I$ $\frac{°F\ Ft^2 Hr}{BTU}$	0.593	0.586	0.569	0.648

*Standard Deviation

TABLE 3. HONEYWELL TEST RESULTS

10/28/76	1	2	3	4
Collector Side °F	67.8(0.7)*	68.3(0.5)	74.2(0.4)	82.2(0.5)
West Surface °F	118.0(0.4)	120.1(0.3)	165.9(0.4)	168.7(0.6)
South Surface °F	108.2(0.2)	109.9(0.2)	158.2(0.6)	165.5(0.6)
North Surface °F	124.3(0.7)	127.3(0.4)	174.3(0.2)	177.1(0.8)
Out-Cover °F	68.9(1.6)	69.6(0.8)	84.1(0.7)	82.1(1.0)
Collector Back °F	51.8(0.2)	54.7(0.2)	62.7(0.1)	68.9(0.1)
Center Surface °F	118.4(0.4)	120.8(0.3)	168.6(0.3)	173.0([illegible].7)
Inner Cover °F	123.6(0.5)	126.1(0.5)	162.3(0.3)	160.6(0.7)
Ambient °F	45.6(0)	48.1(0.7)	53.1(0.4)	55.0(0.4)
WV MPH	8.3(1.8)	8.6(1.9)	9.2(1.9)	5.8(1.1)
WD Degree	74.1(3.1)	120.0(27.7)	121.8(21.0)	63.1(62.8)
Solar Flux $\frac{BTU}{Ft^2\ Hr}$	240.2(	279.6(5.9)	290.0(1.9)	251.2(9.9)
Flow Lbm/Hr		121.8(0.1)	121.3(0.1)	122.8(0.1)
Tin °F	101.3(0.0)	102.6(0.0)	151.0(0.7)	161.4(0.2)
Δ T °F	16.2(.3)	17.2(0.2)	16.5(0.4)	10.7(0.5)
Efficiency %	63.7(.6)	58.6(1.6)	56.1(1.6)	42.5(7.3)
$(T_i-T_a)/I$ $\frac{°F\ Ft^2\ Hr}{BTU}$	.232	.195	0.338	0.424

*Standard Deviation

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TABLE 3 (Continued)

	5	6	7
Collector Side °F	82.9(0.6) *	83.4(0.2)	82.9(0.2)
West Surface °F	163.3(0.5)	156.[illegible](0.4)	155.8(0.1)
South Surface °F	161.0(0.4)	156.0(0.3)	155.5(0.2)
North Surface °F	172.5(0.6)	165.8(0.5)	165.2(0.1)
Out-Cover °F	84.1(1.5)	84.6(0.3)	82.4(1.4)
Collector Back °F	68.9(0.1)	70.2(0.0)	70.3(0.0)
Center Surface °F	168.2(0.6)	162.1(0.3)	161.6(0.1)
Inner Cover °F	156.9(1.0)	150.2(0.2)	150.3(0.2)
Ambient °F	53.8(1.5)	55.0(0.3)	55.6(0.0)
WV MPH	9.3(3.6)	5.6(2.1)	7.3(3.7)
WD Degree	94.2(4.2)	127.9(30.3)	108.6(70.3)
Solar Flux $\frac{BTU}{Ft^2\ Hr}$	220.4(30.9)	192.2(3.6)	198.8(1.2)
Flow Lbm/Hr	118.8(0.1)	119.5(0.1)	119.5(0.0)
Tin °F	156.8(0.3)	152.4(0.2)	151.7(0.4)
Δ T °F	10.5(0.5)	8.6(0.1)	8.8(0.2)
Efficiency %	46.5(7.3)	43.3(1.1)	42.8(1.0)
$(T_i-T_a)/I$ $\frac{°F Ft^2\ Hr}{BTU}$	0.467	0.507	0.482

*Standard Deviation

TABLE 4. HONEYWELL TEST RESULTS

10/29/76	1	2
Collector Side °F	61.9(0.3)*	61.6(0.2)
West Surface °F	110.2(0.4)	108.9(1.7)
South Surface °F	101.0(0.4)	100.6(0.8)
North Surface °F	116.6(0.3)	115.3(1.9)
Out-Cover °F	70.5(0.4)	68.6(1.3)
Collector Back °F	50.6(0.2)	51.3(0.3)
Center Surface °F	110.7(0.4)	110.0(2.1)
Inner Cover °F	117.2(0.6)	113.7(2.6)
Ambient °F	50.3(1.5)	49.2(0.3)
WV MPH	8.1(2.3)	10.5(1.7)
WD Degree	149.2(23.5)	163.3(25.2)
Solar Flux $\frac{BTU}{Ft^2\ Hr}$	242.4(9.5)	184.8(19.3)
Flow Lbm/Hr	124.7(0.1)	125.0(0.1)
Tin °F	94.9(0.3)	95.6(0.1)
Δ T °F	14.9(0.2)	12.5(1.5)
Efficiency %	58.6(3.1)	64.9(7.1)
$(T_i-T_a)/I$ $\frac{°F\ Ft^2\ Hr}{BTU}$	.184	.251

*Standard Deviation

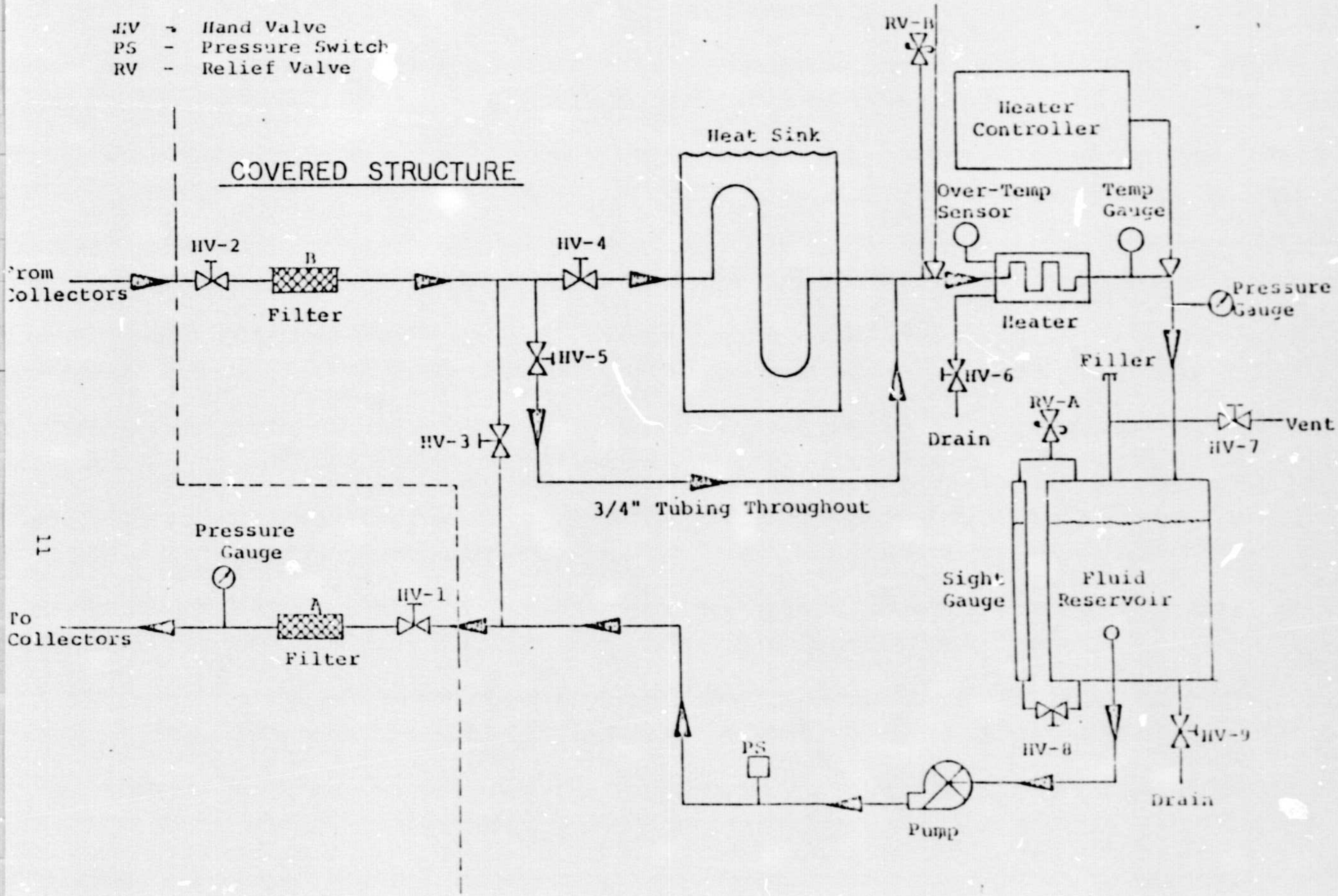

FIGURE 1. M SOLAR SUBSCALE TEST FACILITY FLOW DIAGRAM

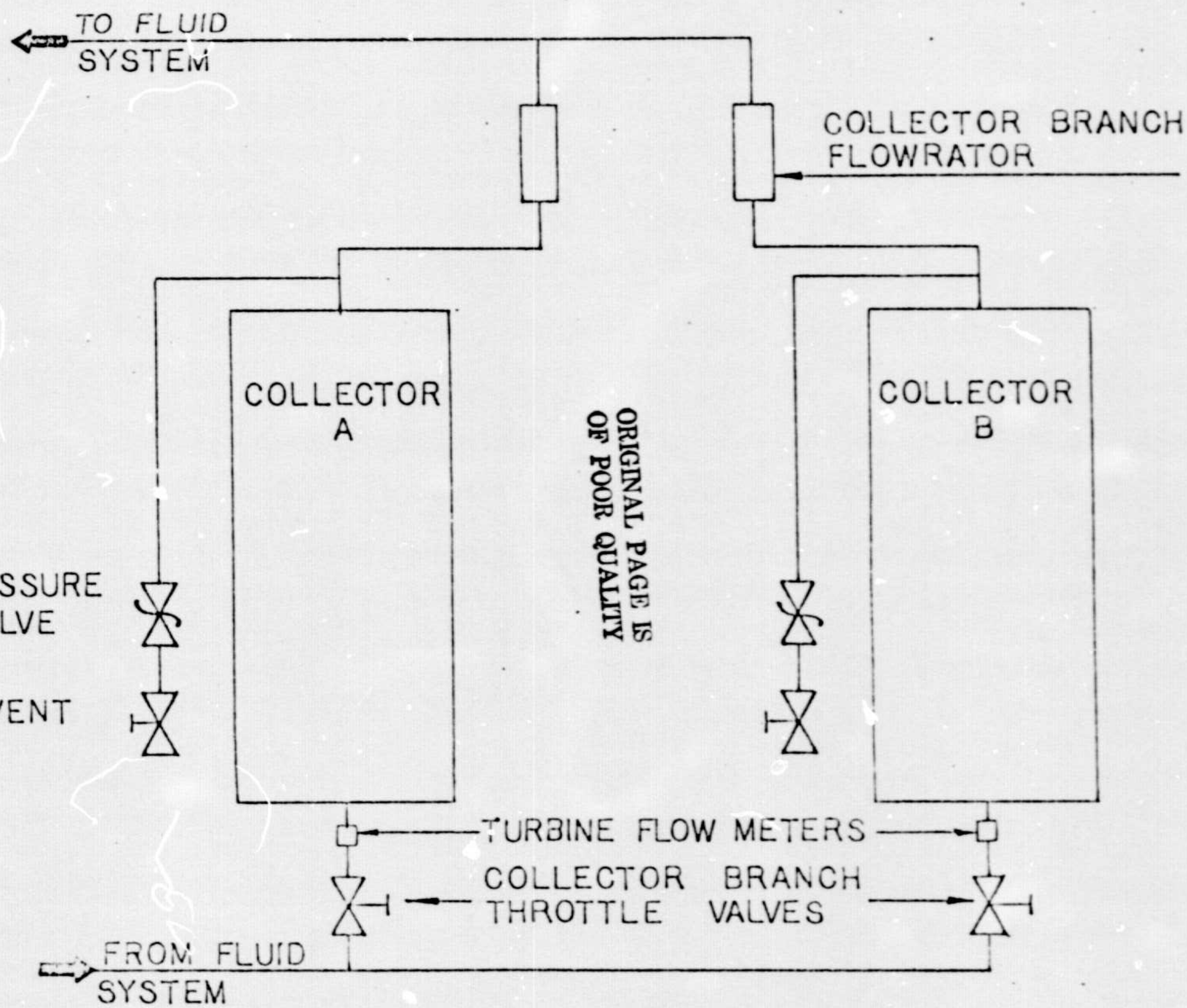

FIGURE 2. TYPICAL COLLECTOR SET UP FOR SUBSCALE FACILITY

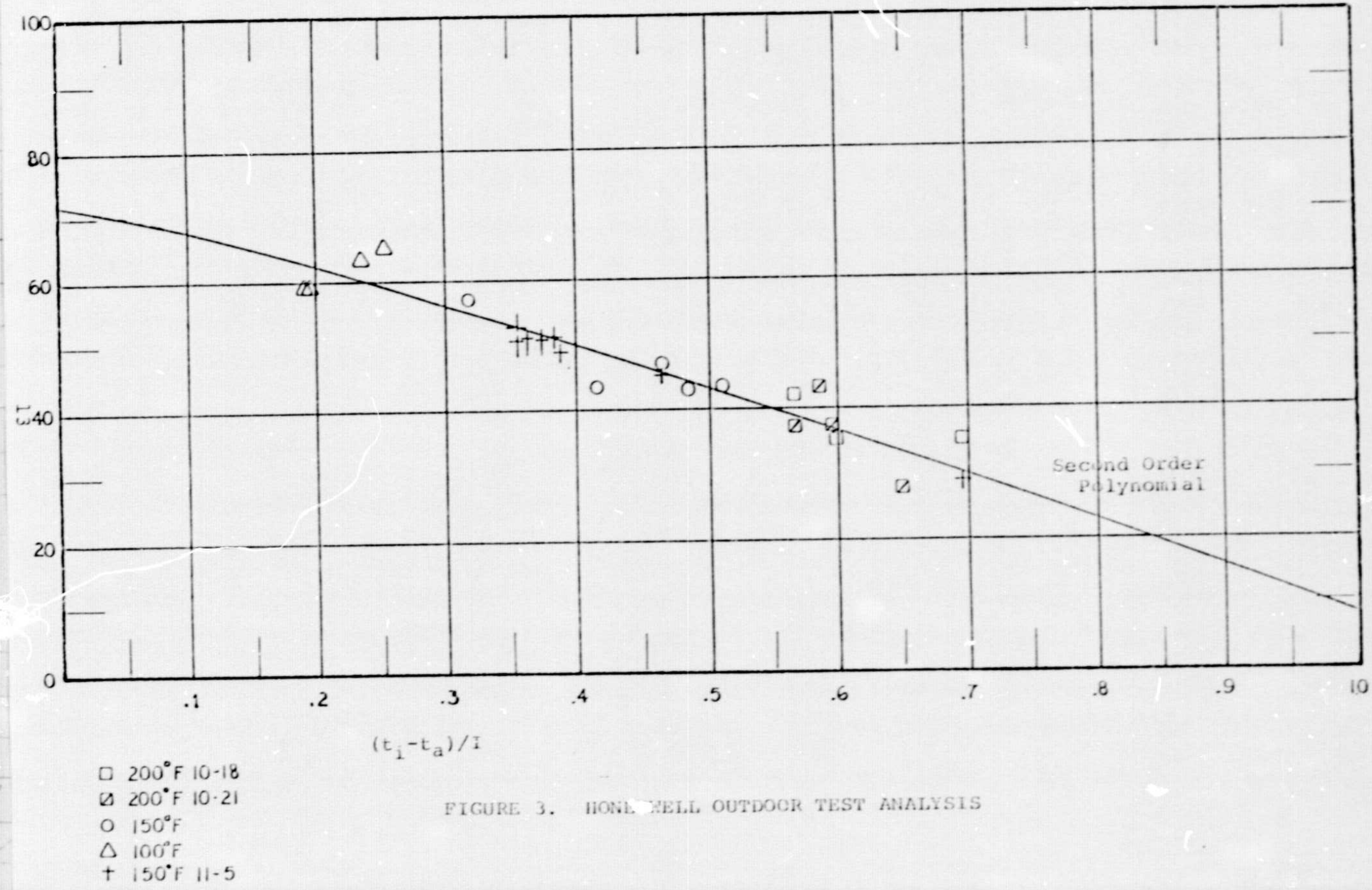

FIGURE 3. HONEYWELL OUTDOOR TEST ANALYSIS

APPENDIX A

CHECKLIST FOR THE
SUBSCALE LIQUID FLOW SYSTEM

PRIOR TO TESTING --

1.0 Assure that:

a) Fluid reservoir is at least 75% full.

b) Fluid pump is OFF.

c) Fluid heater is OFF.

d) Hand Valves HV1, HV2, HV4, HV6, HV8 and HV9 are CLOSED.

e) Hand Valves HV3, HV5, HV7 and Collector Branch Throttle Valves are OPEN.

f) Vent Valves to each Collector Branch are CLOSED.

2.0 Turn ON fluid pump.

3.0 Set power controller to proper set point -- Consult Controller Manual -- for the desired INLET TEMPERATURE.

4.0 Assure that: H-P Computer System is functioning.

5.0 Turn ON heater controller.

6.0 OPEN HV2 completely.

7.0 SLOWLY OPEN HV1. [A surge of fluid into the collectors could cause personal harm or property damage.]

8.0 Adjust HV3 to obtain approximately 0.5 GPM as indicated on the minimum reading flow rate indicator. [A wait of several minutes may be necessary to clear the system of air.]

9.0 Adjust independent Collector Branch Throttle Valves as necessary to balance the flow in all branches.

10.0 Monitor heater inlet temperature and adjust HV-4 as necessary to obtain a temperature approximately 5°F below the desired Collector inlet temperature.

11.0 Adjust the heater controller as necessary to obtain the desired Collector inlet temperature.

12.0 Allow the Collector fluid inlet temperature to stabilize at the proper temperature test parameter.

13.0 Adjust HV3 as necessary to obtain the proper flow test parameter. (Adjustment of HV1 may be necessary at low flow rates.)

<u>IF</u> system is stable, i.e., test parameters have not varied by $\pm 1\%$ over the past 10 minutes, and the test parameters are at their proper values, i.e., Q, F, T-IN are at the value requested for the particular test, <u>THEN</u> the test is ready to begin.

<u>DURING THE TEST</u> --

1.0 Adjust and record as necessary:

a) Collector Throttle Valves to maintain balanced Collector Branch flow.

b) HV3 to maintain proper flow rate.

c) Power set point to maintain proper temperature of inlet fluid.

d) HV4 to maintain heater inlet temperature 5°F below the Collector inlet temperature.

2.0 Underline the printed time if the solar flux falls below the prescribed flux level.

3.0 Notify Test Director if solar flux is less than the prescribed test flux level for a period greater than 10 minutes.

<u>AFTER THE TEST</u> --

1.0 Turn <u>OFF</u> power controller.

2.0 <u>OPEN</u> HV3 and HV4.

3.0 Turn <u>OFF</u> fluid pump.

4.0 <u>OPEN</u> HV8, Throttle Valves and Vent Valves to each Collector Branch.

5.0 Turn <u>OFF</u> teletype.

N O T I C E

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