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Test Methods for Evaluating Performance of Solar Units

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TEST METHODS FOR EVALUATING
PERFORMANCE OF SOLAR UNITS

BY

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ABSTRACT

This report is concerned with the performance of solar hot water units for laboratory and field use. A solar unit is defined as a system consisting of a collector, storage tank, piping system and controls. Older units typically employ the thermosyphon principle (gravity) while more recent models use a water pump to circulate the water. Basically, the collector absorbs solar radiation and transfers thermal energy to the water flowing in the collector tubing. From the collector, the fluid is pumped to the storage tank at which point the hot water is available for usage.

A literature search revealed that very little information was available concerning test procedures. The National Bureau of Standards (NBS) has generated proposed test procedures for separate testing of the collector and storage tank, but they do not include testing of the total system. The only other suggested test procedure found was by Stotter and Robinson , these authors include a discussion of the total system. Stotter and Robinson along with (NBS) provided the starting point for this report.

In the report it is shown that qualitative properties are equally as important as quantitative properties. Quantitative properties are defined as temperature, flowrate, solar radiation or insolation, wind velocity and direction. Qualitative

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properties are defined as shade, weather resistance, corrosion resistance, location and maintenance.

To determine which solar unit properties would be useful in comparing performance values, test reports along with the other references on solar unit testing were studied. After a review of all the reference material the following performance parameters were obtained and are believed to be of use in comparing solar units. These parameters are discussed in detail in the text of the report.

1. η_{th}, the practical thermal efficiency
2. ρ_{STOR}, the heat storage coefficient.
3. Q, the solar unit capacity
4. C_{eff}, capacity efficiency

It was found from the error analysis that the recommended instrumentation and test procedure, presented herein, should result in less than $\pm$ 10% error in the calculation of performance parameters. Temperature measurement error was found to be the largest contributor to the overall error.

It is recommended that the test procedure herein be used for Florida Technological University testing of laboratory and field solar units, and that future work be performed to develop a method of rating solar units.

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NOMENCLATURE

English Letters

A	Collector gross cross sectional area, $M^2 (ft^2)$
A_T	mean heat transfer area of tank wall, $M^2 (ft^2)$
b	odds that experimenter is willing to wager that the error will be less than W
C_{eff}	capacity efficiency (drawoff)
C_P	specific heat of fluid at constant pressure, CAL/GR-^{O}C (BTU/LBM^{O}F)
E_A	daily amount of energy supplied by auxiliary unit for hot water, CAL/HR/DAY (BTU/HR/DAY)
E_R	$E_S + E_A$, daily amount of energy required by user demand for hot water, CAL/HR/DAY (BTU/HR/DAY)
E_S	daily amount of energy supplied by the collector for hot water, CAL/HR/DAY (BTU/HR/DAY)
I	total short-wave radiation from sun and sky as a 30 minute integrated quantity, W/M^2 (BTU/HR ft^2)
I'	$I' = IA$, WATTS (BTU/HR)
M	arithmetic mean of observed value
m	mass of water, GR (LBM)
$\dot{m}$	fluid flowrate, GR/HR (LBM/HR)

Q	capacity of solar unit, CAL/HR (BTU/HR)
R	value of the result (see page 46)
T_{amb}	collector ambient air temperature, $^{o}C(^{o}F)$
T_B	temperature on back of collector, $^{o}C(^{o}F)$
$T_{c,e}$	collector exit fluid temperature, $^{o}C(^{o}F)$
$T_{c,i}$	collector inlet fluid temperature, $^{o}C(^{o}F)$
T_s	storage tank ambient air temperature, $^{o}C(^{o}F)$
$T_{s,e}$	final water temperature for capacity test, $^{o}C(^{o}F)$
$T_{s,i}$	initial water temperature for capacity test, $^{o}C(^{o}F)$
$T_{s,1}$	storage tank temperature (top), $^{o}C(^{o}F)$
$T_{s,2}$	storage tank temperature (middle), $^{o}C(^{o}F)$
$T_{s,3}$	storage tank temperature (bottom), $^{o}C(^{o}F)$
T_{st}	average storage tank water temperature, $^{o}C(^{o}F)$
$T_{st,i}$	supply inlet water temperature, $^{o}C(^{o}F)$
$T_{st,1}$	average storage tank water temperature at beginning of test period, $^{o}C(^{o}F)$
$T_{st,2}$	average storage tank water temperature at end of test period, $^{o}C(^{o}F)$
U	overall heat transfer conductance from the outer tank wall to the ambient, CAL/HR^{o}C (BTU/HR^{o}F)
V	value of one of the variables in uncertainty analysis
W	uncertainty interval or error interval
W_r	uncertainty interval in the result
W_m	uncertainty interval in one of the variables

Greek Letters

η_{th}	practical collector thermal efficiency
ρ_{STOR}	heat storage coefficient
τ	time period, hr.

Subscripts

A	auxiliary unit
amb	ambient
B	back of collector
c,e	collector exit
c,i	collector inlet
eff	efficiency
m	a particular vaiable
P	constant pressure
R	required by user
r	result
S	supplied by collector
s	storage tank ambient
s,e	final
s,i	initial
s,1	storage tank (top)
s,2	storage tank (middle)
s,3	storage tank (bottom)
st	average storage tank

st,1	average of storage tank at beginning of test period
st,2	average of storage tank at end of test period
STOR	storage
T	heat transfer
th	thermal

CHAPTER I

FOREWORD

1.1 Problem Description

The present energy crisis has generated considerable interest in solar energy on a national as well as state and local level. Heat collected from the sun has been used for many years to provide space heating and hot water [1], however, currently only the latter seems economically feasible. Many corporations and individuals throughout the State of Florida are now considering entering the solar energy market, primarily for generation of domestic hot water. There is very little test data or information on test procedures for evaluating solar hot water systems. It would be convenient to have a standard method for testing solar hot water systems both in the laboratory and field to provide performance and relative quality information. This report was prepared to provide a standard test method for the FTU Mobile Solar Laboratory.

1.2 Scope of Work

This report presents the results of an extensive literature search for test procedures related to testing solar hot water systems, it describes in detail recommended test procedures for testing present solar hot water systems. The report is limited to systems utilizing liquids as the heat transfer medium.

1.3 Literature

A solar unit is defined as a system consisting of a collector, storage tank, piping system and controls. Figure 1.3-1 presents a sketch of a typical thermosyphon solar unit. Most of the early solar units are of this type while some of the more recent models employ a water pump to circulate the water.

From the recent publicity, one would think that solar energy collection is a current innovation. However, a solar energy bibliography[2] shows significant works in solar water heating performed as early as 1859. Many of the early efforts involving tests were mainly concerned with the insolation or solar radiation measurements. As a result, this topic has been treated rather extensively down through the years. There have been many studies performed on the flat plate collector -- storage tank solar system. Unfortunately, none of these studies discussed test procedures in any detail. The primary discussion pertained only to the actual test results without any reference to test procedures.

An excellent discussion on the theory and operation of solar units is presented in the article by Jordan[3]. Basically, the collector absorbs solar radiation and transfers thermal energy to the water flowing in the collector tubing. From the collector the water is pumped to the storage tank by a pump or thermosyphon pumping at which point the hot water is available for usage. Many variations exist, however, the basic functions are collection of solar energy and storage of that energy.

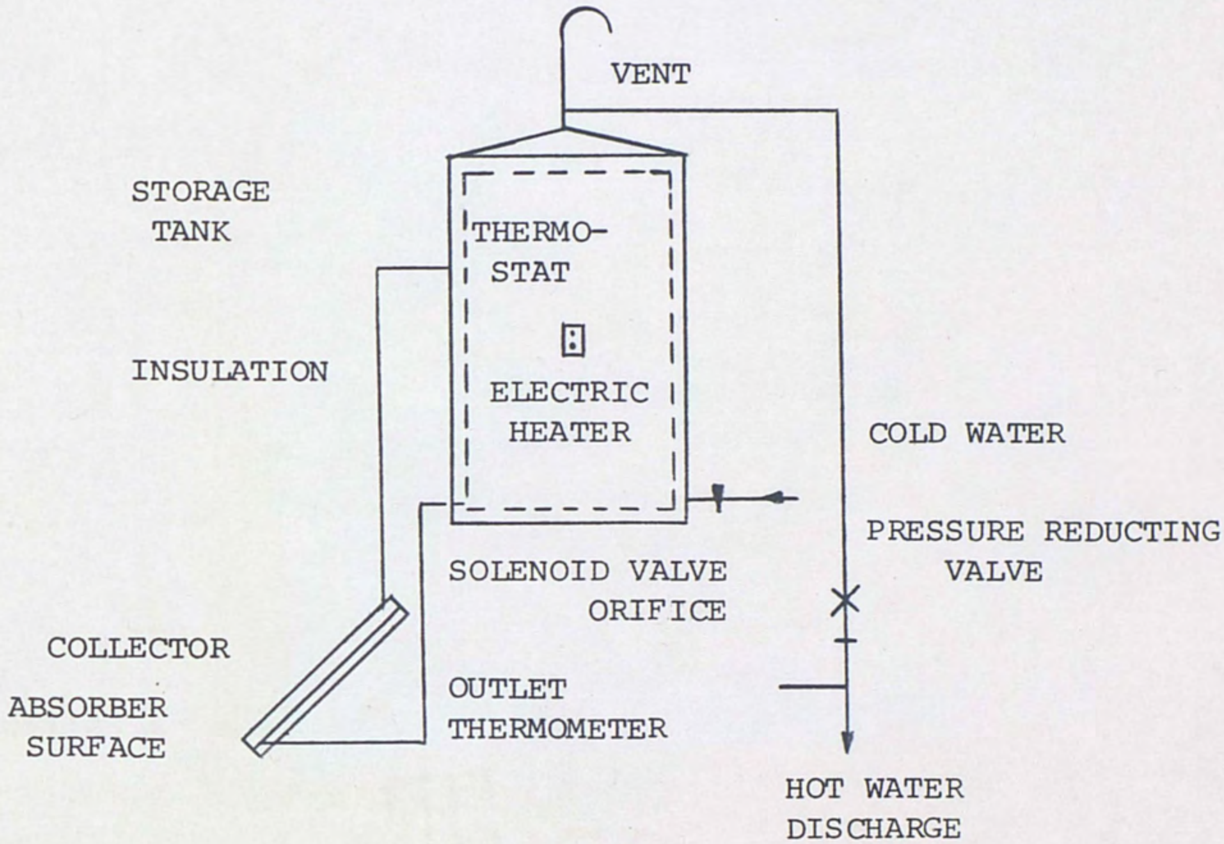

Figure 1.3-1. THERMOSYPHON TYPE SOLAR UNIT

Many of the references included herein do not deal with test procedures but rather with performance properties of solar units. These references were included to indicate the importance of giving equal weight to qualitative and quantitative comparisons between solar units. For example, it is shown that a bad solder bond between the collector tubing and absorber plate can result in an efficiency decrease of 17%.[3,4] Thus, bond conductance is an important parameter in collector testing. A comparison of two identical solar units with different qualitative properties can result in large differences in performance parameters. For example, suppose the only difference in the two collectors is the amount of maintenance provided by the respective owners. How the user maintains the unit directly affects the efficiency, that is, if the user neglects to maintain the unit, external and internal material parts will corrode and this degrades performance. Whillier also points out that even though the absorber is coated with a selective coating, the collector could still exhibit poor efficiency, since the bare metal could have corroded before the coating process. This amplifies the above advice of basing evaluation criteria on both qualitative and quantitative results. In the above examples the quantitative test results would have indicated one collector to be superior, however, with the qualitative results a different conclusion might result. Czarnecki presents useful quantitative data for solar water heaters in Australia. Measurements monitored daily were; amount of hot water discharged, electrical energy consumed, inlet water

temperature, and discharge water temperature. Data is presented in tabular form, the most useful parameter being mean solar contribution. This term is most meaningful when comparing solar units and will be discussed later under capacity efficiency. Czarnecki also shows that use of a screen over the collector for hail protection reduces the efficiency by about 12%, in Brisbane, Australia.[6] A discussion is presented below on solar unit instrumentation and test results.

Penrod and Prasanna discuss some of the practical aspects of the design of a solar unit and indicate "that the randomness in year-by-year variation of monthly average value of insolation may cause efficiency variation as much as 30%."[7] They also point out that Brooks' empirical equation can be used to convert available horizontal insolation data to other orientations with an accuracy of about $\pm$ 5%. With respect to error in insolation measurement it is found that an accuracy of $\pm$ 5% in the insolation measurement is acceptable, since the design data such as instrument friction and the very hypotheses of the efficiency calculations contain greater errors.[8] The overall error in calculation of performance parameters such as efficiency and capacity, resulting from individual measurement errors can be evaluated from Kline and McClintock. Khanna reports water temperature in solar units in India reached about 140°F and dropped approximately 20°F during the night.[9] For the error calculation in this report and other calculations, the following

solar unit water and ambient properties were assumed; 1°F drop for one hour in storage tank water temperature; 150°F maximum storage tank temperature and 75°F storage tank ambient temperature. The assumed value of 1°F decrease in one hour was chosen because it is believed that the solar units tested will have better insulation than those described in Blance and therefore not result in as large a heat loss each night. All of these assumed values will of course vary for different solar units. However, it is believed that the assumed values will achieve representative results in the calculations.

Yellott presents a good history on the measurement of solar radiation. Many studies have been conducted relating to this, and today the accurate measurement of solar radiation is a standard procedure. The NBS test procedure for solar radiation measurement can be used for FTU testing. The NBS recommends that the plane of the pyranometer should be parallel to the plane of the collector, and that the pyranometer surface should be cleaned occasionally.[10]

The affect of dirt on efficiency values was investigated by Garg who devised an equation to normalize the effect of dirt on solar unit efficiency values. "The dirt correction factor for glass plate inclined at 45 degrees from the horizontal is 0.92"[11]. This correction factor can be classified as another qualitative property that if not adequately evaluated will result in false conclusions.

In measuring the fluid temperature in the collector tubing, one must be careful not to create excessive pressure loss and also obtain an accurate measurement. For example, in the case of obtaining an accurate measurement, if a thermometer well were used one could experience large temperature errors due to heat conduction up the well wall [12] . To avoid this the well should be insulated from the pipe system or a small sheathed thermocouple used.

Stotter and Robinson, NBS and Keyes were the only literature found to be directly related to this report. Keyes is a review of the inadequacies of NBS. It indicates that the NBS proposed standards are unacceptable for rating solar systems, however, the component test methods described may be used to generate a test procedure for this report.

Stotter and Robinson present what is believed to be the most complete test procedure for the purposes of this report.

NBS Interim is the latest NBS publication to provide solar unit design information, establish technical performance levels and provide a basis for the development of more definitive performance criteria. In this document NBS addresses the area of qualitative system properties such as shade, unit location and system failure prevention. Stotter and Robinson requires recording of other qualitative properties such as; weather resistance, corrosion resistance and arrangements for water treatment.

In a similar manner, all qualitative solar unit properties are important in performance evaluation and should be recorded. After a careful review of all reference material and practical testing experience, Appendix A (Data to be Recorded) was derived. It is believed that this data provides an adequate basis for comparing solar unit performance parameters.

Many sources were used to obtain the reference material. These were: University of Florida Library, Florida Technological University Library, The Journal of Solar Energy, NASA, National Bureau of Standards and National Science Foundation. In summary, it was found that the literature contained little information pertaining to specific test procedures for properly evaluating solar units.

1.4 Summary of Present State-of-the-Art

The majority of the subject matter reviewed have not addressed specific test procedures. Czarnecki merely states the tests to be performed and never discusses a detailed test procedure. Of the literature reviewed Stotter and Robinson present the most useful test procedure suggestions for the purposes of this report, and therefore will be used as a basis for testing along with NBS. Based on these references, Florida Technological University Test Program requirements and practical constraints, a recommended test procedure was developed. The next

section will present an introduction to the Florida Technological University Test Program, as related to this report.

1.5 Relationship of this Report to FTU Mobile Solar Laboratory

This report was developed to establish test procedures to be used by the FTU Mobile Solar Laboratory for the determination of the thermal performance properties (η_{th}, ρ_{STOR}, Q, C_{eff}) and qualitative properties of solar units for both laboratory and field operating conditions. Nimmo and Larsen state, "It is well known that the laboratory performance of many devices (including for instance home heating systems) differs from the performance one experiences with the device after it has been installed and used for a period of time. In most laboratory tests the conditions of use as well as aging are not comparable to those actually experienced by the field system."[13] Logically then solar units should be evaluated for the effects of aging and weatherability. The Florida Technological University Test Program is described in detail by Nimmo and Larsen,

"The program is composed of three parts:

1. Detailed measurement of system performance characteristics and determination of overall performance parameters.
2. Documentation of the aging, structural integrity and maintainability of the units tested.

3. Compilation of user opinions and attitudes relating to the use of solar hot water systems."[14]

As stated above, the purpose of this report was to develop a test procedure compatible with the requirements set by Nimmo and Larsen. Table 1.4-1 presents the variables to be measured in order to calculate solar unit performance parameters (η_{th}, ρ_{STOR}, Q, C_{eff}).[15] The back of the collector temperature can be monitored to provide heat loss data out of this surface.

Many constraints were placed on the instrument selection and instrument location criteria. These constraints are discussed in detail by Nimmo and Larsen. Table 1.4-2 presents a summary of all the system design constraints.[16] The instrument selection and instrument location constraints related to this report are; instrumentation for solar radiation measurement, testing of pumped and thermosyphon systems related to minimum interference with normal operation and use patterns, and location of storage tank thermocouples.

To avoid the risk of damage or theft experienced while leaving the system unattended, a compromise was made on the choice of the total radiation pyranometer. A sturdy silicon photocell type instrument was selected.[17] This unit provided the additional advantage of a built-in digital integrator circuit.

The vast majority of solar water heating systems to be tested are the thermosyphon type. Khanna indicates flowrate of 0.067 to 0.35 gallons/minute for typical thermosyphon solar

TABLE 1.4-1

VARIABLES MEASURED

TEMPERATURE

Collector Inlet

Collector Outlet

Ambient (Collector and Storage)

Back of Collector

Water in Storage (Up to Three Points)

System Supply Temperature

INSULATION

Total Radiation in Plane of Collector

FLOW RATES

Mass Flow Through Collector

Mass Flow into Water Heating System

WIND

Speed

Direction

AUXILIARY ELECTRIC POWER

SOURCE: COMPLES International Solar Conference, "Development of a Mobile Solar Testing and Recording (STAR) System," (Saudia Arabia: COMPLES International Solar Conference, 1975): 3, table 1.

TABLE 1.4-2

SYSTEM DESIGN CONSTRAINTS

PORTABILITY

AUTOMATED DATA ACQUISITION

AUTOMATED DATA PROCESSING

OPERATOR SAFETY AND CONVENIENCE

EQUIPMENT PROTECTION

- Temperature Limits
- Theft and Vandal Proofing
- Electrical Overload Protection
- Emergency Power Supply for Clock

FLEXIBILITY

- Pumped and Thermosyphon System Testing
- Testing with or without Auxiliary Heaters
- Compatibility with and Ease of Connection to Typical Systems
- Minimum Interference with Normal Operation and Use Patterns

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SOURCE: COMPLES International Solar Conference, "Development of a Mobile Solar Testing and Recording (STAR) System," (Saudia Arabia: COMPLES International Solar Conference, 1975): 19, table 1.

water heaters. These typically low flow rates prevent the use of any flowmeter instruments that would disturb the flow stream lines. Therefore, a thermal sensing mass flowmeter was selected for this application. Nimmo and Larsen present a detailed discussion on this instrument; basically, it introduces a small amount of heat into the fluid by an element on the outside. Sensing elements, inside, then measure the heat conducted away by the flowing stream which is proportional to the mass flow rate of the fluid.[18] This flowmeter can also be used for testing solar units with forced circulation.

Due to stratification effects, the water tank will not be isothermal. Ideally, the thermocouples should be mounted inside the tank in actual contact with the water. This presents no problem for the laboratory test, however, it might be impossible for the field test. The next best thermocouple location would be on the outside of the water tank. To evaluate the difference between the ideal location inside and the necessary one on the outside, during the laboratory test both points can be monitored and the results compared.

This concludes the introduction for this study and its relationship to the test program. The recommended test procedure presented in Chapter 2 is based on field testing but could also be used for laboratory testing as well.

1.6 Objectives of the Present Study

The objectives of this program are as follows:

a. To establish test procedures to determine the thermal performance of solar units for both laboratory and field operating conditions.

b. To establish a test procedure for determination of qualitative properties of solar units under actual field operation.

CHAPTER 2

INSTRUMENTATION, TEST PROCEDURE AND CALCULATIONS

2.1 Introduction

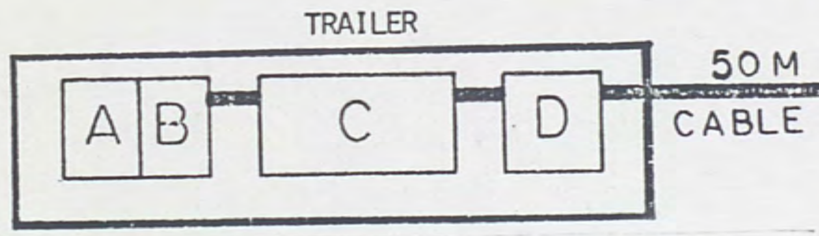
This section presents a recommended test procedure and calculations to be used in field testing and evaluation of solar units. Testing and performance evaluation recommended herein may not necessarily be adhered to for each solar unit tested due to user reluctance to subject the system to the particular test. For instance, the user may not be agreeable to a test restricting usage of hot water and therefore, the nonusage test could not be performed.

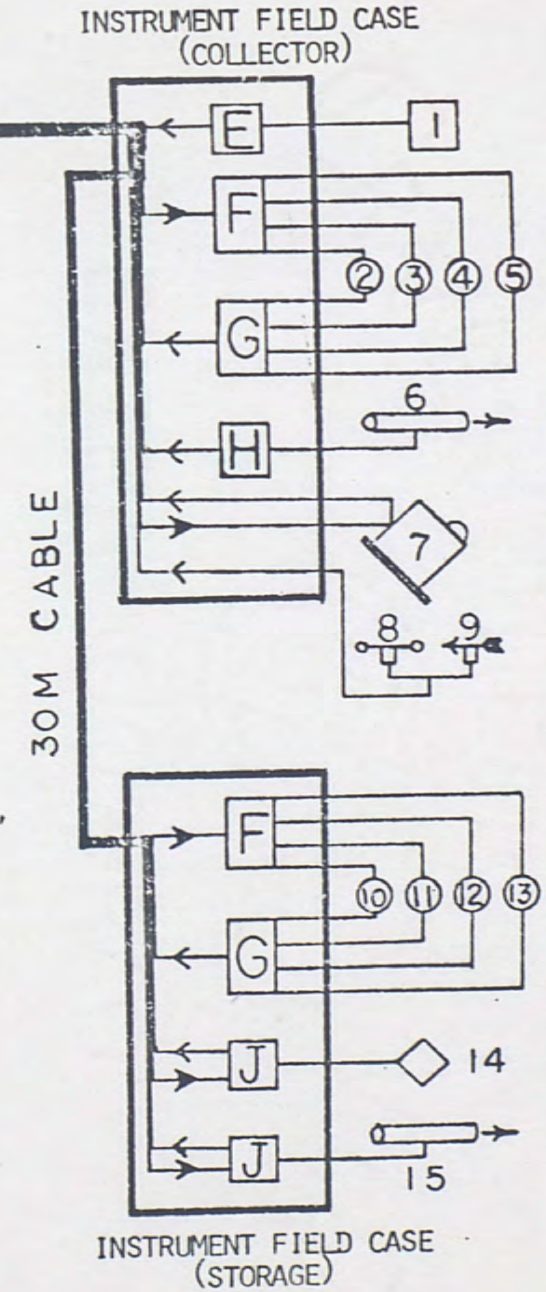
Figure 2.1-1 presents a complete system test flow diagram and allows one to review the entire test program on a schematic level.[19] Figure 2.1-2 presents a diagram of a typical solar unit under test with monitor points identified.

Table 2.1-1 presents a list of instruments that are recommended to perform the solar unit testing.

2.2 Measurements and Instrumentation

From the literature survey it was found that the following temperature measurements, as shown in Figure 2.2-2, would be useful in evaluating performance properties of solar units that are tested.





Instruments No.	Description
1	Heat Flow Senor
2	Collector Inlet Temperature
3	Collector Outlet Temperature
4	Collector Back Temperature
5	Ambient Temperature
6	Collector Flowmeter
7	Pyranometer
8	Wind Speed Anemometer
9	Wind Director
10	Tank Temperature Top
11	Tank Temperature Middle
12	Tank Temperature Bottom
13	Ambient Temperature (in Storage Area)
14	Auxiliary Heating power
15	Drawoff Flowmeter

Data System Letter	Description
A	Paper Tape Punch
B	Printer-Typewriter
	Clock
	Scan Circuit
C	A-D Converter
	Tape Punch Encoder Circuit
D	Units Conversion Amplifiers
E	Signal Amplifier
F	Stepping relay
G	Reference junction and amplifier
H	Controller-Amplifier
J	Counter, D-A converter, Amplifier

——←—— Instrument Signal

——→—— Command Signal

Figure 2.1-1. Signal Flow Diagram

SOURCE: COMPLES International Solar Conference, "Development of a Mobile Solar Testing and Recording (STAR) System," (Saudia Arabia: COMPLES International Solar Conference, 1975): 4, table 3.

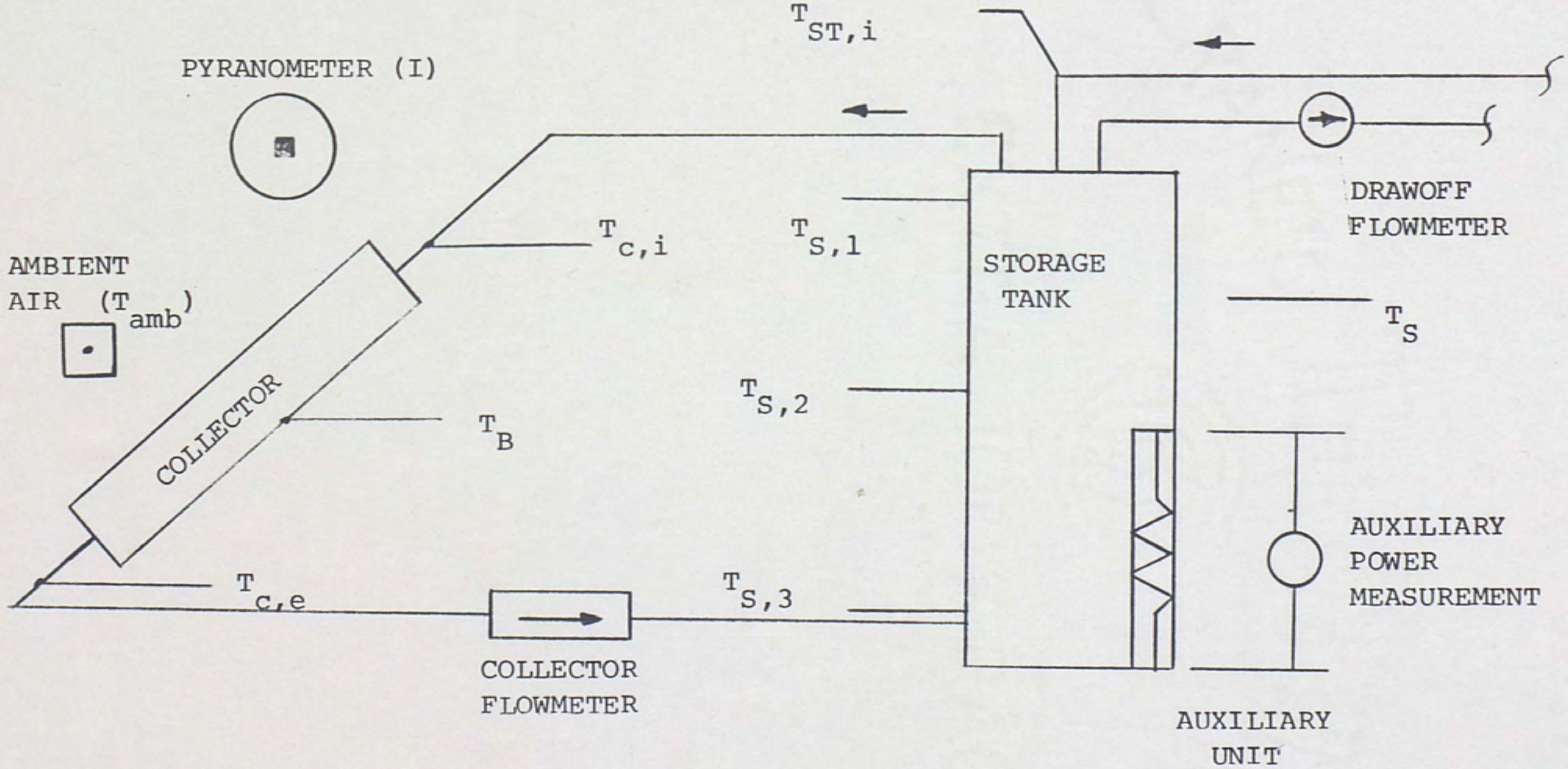


Figure 2.1-2. Typical Solar Unit and Monitor Points

TABLE 2.1-1

RECOMMENDED INSTRUMENTATION

Thermocouple	Copper-constantan
Thermocouple reference Junction and Amplifier	Ommi-Amp II Omega Engineering Inc.
Pyranometer	Model Number 636 Matrix Inc.
Flowmeter	Thermal Instrument Co. Trevose, Pennsylvania
Drawoff (consumption) Flowmeter	Positive displacement or turbine meter type
Wind Velocity	Transducer TV-114 Texas Electronics, Inc. Dallas, Texas
Wind Direction	Transducer TV-104R Texas Electronics, Inc. Dallas, Texas

Storage Tank	T_{ST}	(Average of top, center and bottom thermocouple measurements)
Supply Water Inlet	$T_{ST,i}$	
Collector Inlet	$T_{c,i}$	
Collector Exit	$T_{c,e}$	
Ambient Air	T_{amb}	
Storage Tank Ambient	T_S	
Collector Back	T_B	

Copper-Constantan thermocouples are suggested for use in mildly oxidizing atmospheres up to 750°F where moisture is present,[20] additionallv, errors due to inhomogeneity of wires in zones of temperature gradients are greatly reduced. Therefore, Copper-Constantan thermocouples are recommended for use throughout the entire system, since the thermocouples will definitely be exposed to moisture and oxidizing atmospheres.

Ideally, the storage tank water should be monitored by placing a thermocouple in the water, however, most users probably will not allow this. The next obvious thermocouple location would be mounted to the storage tank wall that is nearest the water. As indicated in the literature survey the differences between thermocouple locations, mounted in water and on tank, can be evaluated during the laboratory test where both points can be monitored and the results compared. Therefore, if the user will not allow the storage tank piping to be cut, it is proposed that

the storage tank thermocouples be affixed to the storage tank wall, in appropriate locations as shown in Figure 2.2-2.

One of the most important parameters in testing a solar unit is the fluid thermal gradient across the collector; to obtain this, the inlet and outlet fluid temperatures must be known. In measuring the fluid temperatures in the pipes, one must be careful to ensure that the fluid is well mixed upstream of the thermocouple to provide true average temperatures.

It is recommended that sheathed thermocouples, mounted inside the inlet and outlet collector tubes, be used to measure the water temperatures. Sheathed thermocouples are suggested because they provide good contact to the water and are compact.

The collector ambient temperature measurement can be accomplished by using a thermocouple mounted on a pole near the collector. In order to avoid false readings it is desirable that the ambient thermocouples be protected from the direct sunshine, wind and rain. The thermocouple wires should be strain relieved.

Incident solar radiation measurement is another important quantitative solar collector parameter. Based on solar radiation measurement discussion in NBS it is suggested that a pyranometer be used to measure the total incident solar energy per unit time per unit area on the collector.

NBS advises that the pyranometer be mounted on a surface parallel to the collector surface in a manner such that it does not cast a shadow onto the collector surface.[21] This procedure is

also recommended for the Florida Technological University Solar Unit Testing.

The flowrate of the liquid flowing through the collector is necessary to calculate collector efficiency. Some of the solar systems tested will be of the thermosyphon type with low liquid flow rates inside the piping system. These low flowrates present a fluid flow measurement problem; therefore, a thermal sensing flowmeter is recommended, as discussed in Chapter 1.

Hot water consumption is another useful parameter to be used in evaluation of a solar unit. This parameter can be measured using standard flowmeters, such as a positive displacement meter or a turbine meter.

The wind velocity and direction are required to allow analytical comparisons to test data and to compare different solar units. These measurements can be monitored using standard instruments.

The auxiliary power measurement can be accomplished by an ammeter and voltmeter connected across the auxiliary unit.

2.3 Qualitative System Properties

To effectively evaluate solar units, many qualitative measurements should be recorded. Appendix A presents the qualitative properties to be recorded. The discussion in the literature survey in Chapter 1 discusses some of the more pertinent qualitative solar unit properties. As with the quantitative

measurements not all parameters will be available; however, it is desirable to obtain all parameters.

2.4 Test Method

2.4.1 Introduction

After a careful review of the related references on testing of solar units it is believed that the following suggested test methods will result in meaningful data that will allow one to adequately evaluate the qualitative and quantitative performance of a solar unit.

The recommended test method consists of two parts, a non-usage test and a usage test. A non-usage test is required to provide a steady state condition for the thermal performance evaluations. During the non-usage test, the user should not use the hot water for a specified period of time. The usage test is as it implies, normal usage of hot water.

At the start of each solar unit test it is recommended that the collector glass be cleaned so as to normalize the effects of dirt that may have been collected on the glass surface. The quantitative and qualitative measurements discussed in Sections 2.2 and 2.3 respectively, should be recorded as indicated in Appendix A. Below are the recommended test methods for the quantitative usage and non-usage tests. These test methods are written in an instruction manual format; however, they are only a

recommended approach and deviations will be expected based on individual test requirements and equipment limitations.

2.4.2 Non-Usage Test

During this test, it is suggested that the hot water not be used for three consecutive days. All monitor points can be recorded during the day while at night it is recommended that all monitor points be recorded with the exception of the solar radiation.

A constant temperature test to determine capacity is proposed to be performed on the third day. The procedure from Stotter and Robinson will be used, "The standard supply temperature will be 66.1°C (or as specified). The temperature on the drain-off point must reach at least 66.1°C then water will be taken from the heater until the temperature of the outcoming water drops 11.1°C; i.e., to 55°C. The quantity of extracted water must be measured and recorded. This procedure should be repeated and the result given as total water extracted during the day. The quantities and times of each extraction should also be given."[22]

2.4.3 Usage Test

During this test, the hot water can be used normally or as specified by the user. It is recommended that all measurements specified in Sections 2.2 and 2.3 be recorded.

2.5 Calculations and Data to be Reported

The data to be reported is presented in Appendix B. Below is a discussion on the various calculations necessary to compute the

performance parameters recommended in Appendix B. These performance parameters were derived from a careful review of all pertinent references.

To determine which solar unit properties would be useful in comparing performance values, test reports on solar unit testing were reviewed.[23,24,25,26,27,28]

After review of all the above references the following performance parameters were derived and are believed to be of use in evaluating solar units:

1. η_{th}, the practical thermal efficiency of a solar collector is defined as the amount of energy removed by the transfer fluid per unit of gross cross sectional area over a 30 minute period divided by the total incident solar radiation onto the collector for the 30 minute period.[29]

$$\eta_{th} = \frac{\dot{m}C_p \int_{\tau_1}^{\tau_2} (T_{c,e} - T_{c,i})\, d\tau / A / \Delta\tau}{I} \qquad (2.5\text{-}1)$$

where

A = collector gross cross sectional area, $M^2 (ft^2)$

$\dot{m}$ = fluid flowrate, GRAM/HR (LBm/HR)

C_p = specific heat of fluid at constant pressure, $\frac{CAL}{GRAM^{O}C} \left(\frac{BTU}{LBM^{O}F} \right)$

I = total short-wave radiation from sun and sky as a 30 minute integrated quantity, W/M^2 ($BTU/HR\ FT^2$)

$T_{c,e}$ = collector exit fluid temperature, ^{o}C (^{o}F)

$T_{c,i}$ = collector inlet fluid temperature, ^{o}C (^{o}F)

τ = time variable, hr

τ_1 = time at beginning of test, hr

τ_2 = time at end of test, hr

The usefulness of the thermal efficiency can be arrived at if the thermal efficiency is thought of as the ratio of heat gained by the water to heat input by solar radiation. The thermal efficiency can range from 0.0 to approximately 0.60 for certain periods of the day.[30] When the thermal efficiency is plotted as a function of an appropriate $\Delta T/I$, it is seen that different collectors can be compared for this parameter.[31,32]

NBS indicates that if the efficiency is plotted against an appropriate $\Delta T/I$, a well defined efficiency "curve" can be obtained with a minimum of scatter. Stotter and Robinson also recommends this plot of efficiency against $\Delta T/I$ and therefore, it is suggested for this test report in Appendix B. This plot will allow an objective comparison between solar units tested.

The thermal efficiency, η_{th}, then can be plotted as a function of $\Delta T/I$,

where,

$$\Delta T/I = \left(\frac{T_{c,e} + T_{c,i}}{2} - T_{amb} \right) /I \quad (2.5\text{-}2)$$

T_{amb} = ambient air temperature, ^{o}C (^{o}F)

Figure 2.5-1 presents an illustrative example of this curve.[33]

2. The heat storage coefficient is defined as the decrease in temperature of the stored hot water per hour divided by the temperature difference between the mean water temperature and the surrounding ambient temperature, for a period when the solar radiation, I, equals zero. To provide adequate performance data the heat storage coefficient can be calculated for the duration of the test and is defined as:[34]

$$\rho_{STOR} = \frac{T_{ST,2} - T_{ST,1}}{(T_{ST,2} + T_{ST,1})/2 - T_{S}} \quad (2.5\text{-}3)$$

where:

$T_{ST,1}$ = average storage tank water temperature at beginning of test period. (Note: this is average of top, middle and bottom storage tank temperature), ^{o}C (^{o}F)

$T_{ST,2}$ = average storage tank water temperature at end of test period, ^{o}C (^{o}F)

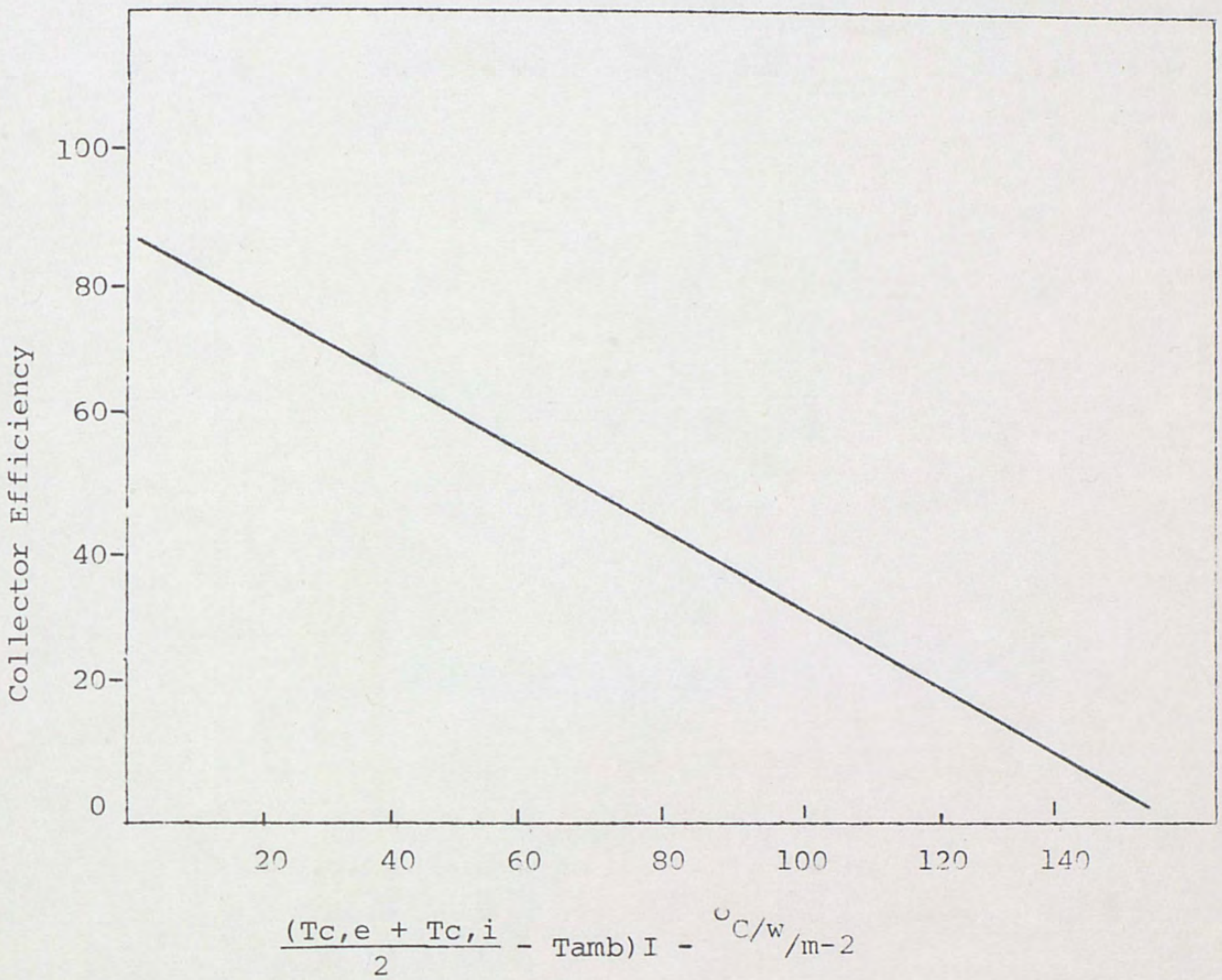


Figure 2.5-1. Collector Thermal Efficiency as a function of ΔT/I

SOURCE: Honeywell, Corporation, Design and Test Report for Transportable Solar Laboratory Program. NSF Grant PTP 74-01555 (Minneapolis, Minnesota: Honeywell Corporation, 1974): A-23, table A-23.

T_S = storage tank ambient air temperature ^oC (^oF)

The usefulness of the heat storage coefficient is not directly obvious. The coefficient title "heat storage coefficient" implies that this parameter should give an indication as to how well the internal heat is stored by the storage system.

Multiplying equation (2.5-3) by mC_P/UA results in equation (2.5-4), where,

m = mass of water, grams (LBM)

C_P = specific heat of water at constant pressure $\frac{CAL}{GRAM^oC}$ $\left(\frac{BTU}{LBM^oF}\right)$

U = overall heat transfer conductance from the outer tank wall to the ambient, CAL/HR^oC $\left(\frac{BTU}{HR^oF}\right)$

A_T = mean heat transfer area of tank wall, m^2 (FT^2)

T_{ST} = average storage tank water temperature, ^oC (^oF)

$$\frac{mC_P}{UA}\ \rho_{STOR} = \frac{(T_{ST,2} - T_{ST,1})\ mC_P}{(T_{ST} - T_{amb})\ UA} \qquad (2.5\text{-}4)$$

The right hand side of equation (2.5-4) can be stated as an energy ratio that is;

$$\frac{\text{decrease in energy in tank}}{\text{heat lost to ambient}} \simeq 1$$

This term is approximately equal to one since the energy lost to the ambient, for a given time period, caused the decrease in energy in the tank.

Rewriting equation (2.5-4)

$$\rho_{STOR} = \frac{UA_T}{mC_P} \qquad (2.5\text{-}5)$$

Three of the terms in equation (2.5-5) will remain constant assuming a non-flow condition. A_T will not change, and for a limited temperature range m will be constant. C_P is a weak function of temperature and for practical purposes can be assumed a constant.
Now equation (2.5-5) becomes

$$\rho_{STOR} = \frac{U}{\text{CONSTANT}} \qquad (2.5\text{-}6)$$

Further inspection reveals that U will not vary drastically as a function of time and for the temperature range

involved. It is concluded from the above that ρ_{STOR} will not vary significantly; however, it can be used for comparison purposes between storage tanks. Additionally, since ρ_{STOR} is essentially a constant in equation (2.5-6), then U may be calculated and used as another comparison between storage tanks.

Stotter and Robinson indicate that the heat storage coefficient should be plotted as a function of $(T_{ST,2} + T_{ST,1})/2-T_S$ and this will also be recommended for the data to be presented in Appendix B. This graph will allow a comparison of heat loss by the storage fluid for each storage tank tested. Figure 2.5-2 presents an illustrative example of this curve. A plot of the heat storage coefficient as a function of time would allow a rapid graphical review of the heat loss coefficient for each night. It is recommended that this curve be included in Appendix B. Figure 2.5-3 presents a sample of this graph.

3. Solar unit capacity can be used to determine the supply capacity of the solar unit. The variables measured are:

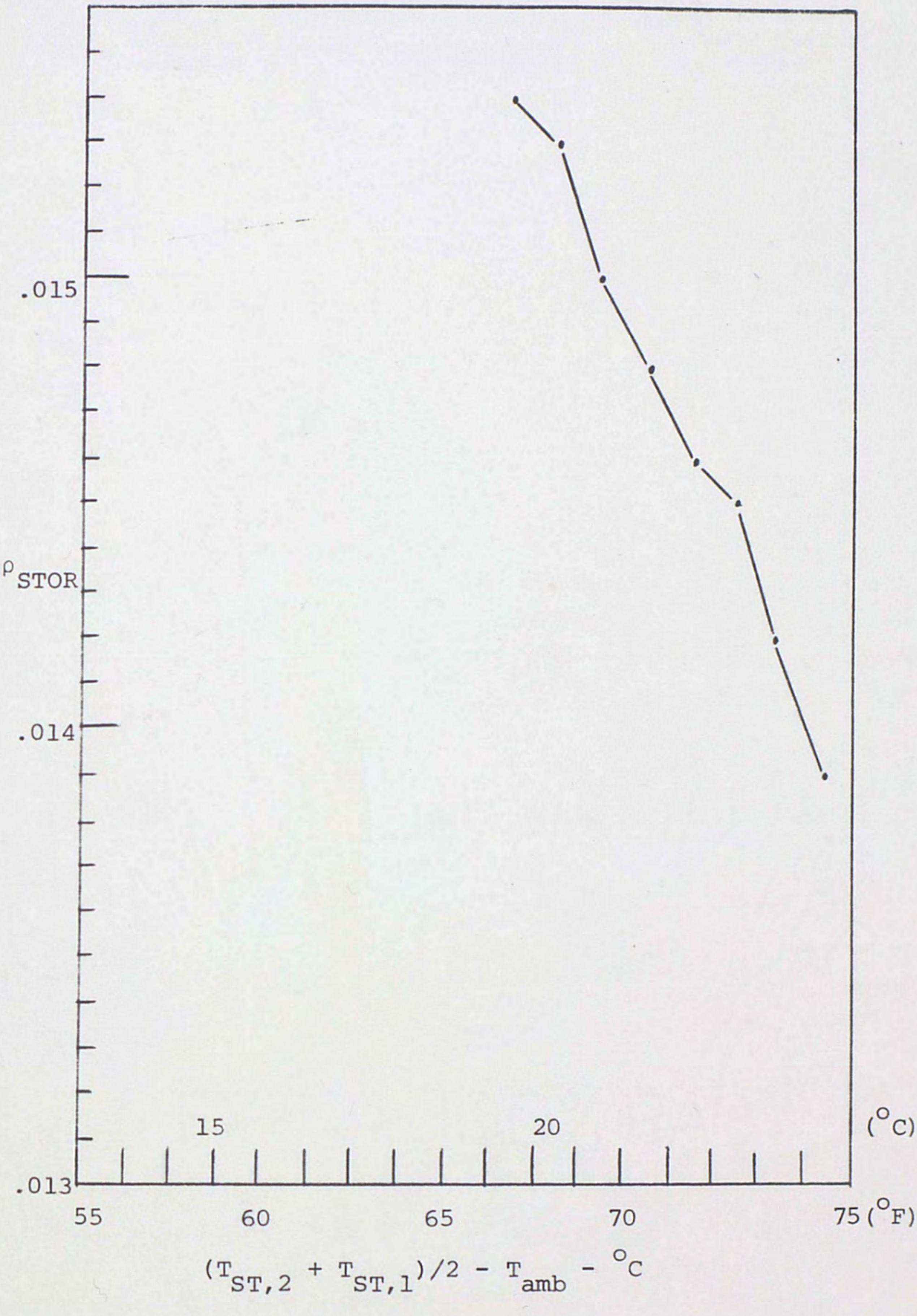


Figure 2.5-2. Heat Storage Coefficient as a Function of $(T_{ST,2} + T_{ST,1})/2 - T_{amb}$

NOTE: Curve as generated by assuming typical values from Kanna of: $T_{ST,1} = 150^{\circ}F$ @ time = 0, $T_{amb} = 75^{\circ}F$ = constant, $\Delta T_{ST} = 1^{\circ}F/HR$

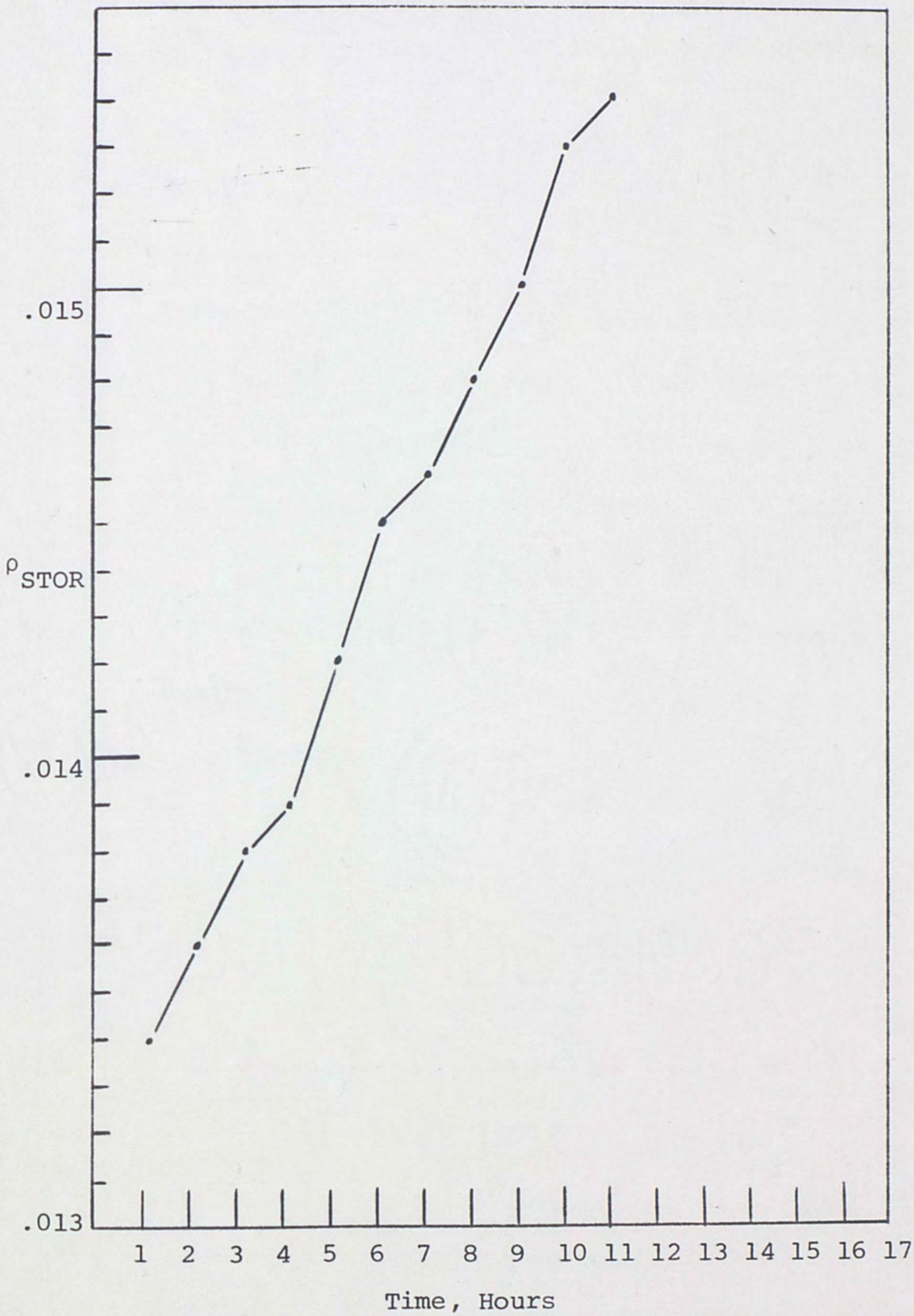


Figure 2.5-3. Heat Storage Coefficient as a Function of Time

NOTE: Curve as generated by assuming typical values from Kanna of: $T_{ST,1} = 150°F$ @ time = 0, $T_{amb} = 75°F$ = constant, $\Delta T_{ST} = 1°F/HR$

a. Initial temperature

b. Final temperature

c. Quantity of water extracted

d. Time to extract this water

With the above quantities known, one can calculate the equivalent amount of energy from the definition of a KG CAL; that is, one KG CAL is the energy required to raise one kilogram of water 1^{o}C.

The following equation can be used to calculate this energy;

$$Q = \dot{m}C_p \; (T_{S,e} - T_{S,i}) \qquad (2.5\text{-}7)$$

where,

Q = energy per hour, KG CAL

$\dot{m}$ = fluid flowrate, Gram/HR.

$T_{S,e}$ = final water temperature, ^{o}C

$T_{S,i}$ = initial water temperature, ^{o}C

It is suggested that the capacity be presented in Appendix B along with the time of day the test was performed. For comparison reasons, it is recommended that the capacity tests on all units tested be performed during the same time of day.

The capacity or drawoff is most useful in answering the question, "How much energy can the solar unit supply?"[17]

4. The flowmeter shown in Figure 2.1-2 on the hot water line to the user can record the number of gallons of hot water used daily. Knowing the total daily consumption of hot water and the average temperature differential, average of $T_{S,e} - T_{ST,i}$ for the day, one can obtain an equivalent of supplied energy as was shown under the capacity test above.

Czarnecki presents $(E_S/E_R) \cdot 100$ for each day of testing, he refers to this term as the solar contribution (%). For this test program, it is recommended that this same ratio be used, E_S/E_R will be referred to as the capacity efficiency as shown below:

$$C_{eff} = \frac{E_S}{E_R} \leq 1 \tag{2.5-8}$$

E_S = daily amount of energy supplied by the collector, KW HR/DAY (BTU/HR/DAY)

E_R = daily amount of energy required by user, KW HR/DAY (BTU/HR/DAY)

E_A = daily amount of energy supplied by auxiliary unit, KW HR/DAY (BTU/HR/DAY)

$$E_S = E_R - E_A$$

E_R, E_S and E_A should be reported in Appendix B for each day of testing.

Figure 2.5-4 presents an illustrative example of this curve.

The capacity efficiency is very useful in evaluating the effectiveness of units with respect to the user demand for hot water. If several solar unit capacity efficiency results are plotted on the same graph, similar to Figure 2.5-4, one can obtain an immediate comparison between the units.

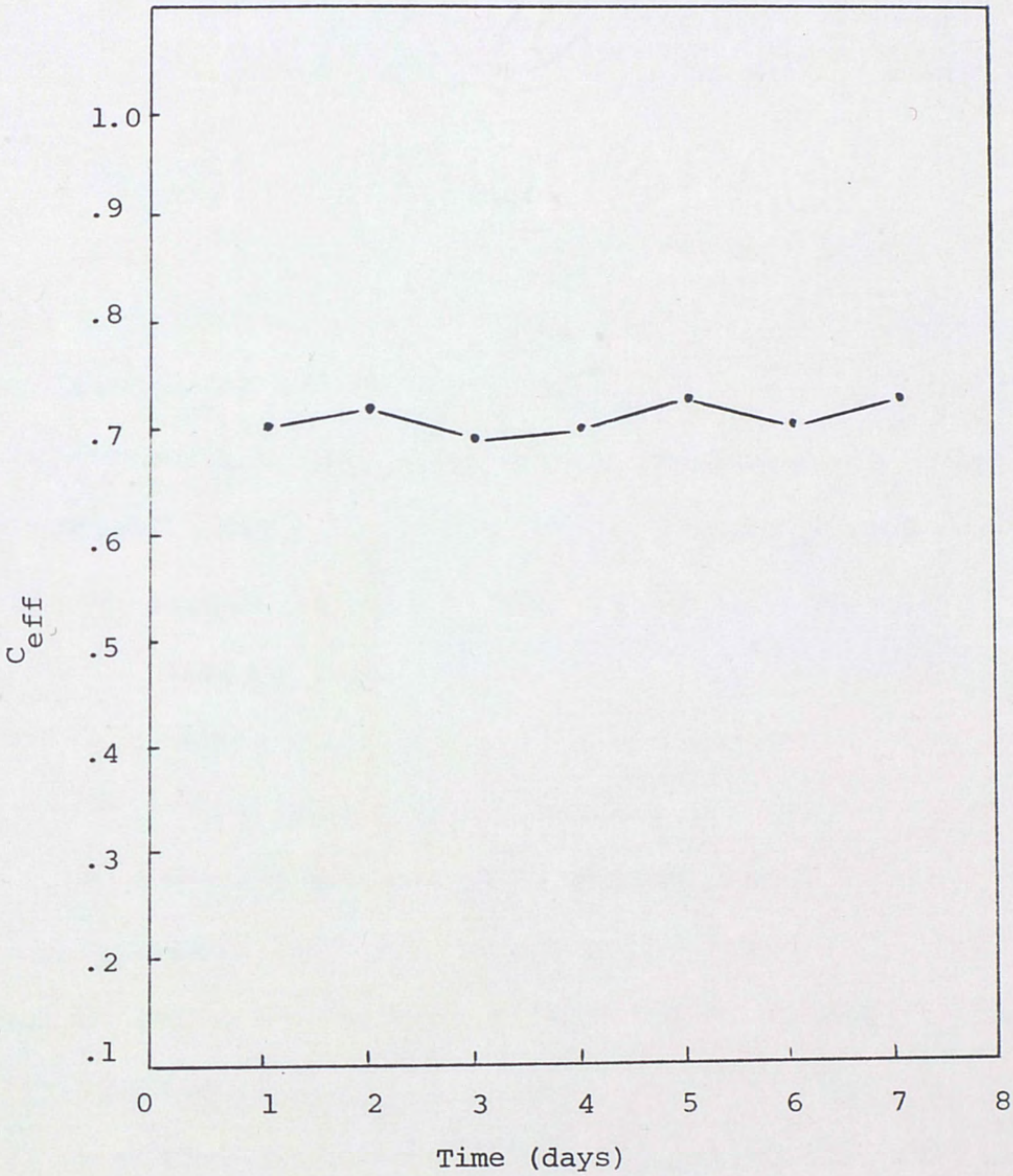


Figure 2.5-4. Capacity Efficiency as a Function of Time

NOTE: This curve does not represent real data; the curve is presented to illustrate the presentation format

CHAPTER 3

COMPARISON OF INSTRUMENTATION AND TEST METHODS FOR FLORIDA TECHNOLOGICAL UNIVERSITY AND NATIONAL BUREAU OF STANDARDS

3.1 Introduction

Chapter 2 discussed a test procedure that is suggested to be used to test complete solar units with the Florida Technological University Mobile Unit. NBS presents test procedures for testing solar collectors and storage devices separately. The NBS test procedure could not be used completely because, (1) the FTU Mobile Unit will test entire existing systems, (i.e. collector and storage tanks) thus limiting the number of access points into the system required by NBS, and (2) the NBS test procedures do not require testing the collector and storage unit as a single unit to provide system performance characteristics. Table 3.1-1 presents a comparison of instrumentation for NBS and the Florida Technological University Mobile Unit. A test procedure for testing flat plate collectors was obtained from the University of Florida Solar Energy Laboratory . Due to the lack of sufficient detail this test procedure was not used for the comparisons in this chapter. Appendix C presents the University of Florida Test Procedure . The following sections present

TABLE 3.1-1 CONT. COMPARISON OF INSTRUMENTATION AND ACCURACIES FOR NBS AND FTU MOBILE UNIT

TEST INSTRUMENT	NBS	FTU
Storage Tank and Ambient		
Temperatures		
Instrument	Thermocouples or thermistor	Thermocouples
Accuracy	± 0.9°F	Approximately ± 1°F
Liquid Flow Measurement Instrument	Positive displacement flow meter turbine flow meter, magnetic flow meter or weight tank	Temperature readout flowmeter
Accuracy	± 1% of measured value	± 1% of measured value
Repeatability	---------	± 0.2% of reading
Response Time	---------	1/2 second
Linearity	---------	± 1%
Pressure Measurements		
Instrument		
Accuracy	± 0.1 inches of water	

TABLE 3.1-1 CONT. COMPARISON OF INSTRUMENTATION AND

ACCURACIES FOR NBS AND FTU MOBILE UNIT

TEST INSTRUMENT	NBS	FTU
Time and Weight Measurements		
Instrument		
Accuracy	± 0.2%	
Recorders		
Instrument	Strip chart recorder	
Accuracy	± 0.5% of temperature difference or measured voltage	
Time constant	less than one second	
Integrators		
Instrument	electronic integrator	electronic integrator
Accuracy	± 1%	
Power Measurement		
Instrument		Voltmeter and ammeter
Accuracy		± 3% total

TABLE 3.1-1 COMPARISON OF INSTRUMENTATION AND ACCURACIES FOR NBS AND FTU MOBILE UNIT

TEST/INSTRUMENT	NBS	FTU
Solar Radiation		
Instrument	Pyranometer	Pyranometer
Accuracy	± 1% of measured value or have temperature compensation	± 5% of measured value, has partial temperature compensation and integrator
Error caused by spectral response variation	± 2%	± 2%
Linearity of response	Within ± 2%	± 3% max.
Time constant	Less than 5 seconds	Less than 1 millisecond
Deviation from a true cosine response	Less than ± 1% for incident angles encountered	Corrected for
Collector inlet and outlet temperatures		
Instrument	Thermocouples or thermistors	Sheathed thermocouples
Accuracy	± 0.9^{o}F	Approximately ± 1^{o}F

comparisons between recommended instrumentation techniques for the NBS and FTU testing of solar units.

3.2 Temperature Measurements

The thermocouples, used to measure temperature, will be as specified by NBS. Accuracy of temperature readings will be similar to NBS specifications, see Table 3.1-1 for differences.

Thermocouple attachment for the collector will be as specified in NBS, or equivalent. Storage tank temperature will be monitored by a thermocouple mounted to the tank wall. NBS requires water temperature measurement. The difference between the two measurements can be evaluated during the laboratory test where both points can be monitored and the results compared. Additionally, user reluctance to cutting into the storage tank piping would probably prevent water temperature measurement.

The thermocouples measuring collector ambient temperature will only be protected on the top side while NBS requires a complete enclosure. If this proves to be unacceptable, the NBS approach can be adopted.

3.3 Solar Radiation Measurement

Table 3.1-1 presents all the pertinent data on the solar radiometer used as a pyranometer. The main difference is the ± 5% accuracy as compared to the ± 1% required by NBS. This is not viewed as a problem as shown by the error analysis in Chapter 4,

the error contributed by the insolation is not significant when compared to other errors.

3.4 Flow Measurements

The flowmeter, a temperature sensitive device, used by Florida Technological University to measure flowrate will exceed NBS requirements. An accurate flowmeter, at low flowrates, was required because of low flowrates resulting from thermosyphon systems.

The flowmeter used to measure the amount of hot water used will be as specified by NBS, a nutating or positive displacement type.

3.5 Auxiliary Power Measurements

NBS does not recommend any instrumentation for power measurements, see Table 3.1-1 for details. The power used by the auxiliary unit is necessary to provide overall system performance.

3.6 Test Methods

Differences between the NBS test methods and the FTU test methods are:

1. NBS requires testing on the collector and storage tank separately and not in actual usage conditions. The FTU test method requires testing of the complete solar unit, collector and storage tank, in actual operating conditions.

2. The NBS testing is performed in a controlled environment and can objectively compare one collector or storage tank against another, however, the NBS testing cannot determine the affects of time, materials, overall system performance or amount of energy supplied by collector as opposed to amount required. The FTU testing is performed in an actual operating environment and it may be difficult to make objective comparisons between solar units tested. However, the FTU testing can attempt to determine the affects of time, materials, overall system performance and amount of energy supplied by the collector as opposed to amount required.

The recommended FTU test method was derived from NBS along with Robinson and Stotter from a careful evaluation of the program requirements and limitations imposed by users and available funds.

CHAPTER 4

ERROR ANALYSIS

4.1 Introduction

As in any experiment or series of measurements accuracy, or the amount of error in the individual measurements and overall results, becomes extremely important. Chapters 2 and 3 discussed the instruments used in obtaining the various measurements as well as the individual accuracy of each instrument. However, no mention was made of the total error involved for the final result. These errors will be discussed in this chapter.

A few definitions from Kline and McClintock are necessary at this point, such as error, result, variable, and uncertainty. There are three main classifications for errors; accidental errors, fixed errors and mistakes. Accidental errors are those errors which cause repeated readings to differ without apparent cause and arise from instrument friction, time lag, personal errors and many other reasons. Fixed errors are those errors which cause repeated readings to be in error by the same amount without apparent reason. Mistakes are false readings of scales, watches, meters and so on. A variable is a basic quantity observed directly from an instrument as opposed to the result which is obtained by making calculations with the recorded values of the variable. The uncertainty is what one thinks

the error might be. It will be assumed that mistakes will be detected in reviewing the data. Therefore, the only errors to be concerned with are accidental and fixed errors, which will be lumped together and referred to as the error.

The article by Kline and McClintock will be used as a guide to calculate the resulting overall error or uncertainty. When calculating the error or uncertainty described in Kline and McClintock the result should be expressed as:

$$M \pm W, \text{ (b to 1)}$$

where,

M = arithmetic mean of observed value (i.e. actual measured value)

W = uncertainty interval or error interval

b = odds that experimenter is willing to wager that the error will be less than W.

The odds (or b) used in the following calculations are 20:1 as recommended in Kline and McClintock such that only 4% of the values will be greater than this value

Equation (4.1-1) below is presented as the uncertainty interval in the result.[36]

$$W_r = \sqrt{\left(\frac{\partial r}{\partial V_1} W_1\right)^2 + \left(\frac{\partial r}{\partial V_2} W_2\right)^2 + \ldots . \left(\frac{\partial r}{\partial V_M} W_M\right)^2} \qquad (4.1\text{-}1)$$

where,

W_r = uncertainty interval in the result

r = value of the result

V = value of one of the variables

W = uncertainty interval of one of the variables

Now an equation is available to calculate the overall result error. This will be performed in detail for all calculated results.

4.2 Sample Error Calculations

In order to calculate the thermal efficiency error, it is convenient to have actual field test data for a collector in the Central Florida Area since field testing will be performed in this location. This data is available in the PPG Solar Collector Catalog[26]. Actual testing was performed on stationary collectors at Melbourne, Florida.

From the PPG Catalog for 12 o'clock noon at Melbourne, Florida, June 19, 1974:[37]

$\dot{m}$ = flowrate = 0.3 Gal/min = 150.LBM/HR

I' = insulation = $290 \frac{\text{BTU}}{\text{FT}^2\text{-HR}} (18 \text{ ft}^2) = 5220 \frac{\text{BTU}}{\text{Hr.}}$

$T_{c,i}$ = inlet water temperature = 185°F

$T_{c,e}$ = outlet water temperature = 205°F

T_{amb} = ambient air temperature = 100°F

The equation for thermal efficiency η_{th}, from section 2.5 is,

$$\eta_{th} = \frac{\dot{m}C_P \int_{\tau_1}^{\tau_2} (T_{c,e} - T_{c,i})\, d\tau/\Delta\tau}{I'} \qquad (4.2\text{-}1)$$

For this analysis equation (4.2-1) can be simplified by estimating the average temperature difference ($T_{c,e} - T_{c,i}$) for a 30 minute period, the resulting efficiency equation is:

$$\eta_{th} = \frac{\dot{m}C_P \, (T_{c,e} - T_{c,i})}{I'} \qquad (4.2\text{-}1a)$$

With an equation for the result and the individual variable errors, the uncertainty may be calculated from equation (4.1-1). For the thermal efficiency calculation four variables are involved; $\dot{m}$, $T_{c,e}$, $T_{c,i}$, and I'. The specific heat is assumed constant. Equation (4.1-1) now contains four terms on the right hand side:

$$W_r = \sqrt{\left(\frac{\partial r}{\partial V_1} W1\right)^2 + \left(\frac{\partial r}{\partial V_2} W2\right)^2 + \left(\frac{\partial r}{\partial V_3} W3\right)^2 + \left(\frac{\partial r}{\partial V_4} W4\right)^2} \qquad (4.2\text{-}2)$$

where,

$r = \eta_{th}$

$V_1 = \dot{m} = 150$ LBM/HR

$V_2 = I' = 5220$ BTU/HR

$V_3 = T_{c,e} = 205^{\circ}F$ } average for 30 minute period

$V_4 = T_{c,i} = 185^{\circ}F$

and

$W1 = \pm 1\%$ (1.5 LBM/HR)

$W2 = \pm 5\%$ (261 BTU/HR)

$W3 = \pm 1^{\circ}F$

$W4 = \pm 1^{\circ}F$

then

$$\frac{\partial r}{\partial V_1} = \frac{\partial \eta_{th}}{\partial m} = \frac{C_P\,(T_{c,e} - T_{c,i})}{I'}$$

$$\frac{\partial r}{\partial V_2} = \frac{\partial \eta_{th}}{\partial I'} = -\frac{\dot{m}C_P\,(T_{c,e} - T_{c,i})}{I'^2}$$

$$\frac{\partial r}{\partial V_3} = \frac{\partial \eta_{th}}{\partial T_{c,e}} = \frac{\dot{m}C_P}{I'}$$

$$\frac{\partial r}{\partial V_4} = \frac{\partial \eta_{th}}{\partial T_{c,i}} = \frac{-\dot{m}C_P}{I'}$$

When all the above parameters are substituted into equation (4.2-2) it is found that:

$$W_{\eta_{th}} = 0.050$$

additionally, equation (4.2-1a) results in:

$$\eta_{th} = 0.575$$

The percent of error is then

$$100 \times \frac{W_{\eta_{th}}}{\eta_{th}} = 100 \times \pm \frac{.050}{.575} = \underline{\underline{\pm\ 8.7\%}}$$

The thermal efficiency and resulting error was also calculated for 5:30 PM and it was found that:

percent of error = $\pm$ 3.5%

The other resulting errors for performance evaluation parameters were calculated in a similar manner. These errors are presented in tabular form in Table 4.2-1.

4.3 Discussion of Error Analysis and Results

In calculating the results, typical values were used for the variables so that the error would approximate values expected in the field testing. For example, for the calculation of the thermal efficiency error, actual test data was used for solar collectors tested at Melbourne, Florida.[26] In a similar manner the other collector parameters were assumed in order to calculate the error in the results.

Table 4.3-1 presents the results of the error analysis. A review of these errors indicates that all calculated errors are less than ± 10%.

In reviewing the error calculations some conclusions were obtained: (1) in the thermal efficiency error calculation the largest contributor was the temperature, at least a factor of two above all other terms combined; (2) because of this effect the ±5% error on the pyranometer appears to be acceptable. In fact, in each of the error calculations shown in Table 4.2-1, the major contribution was the temperature term. In the capacity test the temperature gradient was increased from 5°C, recommended by Stotter and Robinson, to 20°F (16.1°C) in order to keep the error below ±10%. The value of ±10% was chosen because it is generally considered good

TABLE 4.2-1. PARAMETER ERROR CALCULATIONS

Error Function	Thermal Efficiency	Heat Storage Coefficient	Capacity	Consumption	Capacity Efficiency
r	η_{th}=0.575	ρ_{STOR}=.0134	Q=2000 BTU/hr	E_R=7000 BTU/hr/day	C_{eff}=0.857
V1	$\dot{m}$=150 LBm/hr	Tst,2 = 149°F	m=100 LBm	E_A=1000 BTU/hr/day	E_s=6000BTU/hr/day
V2	I'=5220 BTU/hr	Tst,1 = 150°F	τ = 1 hour	E_s=6000 BTU/hr/day	E_r=7000BTU/hr/day
V3	Tc,e=205°F	Tamb=75°F	Tst,2=151°F	N/A	N/A
V4	Tc,i=185°F	N/A	Tst,1=131°F	N/A	N/A
W1	±1% (±1.5 LBm/hr)	± 1°F	±.2% (±.2LBm)	±3% (±30BTU/hr/day)	±7.09% (±425.4 BTU/hr/day)
W2	±5% (+261BTU/hr)	±1°F	±.2% (±.002hr)	±7.09% (±425.4 BTU/hr/day)	±6.09% (±426.5 BTU/hr/day)
W3	± 1°F	± 1°F	± 1°F	N/A	N/A
W4	± 1°F	N/A	± 1°F	N/A	N/A
∂r/∂V1	$\frac{C_p(Tc,e-Tc,i)}{I'}$	see note (1) below	$\frac{C_p(Tst,2-Tst,1)}{\tau}$	1.0	$1/E_R$
∂r/∂V2	$\frac{-\dot{m}C_p(Tc,e-Tc,i)}{(I')^2}$	see note (2) below	$\frac{-mC_p(Tst,2-Tst,1)}{\tau^2}$	1.0	$-E_s/E_r^2$

TABLE 4.2-1 CONT. PARAMETER ERROR CALCULATIONS

Error Function	Thermal Efficiency	Heat Storage Coefficient	Capacity	Consumption	Capacity Efficiency
$\partial r/\partial V3$	$\frac{\dot{m}C_P}{I'}$	$\frac{Tst,2-Tst,1}{((Tst,2+Tst,1)/2-Tamb)^2}$	mC_P/τ	N/A	N/A
$\partial r/\partial V4$	$\frac{-\dot{m}C_P}{I'}$	N/A	$-mC_P/\tau$	N/A	N/A
W_r (from eq(4.2-2)	± 0.050	$\pm .000255$	± 141.8BTU/hr	± 426.5BTU/hr/day	± 0.080
% error	8.75%	1.9%	7.09%	6.09%	9.34%

NOTES:

(1) $$\frac{\partial r}{\partial V1} = \frac{\partial \rho_{STOR}}{\partial Tst,2} = \left[\frac{[(Tst,2 + Tst,1)/2 - Tamb]\,(1) - (Tst,2 - Tst,1)}{[(Tst,2 + Tst,1)/2 - Tamb]^2}\right]\frac{Tst,2}{2}$$

(2) $$\frac{\partial r}{\partial V2} = \frac{\partial \rho_{STOR}}{\partial Tst,1} = \frac{\left[(Tst,2 + Tst,1)/2 - Tamb\,(1) - (Tst,2 - Tst,1)\right]\frac{(Tst,1)}{2}}{[(Tst,2 + Tst,1)/2 - Tamb]^2}$$

engineering practice. If, however, lower error in the results are desired than as stated above, a reduction in the temperature measurement errors would be the most meaningful area to start with. This would be recommended if higher temperature gradients could not be achieved. It was found that reducing the temperature measurement error could be accomplished by minimizing the thermocouple amplifier ambient temperature excursion from the calibration temperature. Another method of reducing the error would be to calibrate the thermocouple system before and after each day of testing and correct the data with the calibration curves.

In conclusion, it was found that the errors resulting from the recommended instrumentation should be less than $\pm 10\%$ for all results.

TABLE 4.3-1

RESULTS OF ERROR ANALYSIS

Measured	Calculated Result	Expected Error 20:1 Odds (from 8)
Temperature		$\pm$ 1^{o}F
Mass Flow Rate		$\pm$ 1%
Insolation		$\pm$ 5%
	η_{th}	$\pm$ 8.7% maximum
		$\pm$ 3.5% minimum
	ρ_{th}	$\pm$ 1.9%
Mass of Water		$\pm$ 0.2%
Time		$\pm$ 0.2%
	Q	$\pm$ 7.09%
Auxiliary Power		$\pm$ 3%
	E_S	$\pm$ 7.09%
	E_R	$\pm$ 6.09%
	C_{eff}	$\pm$ 9.34%

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From this report, it is concluded that the solar unit performance parameters (η_{th}, ρ_{STOR}, Q, C_{eff}) can be used along with the qualitative unit properties to properly evaluate each system. The cost factors should be included in this comparison since the economics of solar water heating share an important role in evaluation of solar units.

It was found from the error analysis that the recommended instrumentation and test procedure, presented herein, should result in overall errors of less than $\pm 10\%$ in the calculation of performance parameters. The error analysis showed that the largest contributor to the error in the resulting calculations was the error involved with temperature measurement. Consequently, a desire to reduce the overall error should begin by reducing the error in the temperature measurements.

The literature survey revealed very little information on test procedures for properly evaluating solar units.

5.2 Recommendations

The test procedure developed is believed to be adequate for evaluation of solar water heaters from a qualitative and

quantitative view. It is recommended that this test procedure be used for Florida Technological University testing of laboratory and field solar units.

It is further recommended that future work be performed to develop a method of rating solar units by using the test data resulting from tests using the recommended test procedure.

APPENDIX A

TEST DATA TO BE RECORDED

USER NAME	UNITS	TIME
Date		
Observer(s)		
Collector tilt angle	degrees	
Barometric pressure	Pascal	
Ambient air (collector ambient)	^oC	
(storage tank ambient)		
Collector inlet temperature, $T_{c,i}$	^oC	
Collector outlet temperature, $T_{c,e}$	^oC	
Temperature on back of collector, T_B	^oC	
Water flow rate	GR/HR	
Wind velocity and direction	KM/HR	
I, the total short wave radiation from sun and sky onto the collector as a 30 minute integrated quantity.	W/FT^2	
Storage Tank Temperatures	^oC	
$T_{S,1}$	^oC	
$T_{S,2}$	^oC	
$T_{S,3}$	^oC	

TEST DATA TO BE RECORDED (CONT.)

USER NAME	UNITS	TIME
Storage Tank Inlet Temperature		
$T_{ST,i}$	^oC	
Daily consumption of hot water	M^3	
Electricity consumed by Solar Unit	KW	
Electricity consumed by Auxiliary Unit	KW	
Data for Capacity		
Test Para. 2.4		
Volume	M^3	
$T_{s,i}$ (initially	^oC	
$T_{s,e}$ (at end)	^oC	

TEST DATA TO BE RECORDED (CONT.)

Manufacturer ____________________________

Model #__________________________________

Serial #_________________________________

Construction details of the collector

Gross dimensions and area (M^2)________________________

Area of absorbing surface (M^2)________________________

Cover plate *

dimensions ____________________

materials ____________________

optical properties (if known)____________________

Absorber plate

material ____________________

dimension layout________________

configuration of flow path______________________

absorptivity for short wave radiation (if known)

____

emissivity for long wave radiation (if known)

____

description of coating (maximum allowable temperature if known)____

Air space(s)*

thickness____

description of contained gas or construction

____

TEST DATA TO BE RECORDED (CONT.)

insulation

material ______________________

thickness ______________________

thermal properties ______________________

specific heat ______________________

density ______________________

thermal conductivity ______________________

transfer fluid used and its properties ______________

*if applicable

TEST DATA TO BE RECORDED (CONT.)

Minimum transfer fluid flow rate (M^3/HR)____________________

Maximum transfer fluid flow rate (M^3/HR)____________________

Maximum operating pressure (PASCAL)*____________________

Description and age of apparatus, including flow configuration and instrumentation used in testing (include drawings and photographs)

____

Location of tests (longitude and latitude)____________________

System Failure Prevention:

water treatment ____________________

descaling ____________________

cleaning and draining ____________________

other ____________________

*if feasible

TEST DATA TO BE RECORDED (CONT.)

Unusual Conditions

vibration ______________________________

stress ______________________________

leakage ______________________________

excessive pressure ______________________

corrosion of dissimilar metals ____________

other ______________________________

TEST DATA TO BE RECORDED (CONT.)

General Information

Weight of Storage System, LB ______________________________

Volume of Storage System, m^3 ______________________________

Shading ______________________________

Daily Hot Water Consumption ______________________________

APPENDIX B

DATA TO BE REPORTED

Manufacturer ____________________________

Model #__________________________________

Serial #_________________________________

Construction details of the collector

Gross dimensions and area (m^2)______________________

Area of absorbing surface (m^2)______________________

Cover plate *

dimensions ____________________

materials ____________________

optical properties (if known)________________

Absorber plate

material ____________________________________

dimension layout ____________________________

configuration of flow path __________________

absorptivity for short wave radiation (if known)

____

emissivity for long wave radiation (if known)

____

description of coating (maximum allowable

temperature if known)________________________

air space(s)*

thickness __________________________________

DATA TO BE REPORTED (CONT.)

description of contained gas or construction

____

insulation

material ______________________________________

thickness ______________________________________

thermal properties ______________________________

specific heat ________________________

density ______________________________

thermal conductivity ________________

transfer fluid used and its properties ______________

* if applicable

DATA TO BE REPORTED (CONT.)

Minimum transfer fluid flow rate (m^3/HR) ______________________

Maximum transfer fluid flow rate (m^3/HR) ______________________

Maximum operating pressure (PSI)* ______________________

Description and age apparatus, including flow configuration and instrumentation used in testing (include drawings and photographs)

____

Location of tests (longitude and latitude) ______________________

collector tilt angle (degrees) ______________________

inlet fluid temperature, $T_{ST,i}$ (^oF) ______________________

Wind Speed/Direction ____________ / ____________

System Failure Prevention:

water treatment ______________________

descaling ______________________

cleaning and draining ______________________

other ______________________

Unusual Conditions

vibration ______________________

stress ______________________

leakage ______________________

excessive pressure ______________________

corrosion of dissimilar metals ______________________

other ______________________

* if feasible

DATA TO BE REPORTED (CONT.)

General Information

Weight of Storage System, grams ____________________

Volume of Storage System, m^3 ____________________

Shading ____________________

Daily Hot Water Consumption ____________________

Electrical Consumption

Solar Unit ____________________

Booster ____________________

Performance Properties

A plot of the efficiency versus $\Delta T/I$ ____________________

A plot of insulation, outlet and inlet fluid temperatures and ambient temperature versus time ____________________

A plot of ρ_{STOR}, (heat storage coefficient) versus ΔT and time ____________________

Capacity (drawoff)

Volume (m^3) ____________________

($T_{ST,2}-T_{ST,1}$) ($^{\circ}C$) ____________________

Time (Hours) ____________________

Plot of capacity efficiency (C_{eff}) versus time (days) ____________________

APPENDIX C

University of Florida

Solar Energy and Energy Converstion Laboratories

Subject: Laboratory Procedure for Evaluating Solar Flat Plate Collectors Under Natural Radiation Conditions

Purpose: To provide collection efficiencies for solar flat plate collectors at different sun angles and for different throughputs and inlet temperatures.

Data Acquisition:

1. Throughput

The fluid system is an open system utilizing a constant head pressure tank. The flow of the heat transfer media is regulated with ball valves.

measurement: a stop watch and a calibrated container are used to measure the volume flow from the collector. The specific gravity of the fluid is determined at the outlet conditions.

range: as requested or if unspecified, flows in the range of 0.5 to 1 gpm are used.

2. Temperatures

The temperatures of the fluid entering and leaving the collector are monitored on a continuous or intermittent basis depending on the extent of testing required.

<u>inlet temperatures</u>: this temperature is normally set at 78^{O}F or 150^{O}F unless otherwise specified.

<u>outlet temperature</u>: this is a variable related to the insulation, flow rate, and characteristics of the collector.

<u>measurement</u>: mercury thermometers located in thermometer wells located less than 6" from inlet and outlet of collector.

Thermocouples can also be installed in these walls for continuous temperature readings.

Ambient temperatures are also monitored.

3. Solar Radiation

An attempt is made to utilize clear days. If this is not possible, then partly cloudy days are acceptable when clouds are scattered.

<u>measurement</u>: utilize an Eppley Pyranometer and Strip Chart recorder to measure radiation incident on the collector's face.

4. Collector Area

Total transparent surface area is taken as the collection area unless otherwise specified; the collector is faced south and tilted at an angle of 30^{O}.

5. Miscellaneous

Miscellaneous temperatures are often recorded for a more detailed analysis of the collector

a) core temperature

b) back temperature

c) glass temperature

Equipment is also available for monitoring

a) insulation on a horizontal surface concurrent to the collector tests

b) wind speed and direction

c) infrared radiation component

A solar calorimeter and guarded hot box-cold box can be used to evaluate the solar and heat transfer properties of the collector glazing.

FOOTNOTES

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[9]M. I. Khanna, "The Development of a Solar Water Heater and Its Field Trails Under Indian Tropical Conditions," Solar Energy 12 (October 1968): 259.

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[15]Ibid., p. 20.

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[18]Ibid., pp. 8-9.

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[23]Thompson, Ramo & Woolridge, Inc., gen. ed., Executive Summary, NSF/RA/N-74-022A, 3 vols. (Redondo Beach, California: Thompson, Ramo & Woolridge, Inc., 1974), vol. 1: Solar Heating and Cooling of Buildings, by John Richards, pp. 54.

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[25]General Electric, <u>Final Report of the Solar Heating Experiment on the Grover Cleveland School, Boston, Massachusetts</u>. NSF/RA/N/74/064 (Valley Forge, Pennsylvania: General Electric, 1974), p. 151.

[26]Pittsburgh Plate Glass, <u>Baseline Solar Collector</u>. #G-4835M84 (Pittsburgh, Pennsylvania: Pittsburgh Plate Glass, 1974), p. 11.

[27]National Aeronautical and Space Administration, <u>The Development of Solar Powered Residential Heating and Cooling System</u>. Document No. M-TU-74-3 (Huntsville, Alabama: National Aeronautical and Space Administration, 1974), p. 110.

[28]Honeywell Corporation, <u>Design and Test Report for Transportable Solar Laboratory Program</u>. NSF Grant PTP74-01555 (Minneapolis, Minnesota: Honeywell, Corporation, 1974), p. 89.

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[30]Khanna, "Solar Water Heater," p. 256.

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