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Test Methods and Standards Development for Active Solar Heating and Cooling Systems

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Washington, DC 20234

May 1984

Prepared for

U.S. Department of Energy
Office of Solar Heat Technologies
Active Heating and Cooling Division
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TEST METHODS AND STANDARDS DEVELOPMENT FOR ACTIVE SOLAR HEATING AND COOLING SYSTEMS

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

Since test methods and standards for active solar heating and cooling systems did not exist in 1976, the Department of Energy sponsored research at the National Bureau of Standards (NBS) and other laboratories to aid in the development of research-based standards. This research was intended to facilitate a sound data base for the development of national consensus standards and test methods. In the present report, research by NBS and other laboratories is described for solar domestic hot water systems, solar collectors, thermal storage devices and collector materials. For collectors, the report describes research and test methods for determining the performance of cover plates, absorber materials, collector insulation, gaskets and sealants, rubber hose, containment materials, and heat transfer fluids.

Key words: absorbers; collectors; materials; consensus standards; domestic hot water; durability; heat transfer fluids; reliability; solar energy; test methods; thermal performance; thermal storage devices.

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1. INTRODUCTION

1.1 BACKGROUND

The purpose of voluntary consensus standards for solar heating and cooling applications is to provide industry and government with a technical basis for:

- Measuring and comparing performance (thermal, durability, safety),
- Evaluating new and advanced materials, components, and systems,
- Selecting and specifying materials, components and systems, and
- Establishing rating and certification programs.

The development of consensus standards, which include test methods, recommended practices, and specifications, for solar applications is complex. It involves the interaction of many different entities, from the Federal government to lending institutions to consumers, as well as designers and researchers. As a result, in 1976, the National Bureau of Standards (NBS) recommended the development of an ANSI (American National Standards Institute) Steering Committee on Solar Energy Standards Development. The purpose of this committee as established was to identify needs and formulate specific tasks leading to the development of national consensus standards for using solar energy for heating and cooling. The committee also had the responsibility of assigning standards development activities to standards-writing organizations and maintaining an overview of their activities to avoid duplication of effort or conflicting standards.

In a related activity, the National Bureau of Standards (NBS), under sponsorship of the Energy Research and Development Administration (ERDA), initiated a planning exercise for the development of standards for solar heating and cooling. This plan, published by NBS in 1976 [1][1] and revised in 1978 [2], was designed to identify needed standards and to coordinate the development and implementation of voluntary consensus standards on a systematic basis. In addition, a Federal government program was undertaken to develop research data and technical information which could provide a sound basis for developing national, voluntary consensus standards. This program involved NBS, standards developing organizations such as American Society for Testing and Materials (ASTM), American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), as well as industry and consumers. The ANSI steering committee, which represented at least 22 organizations, approved the original NBS standards development plan given in [1], and revised in [2]. The plans attempted to identify those standards known to require further development as well as to assign priorities for their development. Recommended practices for the development of thermal performance and durability/reliability test procedures are given in table 1. This table does not list applicable standards which did

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[1] Refers to numbers for the references given at the end of the text.

Table 1. Recommended Priorities for the Development of Test Methods for Active Solar Systems (from Ref. 2)

Thermal Performance		Durability/Reliability	
Hardware Category	Priority*	Hardware Category	Priority*
1. Systems		1. Systems, Subsystems and Components	
a. Active		a. Materials Interactions	High-1
1. Domestic and Service Hot Water	High-2	2. Components	
2. Heating	High-2	a. Collector Reliability	High-1
3. Cooling	High-3	b. Collector Durability	High-2
4. Swimming Pools	High-1	c. Pumps, Valves, Regulators, Heat Exchangers, Absorber Plates, Reflectors, Filters	Medium
2. Subsystems		3. Materials	
a. Thermal Storage Devices	High-1	a. Cover Plates	High-1
b. Collector/Storage	High-3	b. Absorber Materials and Coatings	High-1
3. Components		c. Insulation (collector)	High-2
a. Collectors including flat-plate and low concentration	High-1	d. Gaskets and Sealants	High-2
b. Collectors - high concentration	Medium	e. Reflector Materials	Medium
c. Heat Exchangers (Double Wall only)	High-2	f. Heat Storage Media	High
		g. Heat Transfer Fluids	High-1
		h. Piping Materials	High-2
		i. General Materials (Outgassing)	High-2

* In descending order, priorities are: High-1, High-2, High-3, Medium or Low.

not appear to need modification. The plans also suggested the likely responsible organization and an estimated time schedule.

1.2 SCOPE

Since 1976-78 when the planning process was initiated, a large body of research has been accomplished. Where possible, much of this research has been translated into voluntary standards, often at an accelerated pace, since many of the research reports also contained draft standards that could be immediately considered for consensus approval. The present report will identify those areas listed in the planning document where standards were actually promulgated, and document the research that led to their development or validation. Although considerable research was accomplished at a number of different national laboratories and research institutions, the present report will focus on research at the National Bureau of Standards. (Companion reports are currently being developed to document research performed elsewhere.) The NBS research efforts generally followed the following framework:

- Identification of the performance requirements.
- Identification and assessment of existing test methods.
- Development of new test methods, as needed for evaluation.
- Performance of laboratory and field research to evaluate the effectiveness of the test methods in predicting performance.
- Preparation of a draft standard for consideration as consensus standard, based on data and test method evaluation.
- Submittal of draft standard to relevant consensus standard organization.
- Validation of provisions in standard by further research, as needed.

The present report documents the research efforts that led to the development of at least 21 consensus standards for solar heating and cooling applications during the period 1976-78 and 1982. These standards were developed for evaluating the thermal performance of domestic hot water systems, thermal storage devices, and solar collectors. In addition, standards were developed to evaluate the performance of individual materials used in collectors, such as cover plates, absorbers, insulation, gaskets and sealants, rubber hose, and containment materials. Each research project is discussed in detail to provide a synopsis of the procedure and results. The resulting standard is then reviewed to demonstrate how the research procedures were translated into standard testing and evaluation procedures. As a result, the document provides a ready reference for someone interested in the evaluation procedures, test results, and voluntary standards developed as a result of NBS research on solar energy applications. The NBS research also was successful in establishing valid, reliable evaluation procedures which were suitable for consideration as consensus standards. The success of this research can be seen in the number of standards and speed with which they were adopted.

1.3 DEFINITION OF STANDARDS

While the American Society for Testing and Materials (ASTM) defines four major types of standards, the standards of interest in the present report are those related to test methods. ASTM defines a "test method" as the following (ASTM,

1977) [3]: "A form of standard that covers sampling and describes the subsequent testing procedures used in determining the properties, composition, or performance for materials, products, or services that may be specified. A test method shall not include the kind of numerical limits for the properties, composition, or performance that should normally be included in a specification." A "specification" sets forth a set of requirements that a material, product, etc. should satisfy, while a "classification" defines an arrangement of objects into groups with similar characteristics. Finally, a "definition" sets forth the meaning of terms used in the standards. ASTM also defines a "practice" as a "procedure guide or service which may or may not be auxiliary to a test method or specification."

Such standards are typically developed through the voluntary consensus process which uses the consensus of a broad range of interested parties (government, industry, producers, consumers, institutions, and individuals) to ensure that the standards will have widespread acceptance and use. Thus ASTM defines a consensus standard as: "A standard produced by a body selected, organized, and conducted in accordance with the procedural standards of 'due process'. In standards development practice, a consensus is achieved when substantial agreement is reached by concerned interests according to the judgment of a duly-appointed review authority" [Ref. No. 3, pg.8]. For further information about standards developing bodies, the reader is referred to NBSIR 78-1143A [2], which delineates the various organizations involved in the development of building codes and standards. For the present report, the primary standards-developing organizations of interest include ASHRAE, ASTM, and ANSI.

2. SOLAR HOT-WATER HEATING SYSTEMS

2.1 THERMAL PERFORMANCE

Some of the first commercial applications of solar technology included solar domestic hot water systems. For example, such water heaters were introduced in Florida in 1923. During their peak use (1936 to 1941), an estimated 60,000 solar units were in service--more than twice as many solar units as electric [4]. However, lower energy costs, increased hot water use, utility company promotion, and poor performance, particularly in the area of durability, caused a sharp decline in the use of solar domestic water heaters in the 40s and 50s [4]. With increased energy costs after the oil embargo in 1973, and with the development of new technology and materials, solar domestic hot water systems were again considered the most economically competitive of all the possible solar energy applications [5,6]. The increasing interest in solar hot water systems led ASHRAE to form Standards Project Committee 95 in 1977. Because solar domestic hot water systems tend to be designed, assembled, and sold as packaged systems, this committee was charged with developing standard test methods for the thermal performance of the whole system. NBS conducted research which supported the activities of this committee.

An initial NBS research effort was the analysis of the thermal performance of typical solar domestic hot water systems through simulations using the University of Wisconsin computer program TRNSYS [7,8]. The major objective of this analysis was to determine the extent to which short-term outdoor exposure tests could be used to predict long-term performance.

The results of the initial effort were published by Liu and Hill [9]. Figure 1 shows the diagram of the solar domestic hot water system, including the flat-plate collectors used in the simulation. Figure 2 provides the hot water draw profile used in the TRNSYS simulations. These figures show that the thermal performance of the domestic hot water heater studied could be adequately described by a plot of solar fraction f (fraction of hot water load provided by solar energy) against F (a combination of variables which include primary thermal characteristics of the collector, incident solar radiation, ambient air temperature, and hot water load). The results shown in figure 3 indicate that the correlation for monthly and yearly periods is adequate, but not very satisfactory for daily values. The types of correlations used were shown to be valid for an actual in-service installation.

The main conclusion drawn from the exploratory computer simulation was that actual outdoor exposure could be used for predicting long-term thermal performance, but that relatively long exposure periods (10 to 20 days) would be required. As a result, the ASHRAE project committee decided to give prime consideration to alternate testing procedures that could be conducted entirely within a laboratory [10]. The continuing NBS technical support for the development of a testing standard for rating solar domestic hot water systems is described in [10] and [11].

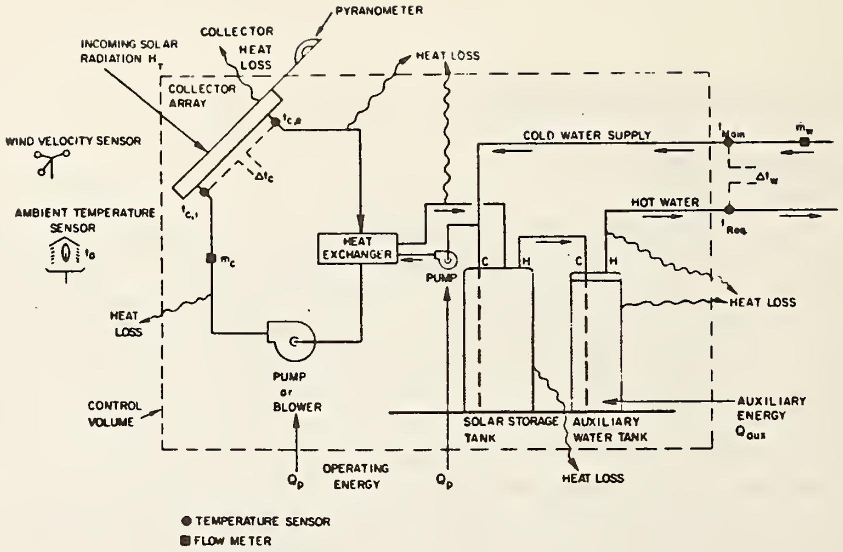

Figure 1. Schematic diagram of a solar domestic water heating system (from Ref. 9)

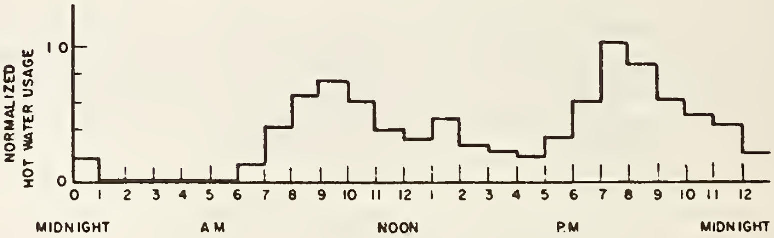

Figure 2. Hourly hot water draw profile used in the TRNSYS simulation (from Ref. 9)

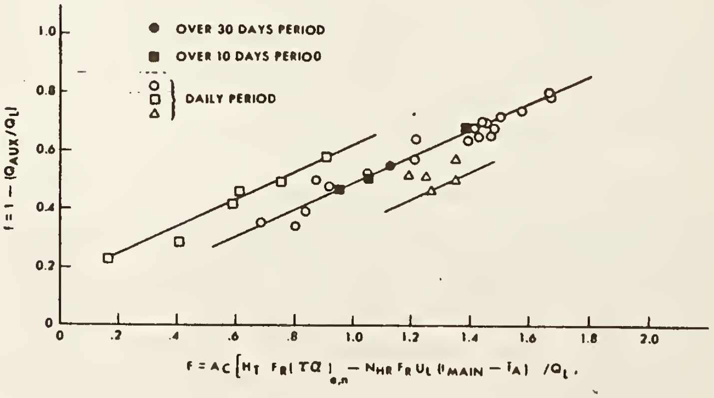

Figure 3. Correlation of solar fraction for the solar domestic water heating system for Santa Maria, CA (from Ref. 9)

Concurrent with the exploratory study, an analytical model [11] was developed to predict the thermal performance of a solar domestic hot water system under prescribed conditions. Each component of the system (i.e., solar collectors, storage tank, heat source, piping, etc.) was modeled, and equations for calculating relevant thermal parameters were developed. Parameters, such as the collector efficiency, useful energy delivered to the storage tank, and daily fractional energy savings, were predicted by the model and compared with results obtained from testing a single tank direct system for four selected days. Analytical results from the model were in close agreement with the experimental results.

2.2 ASHRAE STANDARD 95-81

Formed in 1977, ASHRAE Project Committee 95-P evaluated different methods of measuring the thermal performance of solar domestic hot water systems. The first draft standard was published in 1979, with the final standard (95-81) being promulgated in March 1981 [12]. Early in the development of the standard, the ASHRAE project committee considered the following options for laboratory test procedures:

a. Irradiate the solar collector panels of the water heater with a solar simulator as specified in ASHRAE 93-77 [13]. (Although this option was included in standard 95-81, it was not anticipated that this option would be used frequently, since solar simulators were not widely available. NBS did not evaluate this option.)

b. Determine the thermal performance of the irradiated solar collectors using ASHRAE 93-77, and replace the collector array with a conventional heat source. If the flow rate of the transfer fluid through the collector during the systems test is different from the value used in the collector test, the correction given in ASHRAE 95-81 must be made.

c. Determine the thermal performance of the irradiated solar collectors and replace the irradiated array with a conventional heat source in series with a nonirradiated array. The conventional heat source can be located either upstream or downstream of the nonirradiated array.

d. Determine the thermal performance of the irradiated array and replace this array with strip heaters attached to a nonirradiated solar collector. One advantage of this method is that it can be readily used to test thermosyphon systems which cannot be tested with procedures b or c. Because this procedure was proposed by NBS after the standard had been approved, it has not yet been incorporated into the standard.

The final version of the standard applies to laboratory tests for the thermal performance of a domestic solar hot water system with a storage capacity of 0.45 m^3 (120 gal) or use demands on the order of 0.38 m^3 (100 gal) of hot water per day. It does not specify the test conditions to be used for obtaining a standard rating. The test procedure in the standard employing a nonirradiated solar collector array in series with a conventional heat source does not apply to integral collector storage systems or to thermosyphon systems. Test procedures are given for assessing the performance of three categories of solar domestic hot water systems: solar only, solar-preheat, and solar-plus-supplemental. In these tests, the system is tested until performance is the same for two sucessive days. Either the solar fraction, f, or the fractional energy savings, e, are determined. The standard provides for tests using solar simulators or tests using a conventional heat source in series with a nonirradiated collector array (after the array is tested following ASHRAE 93-77). Procedures are also given for determining the energy delivery capacity of the system during continuous draw-down.

2.3 EXPERIMENTAL VALIDATION OF ASHRAE 95-81

NBS built an experimental apparatus to assess the proposed standard test methods of ASHRAE 95-81 for solar domestic hot water heaters. This apparatus, which is described in [11], contained both an irradiated system (figure 4) and one using the thermal simulators mentioned above (figures 5 and 6).

In the experimental assessment, the outdoor irradiated system was operated normally for several days, to serve as a baseline for comparison. Tests were then conducted on the nonirradiated system with power supplied to the heat source as determined by analysis of the recorded irradiance and temperature from the baseline operation. This procedure allowed a direct comparison of the thermal performance of the two systems. In no case did the daily fractional energy savings for the systems differ by more than three percent between the measurements for the irradiated array and for the simulated energy input. Similar agreement was achieved in tests with an electric heat source only, and for the nonirradiated array with attached strip heaters. Of particular concern was the sensitivity of the test procedures to stratification within the storage tank. Since this stratification is influenced by the tank design and dimensions, as well as the velocity and manner in which fluids are introduced into the tank, several return-tube designs were tested. (The return-tube introduces the solar heated water into the storage tank.) In these tests, the storage tank itself and the flow rate were not altered. These tests showed that the alteration of the return tubes produced different levels of stratification, resulting in differences of up to 8.7 percent in fractional energy savings. (Maximum stratification resulted in the greatest savings.) The tests also showed that the test procedures of ASHRAE 95-81 are sensitive to the degree of stratification which occurs in storage tanks.

An analytical model [14] was also used to determine the quantitative effect of various test methods for the solar domestic hot water heaters. For tests conducted on two different days, the analysis indicated that data from the various test procedures (irradiated array, nonirradiated array with downstream heat source, nonirradiated array with upstream heat source, and nonirradiated array with strip heaters) were all in good agreement. The effect of wind speed and thermal losses from the heat source were each found to be less than one percent.

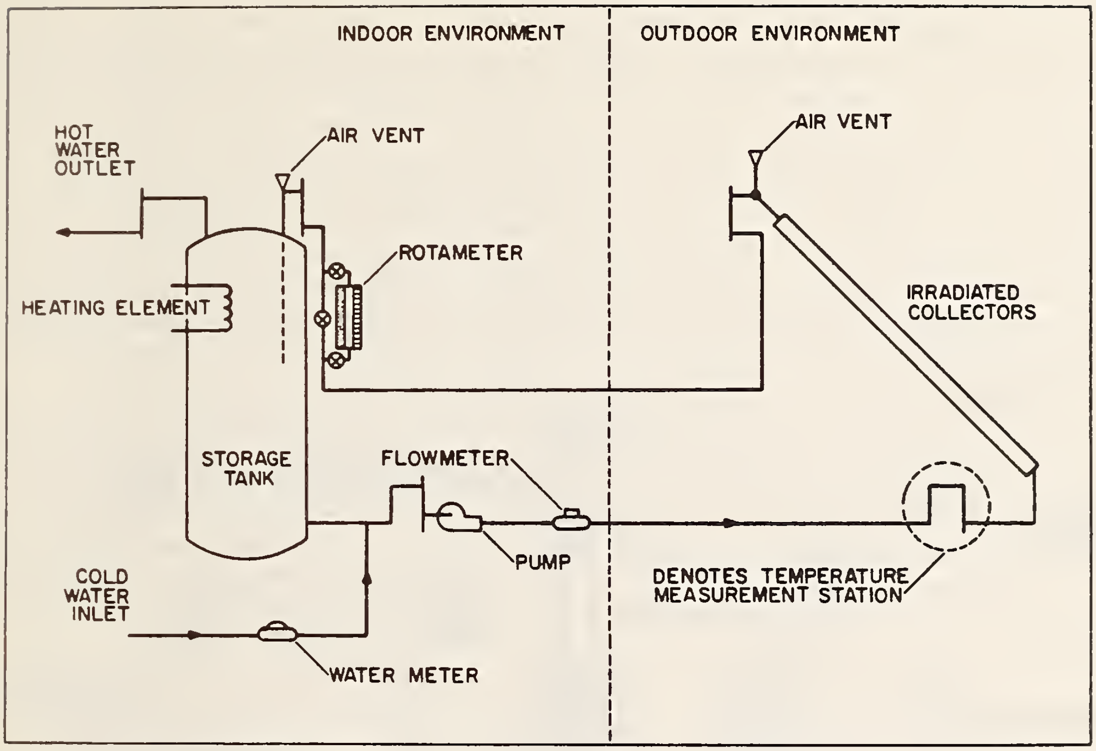

Figure 4. Single-tank direct system schematic (from Ref. 11)

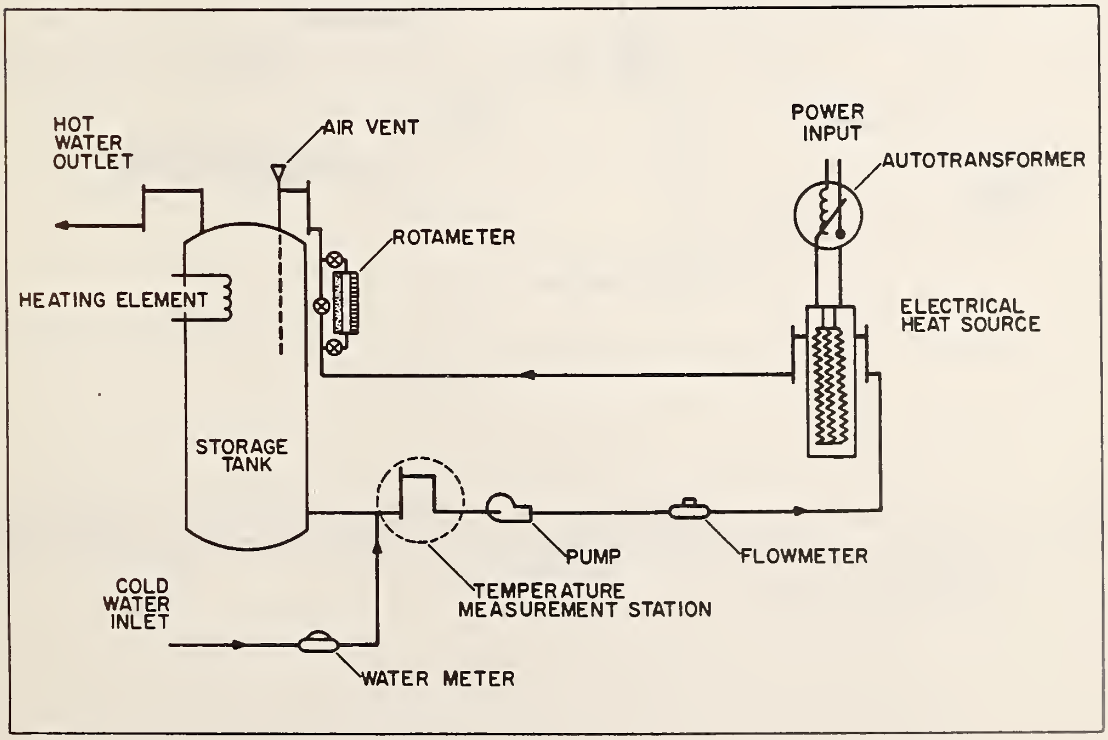

Figure 5. Solar hot water system with the irradiated collector array replaced with an electric heat source (from Ref. 11)

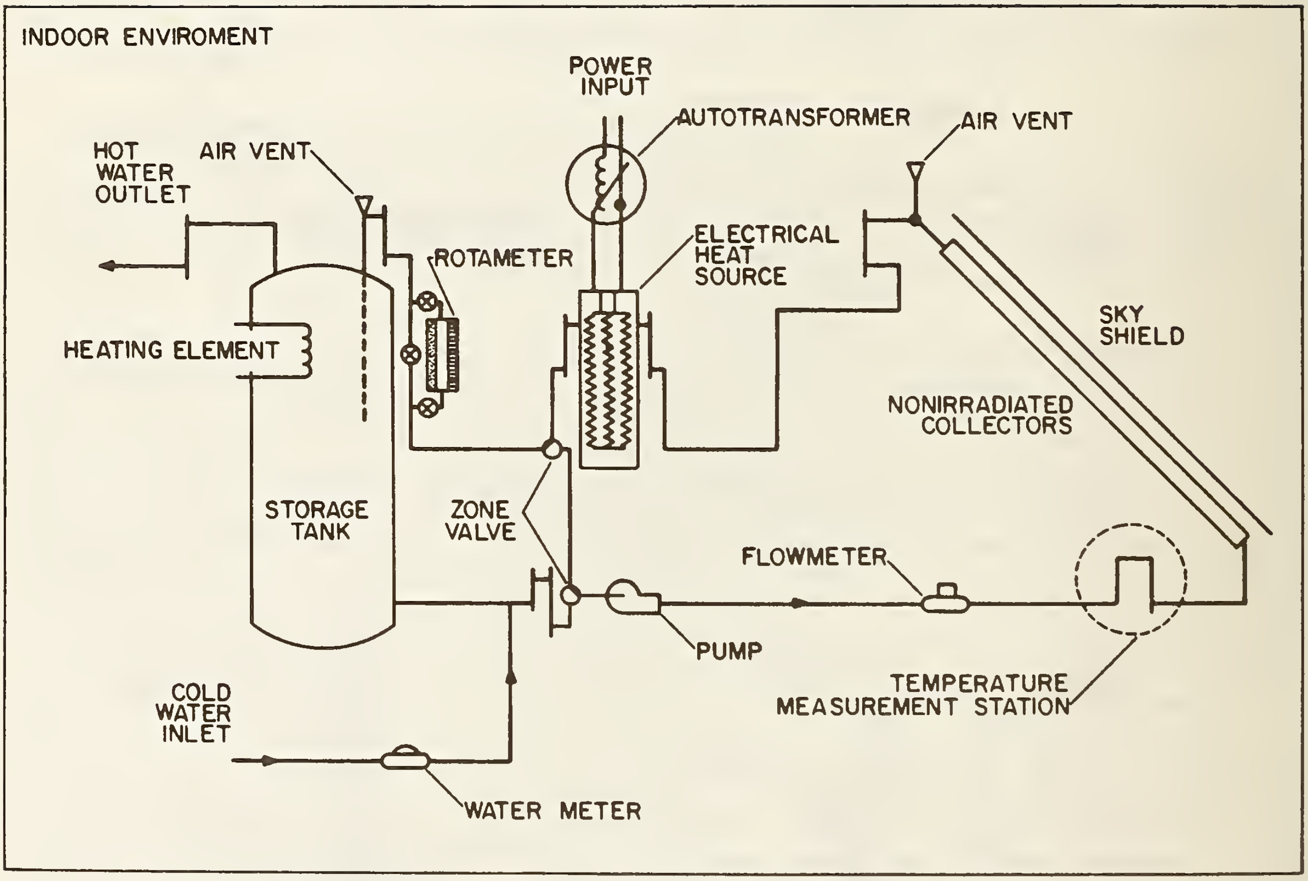

Figure 6. Solar hot water system with the irradiated collector array replaced with a nonirradiated collector array with downstream heat source (from Ref. 11)

In summary, both the analytical and the experimental work indicated that the thermal performance of domestic solar hot water systems can be duplicated under indoor laboratory conditions without solar simulators. The research indicated further that outdoor stagnation conditions cannot be duplicated by using an electric heat source only. Strip heaters must be attached to the back of absorber plates within nonirradiated collector arrays, or an electric source must be used with a nonirradiated collector array. The research also indicated that the test methods prescribed in ASHRAE 95-81 are sensitive to temperature stratifications within the storage tank. Finally, test result repeatability was found to be excellent for the experimental technique using a nonirradiated collector array in series with a downstream heat source.

Recommendations made by NBS for future work included the development of correlations of ASHRAE 95-81 results with meteorological conditions, the conduct of experiments to validate suggested test methods for thermosyphon systems, and an investigation of the effects of liquid flow rates, with the objective being to eliminate the need to use the same fluid in testing both the collector and the entire system.

3. THERMAL STORAGE DEVICES

3.1 THERMAL PERFORMANCE

With support from the National Science Foundation (NSF), NBS undertook the development of standardized test procedures for thermal storage devices, beginning in 1974. This effort continued in parallel with the development of NBS-recommended procedures for evaluating the performance of solar collectors. The NBS research, its development into an ASHRAE standard, and the experimental evaluation of the effectiveness of this standard are outlined below, along with some additional research performed by the Argonne National Laboratory.

Initially, NBS personnel reviewed the available literature on the analysis of the performance of thermal storage devices and applicable test methods, and developed a framework for evaluation. Thermal storage devices for solar heating and cooling systems can be classified as either sensible-heat or latent-heat devices. In sensible-heat devices, the heat absorbed or removed from the unit changes the temperature of the storage medium, with no change of phase. Typical storage media include water (pressurized or unpressurized), rock, brick, or concrete. In latent-heat devices, the heat (added or removed) changes the enthalpy of the storage medium through a change of phase in the storage medium--typically inorganic salt hydrates or organic materials. The choice of thermal storage device is frequently related to the type of solar collector, so that storage devices for water-heating collectors are usually the sensible-heat type, while a storage device for an air-handling collector could be a latent-heat device.

Performance of thermal storage devices is governed by:

1) Thermal capacity;
2) Operational temperature range;
3) Means of addition or removal of heat and the associated temperature differences;
4) Temperature stratification in the unit;
5) Power requirements for the addition or removal of heat;
6) Containers or other structural elements associated with the system;
7) Thermal losses;
8) Cost.

The emphasis in the NBS research program was placed on developing a testing procedure for evaluating thermal storage devices on the basis of thermal performance--as was also done with solar collectors. The test procedures for thermal storage devices differ from those for solar collectors in one significant area. Because solar collector performance is largely determined by its characteristics under steady or "quasi-steady"* state conditions, the ASHRAE

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* Quasi-steady is the term used to describe the state of the solar collector test when the flow rate and temperature of the fluid entering the collector is constant, but the exit temperature changes gradually due to the normal change of insolation that occurs with time for clear sky conditions.

standard test is conducted under "quasi-steady" conditions. Performance of a thermal storage device, however, is determined by its characteristics under transient operating conditions.

In the research program, NBS evaluated the effectiveness of three different methods of determining the thermal performance of thermal storage devices (both sensible and latent heat), used primarily in conjunction with solar space heating, cooling, and domestic hot water supply.

The first, and most commonly used, method for evaluating the thermal performance of storage devices is to change the temperature (by a known amount) of the transfer fluid entering the device, and then measure the temperature of the fluid leaving the device. By integrating this temperature difference over the testing period and multiplying the result by the mass-flow rate and specific heat of the transfer fluid, the amount of heat added or removed during the testing period can be calculated.

In the second method, the heat transfer fluid is subjected to a constant influx of heat and the time-dependent outlet temperature is measured. While this method is a close simulation of the real interaction between a collector and a storage device, it does not allow measurement of the energy storage and removal capacity of the unit.

In the third method, a time-varying influx of heat is applied to the transfer fluid, and the outlet temperature is measured as a function of time. This method simulates the output of a collector, and the response of the storage device over several days. Neither method 2 or 3 allows ready comparison of different devices, however.

While methods 2 and 3 simulate more closely the real interaction between solar collectors and heat storage devices, they do not allow the measurement of the energy storage and removal capacity of the units. As a result, the comparison of the performance of different units is very difficult. Method 1 allows easy comparison between units, and appears to be the most fundamental approach.

As a result, NBS devloped a test procedure which uses the approach outlined in method 1. This procedure specifies a series of tests for determining thermal performance. This includes:

1) One test to determine a heat-loss factor for the storage unit;
2) A series of tests to determine the response characteristics of the device to a step increase in the temperature of the entering fluid (energy addition);
3) Another series of tests to determine the response to a step decrease in the temperature of the entering fluid (energy withdrawal).

This procedure was contained in a draft test method [15,16,17] submitted by NBS to ASHRAE for consideration as a voluntary consensus standard. At the same time, the draft was submitted to a broad two-step review by experts during NSF/RANN (Research Applied to National Needs) workshops at Colorado State University on August 23, 1974, and at Charlottesville, VA, on April 16-18, 1975.

3.2 ASHRAE STANDARD 94-77

In 1977, ASHRAE promulgated standard 94-77 (ANSI Standard B199.1, 1977) [18], entitled "Methods of Testing Thermal Storage Devices Based on Thermal Performance." The ASHRAE standard closely follows the format and technical requirements of the NBS-developed draft.

ASHRAE Standard 94-77 applies to both sensible and latent-heat type storage devices in which a transfer fluid enters the device through a single inlet and leaves through a single outlet. It describes the required accuracy and precision, the apparatus and test configuration (see figure 7), the test procedures, the data to be recorded, and the test report format. It also specifies the instrumentation (such as thermopiles, thermometers, or thermistors) for measuring the temperature of the transfer fluid, the liquid or air flow, pressure, and time and mass. Test procedures are given for both air and liquid as the transfer fluid.

The test procedures consist of three elements:

a) A heat-loss rate test, to be performed before any other test;
b) Two charge tests; and
c) Two discharge tests.

These tests allow the determination of both the heat-loss rate and the overall storage capacity. All tests require that the temperature of the storage medium be uniform at the desired temperature, and that there be a steady flow of transfer fluid through the storage system during the test.

For both the charge and discharge tests, the transfer fluid, at a constant temperature, is passed through the storage device until the device is brought to a uniform initial temperature. After adjusting the flow to the charge test flow rate, the temperature of the transfer fluid entering the storage device is then increased in a step-like manner, and maintained until the temperature of the transfer fluid leaving the storage device no longer changes with time (see figure 8). The standard recommends inlet temperature steps of 15°C (27°F). During the charge and discharge test time, the differences between the temperatures of the transfer fluids entering and leaving the storage device is to be recorded and integrated over time, and the charge or discharge capacities determined as:

$$C_c = W_c C_{tf} \int_o^{\tau_c} (t_{in} - t_{out}) d\tau \text{ and}$$

$$C_d = W_d C_{tf} \int_o^{\tau_d} (t_{in} - t_{out}) d\tau$$

Where:

C_c = Charge capacity J(Btu)
C_d = Discharge capacity J(Btu)

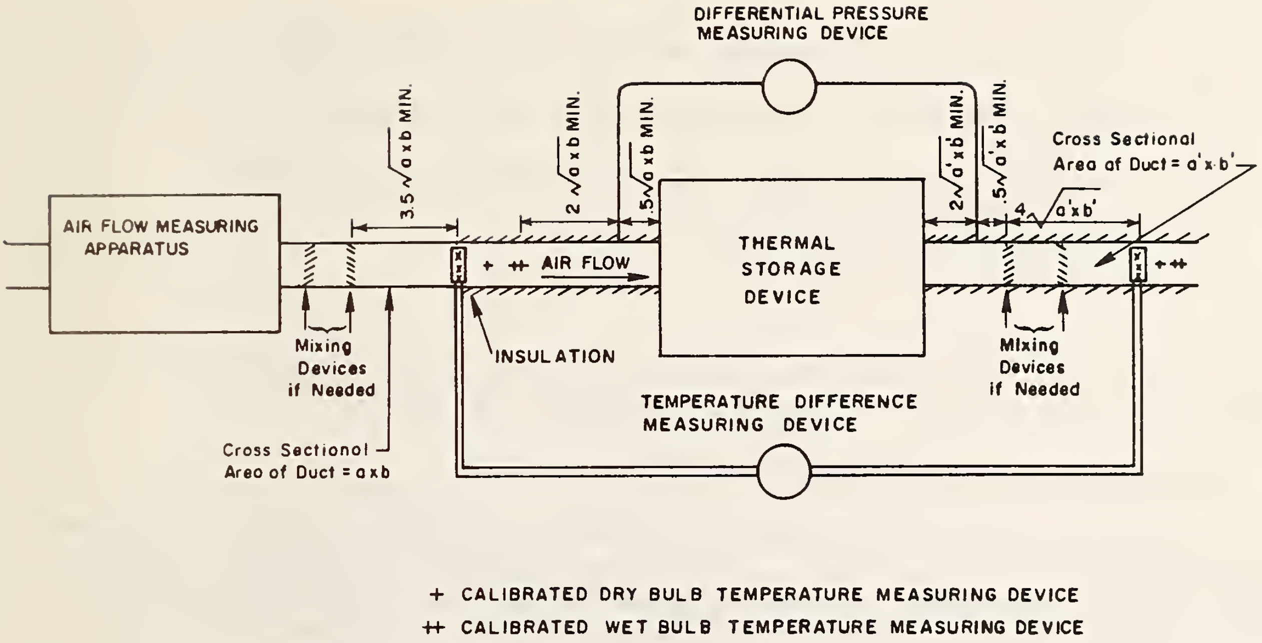


Figure 7. Representative test configuration for a thermal storage device using air as the transfer fluid (test configuration for liquid as transfer fluid is similar) (from Ref. 18)

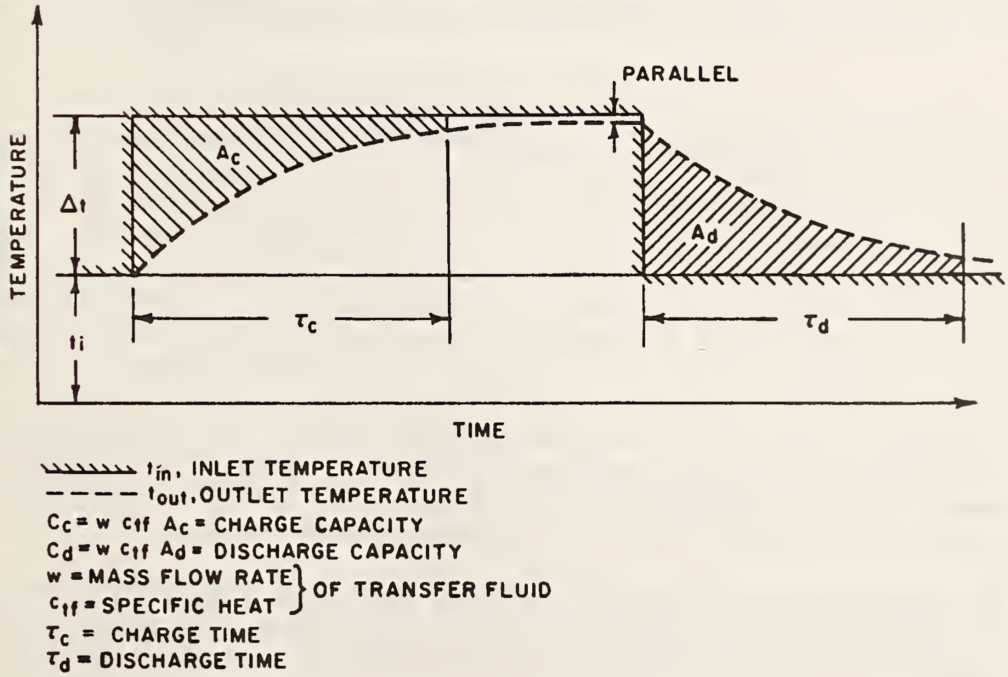


Figure 8. Time-temperature variation of transfer fluid during a charge/discharge test cycle (from Ref. 18)

W_c = Mass flow rate of transfer medium during charge test, kg/s (ℓbm per hr)
W_d = Mass flow rate of transfer medium during discharge test, kg/s (ℓbm per hr)
C_{tf} = Specific heat of transfer fluid (J/kg°C), (Btu per ℓb°F)
τ_c = Charge test time, s(hr)
τ_d = Discharge test time, s(hr)
τ = Time, s(hr)

The method also requires that the time variation in outlet temperature of the transfer fluid be plotted as shown in the graph in figure 9.

3.3 EVALUATION OF ASHRAE STANDARD 94-77

NBS performed a number of experimental studies to evaluate provisions of ASHRAE 94-77 [19,20,21]. In the first, a preliminary analytical model was developed; in the second, procedures for testing water storage tanks were assessed; and in the third, both a pebble-bed and a phase change material were evaluated.

In a preliminary report, Peavy and Dressler [19] evaluated sensible heat changes in porous thermal storage material with fluid transpiring through it. Using the test methods described in ASHRAE 94-77, they subjected a porous bed of sand, with water flowing through it at a uniform temperature, to a sudden change in the entering fluid temperature. The transient temperature distribution was determined until steady-state conditions were again achieved. The analytical model which was developed for predicting the thermal performance of transpiration energy storage units showed good agreement with the experimental data.

In a second study, Hunt, Richtmyer, and Hill evaluated the thermal performance of a water tank used as a thermal storage device [20]. These tests were conducted on a 1.9 m^3 (500 gal) water tank built into a complete solar heating and cooling system at NBS. The tests, which followed the procedures outlined in ASHRAE 94-77, determined that the ASHRAE methods allowed an accurate quantification of the heat loss characteristics, and of the energy charged and discharged in sensible heat storage devices (water tanks) for liquid systems. The research also determined that a number of minor modifications could be made to the standard to improve the ease of testing. These modifications included:

1) A precise 15°C (27°F) temperature step change, as recommended by the standard (see 2.3.2), does not appear to be necessary. Adequate results were obtained without an exact 15°C (27°F) step, provided these results were presented in dimensionless terms.

2) The dimensionless plots described in reference [18] should be used in the analysis of the results. Use of such plots allows a means for comparing the thermal performance of different storage devices.

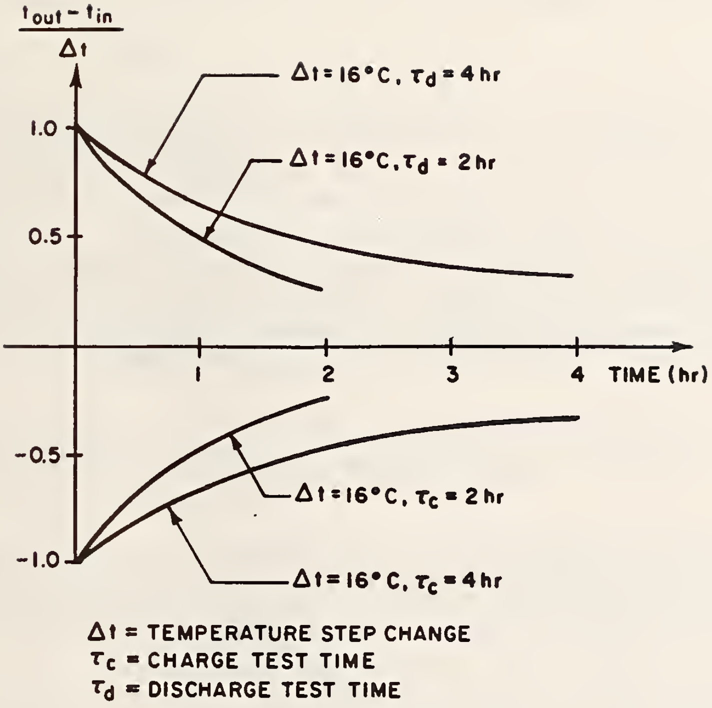


Figure 9. Suggested plot of transfer fluid temperature (from Ref. 16)

3) A "Stagnant Heat Loss Test" as described in [18] should be incorporated into the standard as an alternate technique to the heat loss test prescribed.

Another study conducted at NBS [21] evaluated the effectiveness of ASHRAE 94-77 for storage devices using air as the transfer fluid. This study again used the the procedures given in the standard to evaluate the thermal performance of a 7 m^3 (250 ft^3) pebble bed, and of a similarly-sized phase change unit (264 MJ or 250,000 Btu), which used 726 plastic trays containing a glauber salt-water mixture (sodium sulfate decahydrate) [21]. Air was the transfer fluid in both test series.

Although the tests were found to permit the quantification of heat loss and the amounts of energy charged into or discharged from the devices, a number of problems were encountered. These included problems with variations in temperature difference across a pebble bed, and major difficulties in quantifying the exchange of moisture with the air stream in pebble beds. Problems for phase change devices included heat loss due to air leakage, temperature stratification in the trays containing the phase-change material, and difficulties in calculating discharge capacities. As a result, a number of recommendations were suggested for the ASHRAE standard. These included:

1) The flow rate for devices using air as the transfer fluid should be changed to reflect the flow rates normally measured in installed solar systems.

2) The temperature difference for the heat loss test should be increased from 25°C to 35°C (77°F to 95°F) so that this test can easily be conducted in conjunction with the transient charge and discharge tests.

3) Dimensionless plots should be used for the analysis of the test results (as was recommended for water tank tests.)

4) Establishment of the relationship between test results and real-world system performance, although the test results should allow a relative ranking of different thermal energy storage devices.

5) Other specific suggestions included: reporting requirements for latent-heat storage devices; specification of inlet air conditions for devices using air as the transfer media; and the basing of charge/discharge capacities only on sensible-heat exchange for pebble-bed devices.

In addition to the work performed at NBS, ANL also conducted research to evaluate the effectiveness of the ASHRAE standard for evaluating devices which use latent-heat thermal storage (an area not addressed in detail by NBS). Experience since 1977 had demonstrated that ASHRAE 94-77 did not yield reliable results for latent-heat thermal energy storage (LHTES) devices. As a result, Argonne identified problems areas in the standard and developed a proposed test procedure for use with latent heat units [22].

The modifications proposed by ANL refer only to LHTES units with one inlet and one outlet for the heat transfer fluid. This fluid may be either a nonevaporating liquid or a noncondensing gas. The proposed procedure specifies the test apparatus and instrumentation given in ASHRAE 94-77, but requires the installation of additional thermocouples to measure the unit's surface and storage medium temperature.

The proposed test procedure calls for a minimum of six tests.
These include;

- Cycling
- Full Capacity Charge
- Heat Loss
- Full Capacity Discharge
- Partial Capacity Charge
- Partial Capacity Discharge.

A major departure from ASHRAE 94-77 is the addition of the cycling test. The proposed procedure specifies 50 continuous charge/discharge cycles of 2 hours each. The proposed method also introduced and defined parameters for comparing the performance of different LHTES units. These parameters, which are to be determined from the test data include;

- Effectiveness
- Charge/discharge capacity per unit volume
- Effectiveness degradation.

ANL indicated that this proposed test method for LHTES units is preliminary and requires further validation in both bench and full-scale tests. It also attributed the problems with the ASHRAE standard to the combination of test procedures for both sensible-heat and latent-heat thermal-storage devices into a single format. As a result, the method cannot provide either representative charge or discharge capacities, or a base for comparing different LHTES units. As a result, ANL proposed the changes mentioned above to the ASHRAE standard for latent-heat storage devices. These changes were submitted to ASHRAE for consideration at the June 1983 meeting.

4. SOLAR COLLECTORS

4.1 INTRODUCTION

Various standards have been developed to rate the thermal efficiency and provide for the safety of conventional fuel-burning equipment. Such standards and rating systems allow the establishment of design guidelines, as well as the systematic comparison of component performance. In the early 1970s, solar space and domestic hot water heating systems began to receive serious attention. Yet, because there were no standardized test procedures, there was no way to rate various components or to compare the performance and safety of different products. The lack of standardized test procedures, although true to a degree for all solar components, was particularly noticeable for solar collectors. Their thermal performance varies as a function of many parameters, such as operating temperature, fluid flow rate, insolation, orientation, tilt, time of day, day of year, wind, temperature, sky condition, etc, making standardized evaluation difficult.

In an effort to assist the young industry and to pave the way for increased use of solar space- and domestic-hot-water heating systems, the National Bureau of Standards (NBS) began a program in 1974 to develop procedures for testing the thermal performance of solar collectors. The testing procedures for thermal performance were intended to be submitted to ASHRAE for consideration as voluntary consensus standards. In the research program, NBS constructed a set of test facilities at the NBS-Gaithersburg, MD site, conducted a set of round-robin tests, and completed a series of comparison and validation tests using test procedures from both the United States (U.S.) and Europe. The test program for evaluating solar collectors was sponsored initially by NSF, and later by the Department of Energy (DoE), and the Department of Housing and Urban Development (HUD).

While thermal performance was the primary criterion for evaluating any space- or domestic-hot-water system or component, NBS also recognized that safety and durability should be evaluated. As a result, NBS studied the operational performance of solar collectors in terms of overall durability, snow and wind loads, hail, over-pressure, and fire. Appropriate existing test methods were identified for various characteristics, while modifications or new methods were outlined as needed. Many of the test methods for durability and safety were submitted to ASTM for consideration as voluntary standards. In the following pages the NBS research and the applicable ASHRAE and ASTM standards for solar collector performance will be discussed. In section 4, the performance of the solar collector as a unit is described, while in section 5, the performance of individual materials or components of solar collectors is discussed. Section 4 treats thermal performance first, followed by durability and reliability considerations.

4.2 THERMAL PERFORMANCE OF SOLAR COLLECTORS

4.2.1 Initial Evaluation and Standards Development

The NBS research began with an extensive review of the literature on methods of analysis and testing of collector thermal performance. In the project, it was soon realized that the performance of solar collectors depends to some extent on the system in which they are used. Yet, it was also realized that evaluating the collector within a total system was impractical because of the many ways that solar energy could be used within a building. As a result, the NBS efforts focused on developing test procedures for evaluating solar collectors as individual components of the system.

Based on the literature review and preliminary research, NBS drafted test procedures for evaluating the thermal performance of solar collectors. These procedures were reviewed by participants at three NSF/RANN workshops, held during 1974 and 1975. These procedures were also contained in a document entitled "Interim Performance Criteria for Solar Heating and Cooling Systems" [23] prepared by NBS for HUD as part of its implementation of the Solar Heating and Cooling Demonstration Act [24]. The proposed test procedures were then submitted to ASHRAE for consideration as a standard.

4.2.2 NBS Research

The development of the interim ASHRAE standard, and the investigations preceding it, were discussed in NBS Technical Note 899 [16]. This report discussed methods of analysis that provide the theoretical basis for the thermal performance test methods contained in the interim ASHRAE standard.

NBS classified solar collectors as either flat-plate or focusing (concentrating) types. In a flat-plate collector, the absorber surface is basically flat, and the aperture size for incident radiation is equal to the absorber area. In a focused collector, the absorber area is smaller than the aperture so that energy is concentrated onto its surface. This results in higher temperatures for the transfer fluid.

NBS identified fundamental characteristics of collectors were identified as: heat loss coefficient, transmittance-absorptance product, and short- or long-term efficiency. These characteristics can be evaluated by two basic test procedures: instantaneous and calorimetric. Calorimetric procedures are limited to collectors which use liquid rather than gas as the heat transfer medium. Collector efficiency was defined as:

$$\eta = \frac{\text{[Actual Useful Energy Collected]}}{\text{[Solar Energy Incident Upon or Intercepted by the Collector]}}$$

or in equation form $\eta = \frac{q_u/A}{I}$

where q_u = rate of useful energy extracted from solar collector, W
A = cross-sectional area, m^2, of the collector
I = total solar energy incident upon the plane of the solar collector per unit time per unit area, W/m^2

In the instantaneous method of calculating collector efficiency, the mass flow rate of the transfer fluid, the difference in fluid temperature between the inlet and outlet, and the insolation, are all measured simultaneously and under steady-state conditions. The instantaneous efficiency is then determined by:

$$\eta = \frac{q_{uA}}{I} = \frac{\dot{m}\, c_{tf}(t_{fe}-t_{fi})}{I}$$

where: $\dot{m}$ = working fluid mass flow rate through the collector per unit cross-sectional area, $kg/(s \cdot m^2)$
c_{tf} = specific heat of transfer fluid, $J/(kg \cdot °C)$
$t_{f,i}$ = temperature of fluid entering collector, °C
$t_{f,e}$ = temperature of fluid leaving the collector, °C.

The apparatus used for the instantaneous method is an open-system type, while the apparatus used for the calorimetric method is a closed-system type. Figure 10 provides a schematic representation of these two types of testing apparatus.

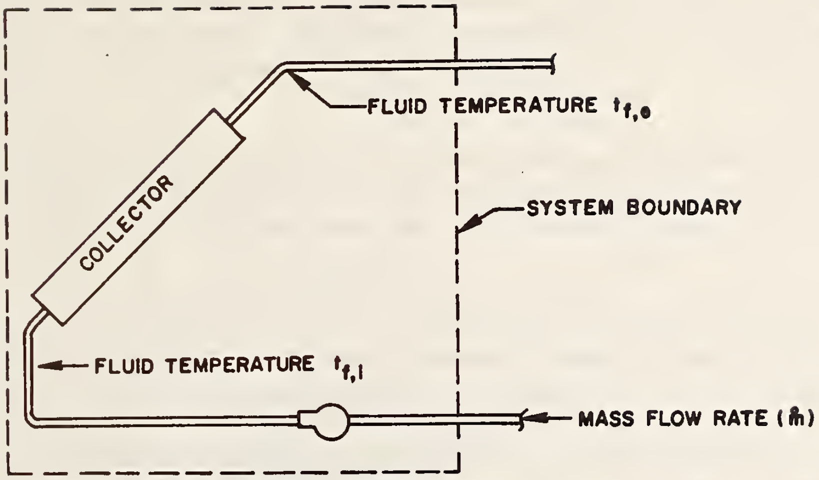
NBS also reviewed specific state-of-the-art procedures used for determining thermal efficiencies. This extensive review included some ten different approaches used throughout the world:

- Procedures for determining collector efficiency (South Africa)
- Studies of heat transfer (Israel)
- Procedures for assessing collector performance (Australia)
- Testing of plastic bag solar hot water heaters (Japan and U.S.)
- Modified instantaneous testing procedures (Jet Propulsion Lab)
- Use of supplementary heating (University of Pennsylvania)
- Determination of daily average efficiency (U.S.)
- Use of Solar Calorimeter (Arthur D. Little)
- Collector performance testing (NASA Lewis Research Center), and
- Testing of air solar collectors (South Africa and the U.S.)

4.3 ASHRAE STANDARDS FOR THERMAL PERFORMANCE

4.3.1 ASHRAE 93-77

Based on the literature review [16], NBS developed a test method for rating solar collectors based on their thermal performance [25]. This method was submitted to ASHRAE and adopted in large measure as ASHRAE Standard 93-77. This standard provides test methods for determining the thermal performance of solar collectors for heating fluids for thermal systems. Some of its provisions will be discussed briefly here.

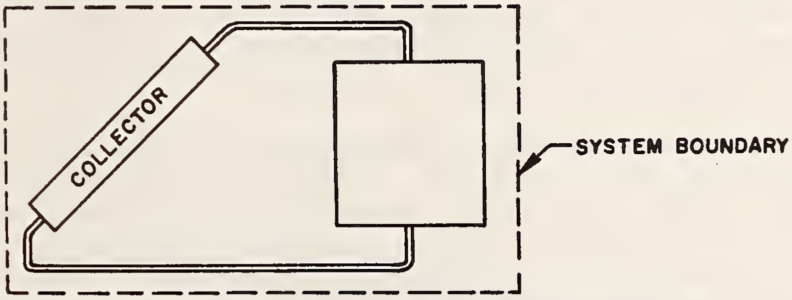


OPEN SYSTEM - INSTANTANEOUS PROCEDURE

Governing Equation : $\dot{Q} = \dot{m}c_{tf} (t_{f,e}-t_{f,i})$

Where $\dot{Q}$ = Heat Delivered by Collector,

$c_{t,f}$ = Fluid Heat Capacity



CLOSED SYSTEM - CALORIMETRIC PROCEDURE

Governing Equation: $\dot{Q} = \dot{m}c_p \frac{dt}{d\tau}$

Where m = Total System Mass,

$\frac{dt}{d\tau}$ = Time Rate of Change of Temperature

Figure 10. Schematic representation of the two basic methods for determining solar collector thermal efficiency. (Adapted from: Thomason, Jr., "Solar Houses/Heating & Cooling Progress Report," Solar Energy, Vol. 15, No. 1, pp. 27-40, 1973.)

The standard applies only to collectors in which fluid enters through a single inlet and leaves through a single outlet, or to collectors with more than a single inlet/outlet in which the piping can be so connected as to effectively provide a single inlet and outlet. The transfer fluid may be either a liquid or a gas. The standard does not apply to collectors in which the thermal storage unit is an integral part so that the collector and storage processes cannot be separated for the purpose of measurement. The method is applicable only for determining steady-state efficiency and not transient responses. The standard further specifies mounting precautions, average irradiation, collector orientation, and wind velocity measurements as appropriate for specific tests.

Instrumentation is required for measuring: shortwave radiation (pyranometer); direct normal irradiation (pyrheliometer); temperature and temperature differences; liquid flow; air flow; pressure; time and mass; and wind velocity.

The standard provides three test configurations for testing liquid solar collectors. It specifies mounting tilt, ambient temperature sensor location, measurement of solar radiation, temperature difference and pressure drop measurements across the solar collector. It also specifies procedures for measuring air as the transfer fluid. Allowable tolerances and levels of accuracy are given for all required instrumentation and measurements.

Parameters to be measured during the testing procedure include: temperature, temperature differences, direct pressures, air flow measurements, air leakage, and air reconditioning. The standard further provides procedures for indoor testing with a solar simulator.

The test procedures require experimental measurement of the rate of incident solar radiation onto the solar collector, as well as the rate of energy addition to the transfer fluid as it passes through the solar collector. From a combination of values of incident radiation, ambient temperature, and inlet fluid temperature, values of instantaneous efficiency can be obtained. In addition, tests are specified for determining the time response characteristics of the collector and the way in which steady-state thermal efficiency varies with the incident angle between the direct beam and the collector.

Performance equations are given for calculating collector thermal efficiency, collector time constant (for evaluating transient behavior), and collector incident angle modifier.

The testing procedure provides for a sequence of tests. First is the experimental determination of the collector time constant (by one of two methods). Secondly, a series of thermal efficiency tests are conducted to determine the governing efficiency curve. Finally, the value of the collector incident angle modifier is determined experimentally. This latter procedure is not necessary for flat-plate collectors whose angular response characteristics are known. Following the experimental determination, a sequence of computations are to be performed. These include computation of collector time constant, collector thermal efficiency, collector incident angle modifier, air flow rate, nozzle Reynolds number, and theoretical power requirements. Equations are given for each computation.

The standard specifies that tests are to be conducted only on days having weather conditions in which the 15 minutes integrated average solar radiation is a minimum of 630 W/m^2 (200 $Btu/h \cdot ft^2$). Further restrictions are given for incident angle and the range of ambient temperatures for test points comprising the efficiency curve.

Figure 11 gives the testing configurations to be used with the solar collector when the transfer fluid is a liquid, and figure 12 shows the configuration for a collector using air as the transfer fluid.

The standard details the instrumentation requirements including those for the pyranometer and its location, and for flow metering in air systems. The test procedure and calculations call for obtaining values of instantaneous combination of values of incident solar radiation, ambient temperatures, and inlet fluid temperatures. This requires measuring the rate of solar radiation incidence onto the solar collector, as well as the rate of energy addition to the transfer fluid as it passes through the collector under quasi-steady conditions. Based on the definition of collector efficiency given above it can be stated that:

$$\eta = F'_{(\tau\alpha)e} - F'U_L \frac{\frac{t_{f,i} + t_{f,e}}{2} - t_a}{I}$$

Where: F' = Solar collector efficiency factor
$(\tau\alpha)_e$ = Effective transmission - absorptance factor for the solar collector
U_L = Heat transfer loss coefficient for the solar collector, $W/m^2 \cdot °C$)
t_a = Ambient air temperature
$t_{f,i}; t_{f,e}$; I = As defined previously

This equation indicates that if the efficiency is plotted against an appropriate $\Delta t/I$, a straight line will result where the slope is some function of U_L, and the η intercept is some function of $(\tau\alpha)_e$. Figure 13 shows typical results of tests performed on air heaters with single-glass cover plates [26]. For determining the efficiency curve, at least four different values of inlet fluid temperature must be used, and for each inlet fluid temperature, at least four data "points" must be taken, two preceeding and two symmetrically following solar noon. Each data "point" is to represent 15 minutes integrated efficiency value.

While ASHRAE Standard 99-77 follows closely the NBS interim standard, it is a further development and thus differs in several significant ways. The most significant of these are:

- Additional tests are required to determine the collector time constant and the incident angle correction factor.

- It allows for indoor testing using a solar simulator,

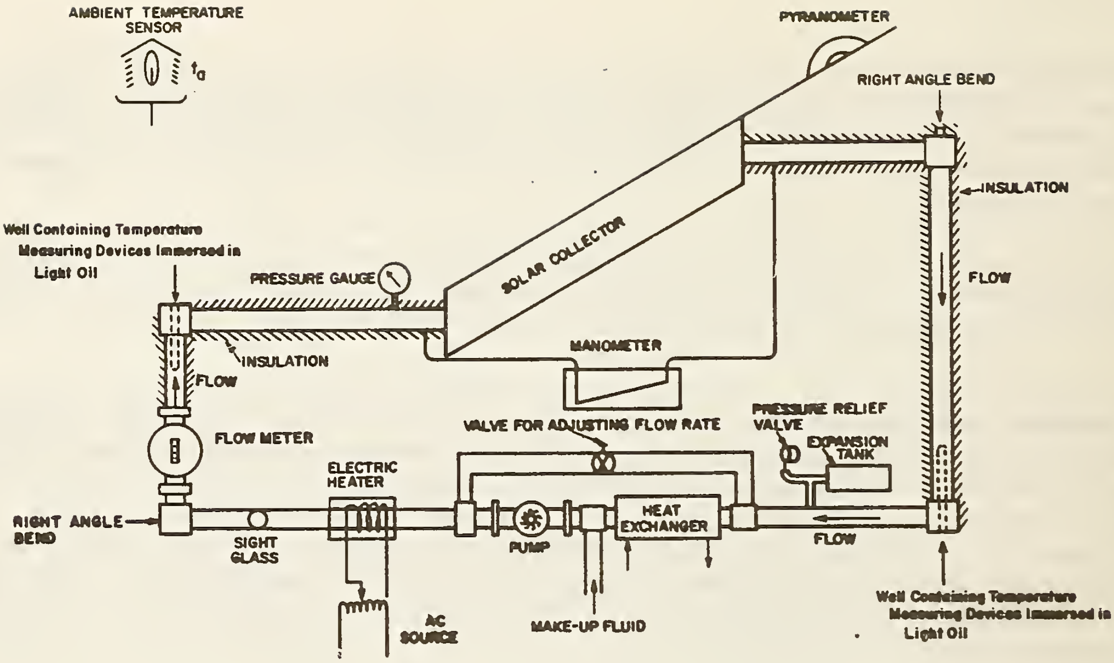


Figure 11. Testing configuration for the solar collector when the transfer fluid is a liquid (from Ref. 25)

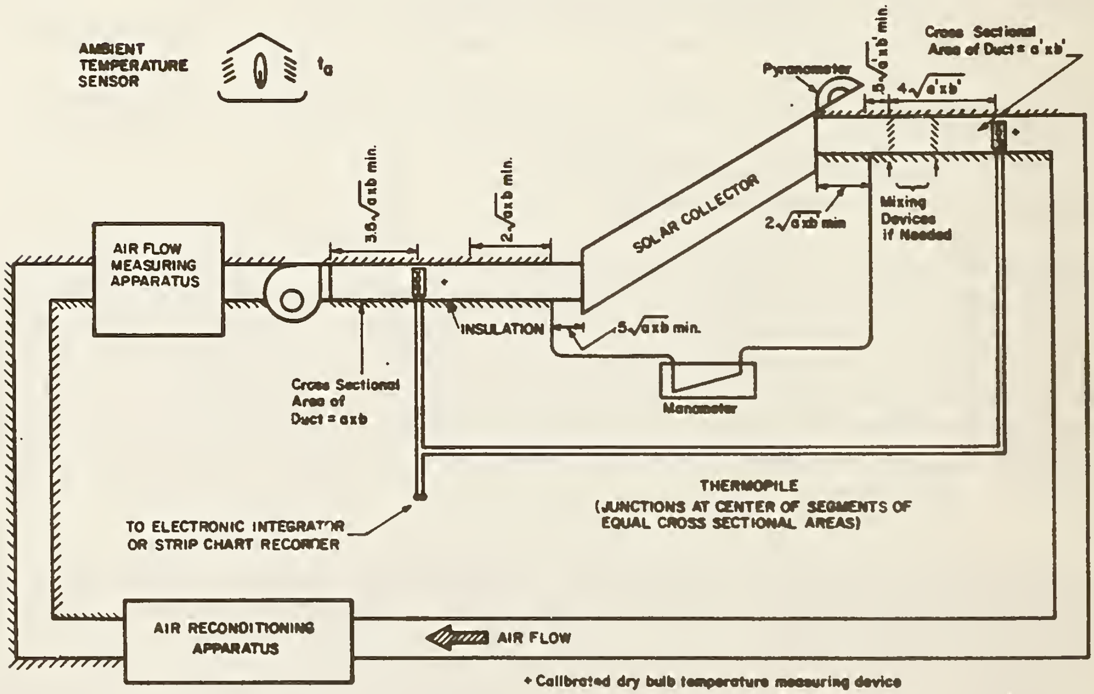


Figure 12. Testing configuration for the solar collector when the transfer fluid is air (from Ref. 25)

1.23 m by 0.76 m Air Heaters
single glass cover plate
.15 m glass wool edge insulation
.05 m glass wool back insulation

- ○ corrugated galvanized iron absorber surface, carbon black paint
- ● corrugated aluminum absorber surface, commercial chimney paint

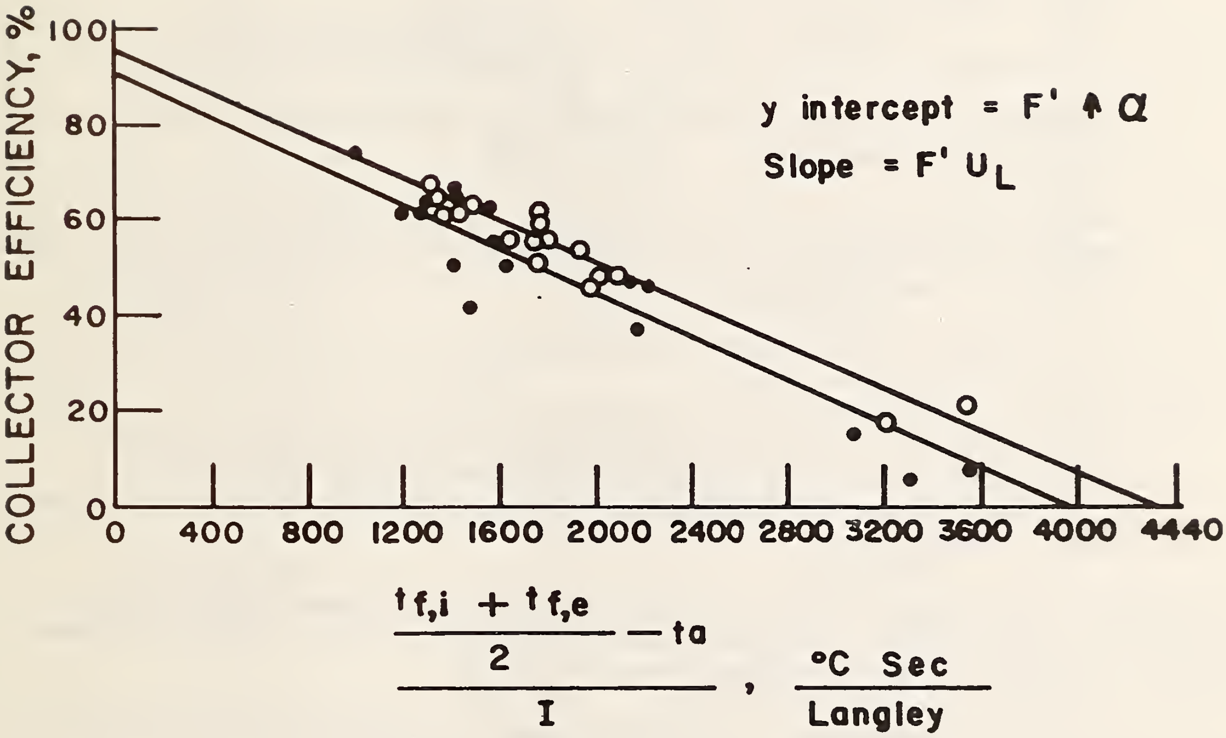


Figure 13. Efficiency curves for two flat-plate collectors using air as the transfer fluid (from Ref. 26)

- The specimen shall be preconditioned by stagnation heat in a nonoperational, dry condition for three days.

Specific technical changes include:

- Modifications to the test loop to add a storage tank with by-pass for dampening-out thermal transients.

- Rearrangement of the air heater test loop to "pull" the air through rather than blowing it through.

- Tightening-up the requirements for measuring solar radiation.

- Requirement that the incident angle must be less than 30 degrees (instead of 45 degrees).

- Reduction of the time period for integrating energy quantities for computing efficiency values from 15 minutes to either 5 minutes or one time constant, whichever is larger.

- Use of gross frontal area of the collector for computing efficiency instead of aperture area.

- Dividing by the incident solar radiation rather than the average fluid temperature in drawing the efficiency curve which plots efficiency versus the difference between inlet fluid temperature and ambient temperature.

In addition, the standard also provides information on open loop testing configurations for liquid transfer fluids, both with (figure 14) and without (figure 15) continuous fluid supply.

The preconditioning consists of stagnation heat in nonoperational mode under dry conditions for three days with a cumulative mean incident solar radiation of not less than 4722 $(W\cdot hr)/(m^2\cdot day)[1500\ Btu/(ft^2\cdot day)]$.

For indoor testing with a solar simulator, the standard specifies spectral qualities to duplicate average North American irradiation as closely as possible, and best represented by an air-mass 2 solar spectrum [27]. It further requires a uniformity of illumination over the collector aperture of not more than ± 10 percent, collimation such that at least 95 percent of the energy output is within a subtended angle of 12 degrees or less, and maintenance of a substantially uniform air flow across the collector of at least 3.5 m/s (7.6 mph). It also specifies that the collector configuration factor between the solar simulator surface and the solar collector not exceed 0.05.

To evaluate the transient behavior of the collector, the standard requires that the collector time constant be determined. The time constant is defined as the time required for the fluid leaving a solar collector to attain 63.2 percent of its steady-state value following a step change in irradiation or inlet fluid

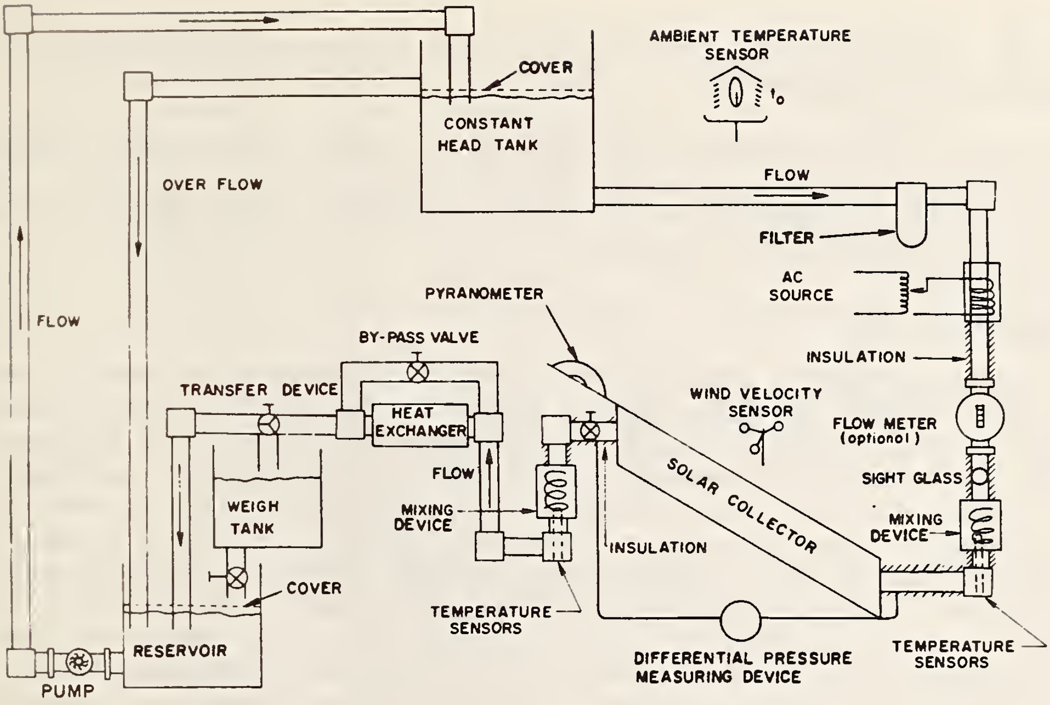


Figure 14. Open-loop testing configuration for the solar collector when heat transfer fluid is liquid and fluid is not supplied continuously (from Ref. 30)

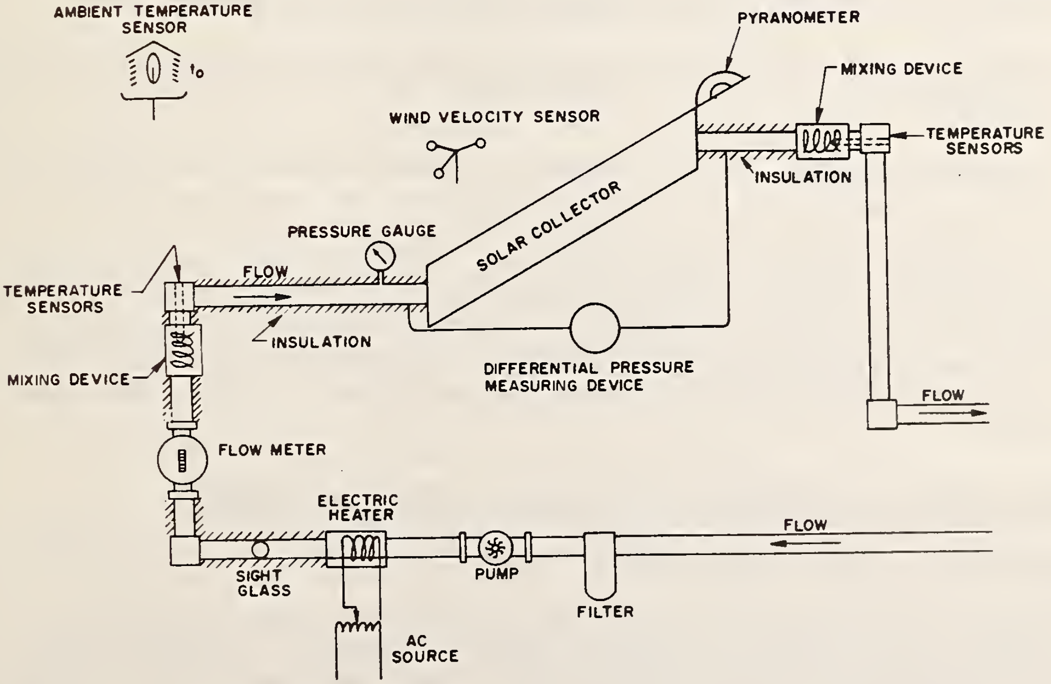


Figure 15. Open-loop testing configuration for use when fluid is supplied continuously (from Ref. 30)

temperature. Two methods are provided for the experimental determination of the collector time constant.

To permit the prediction of the collector performance under a wide range of conditions and/or time of day, with varying angles of incidence, the standard requires the determination of the collector incident angle modifier, using either of two experimental methods.

4.3.2 ASHRAE 96-80

While the scope of ASHRAE Standard 93-77 does not specifically exclude unglazed flat-plate collectors operating with a liquid as the transfer fluid, such collectors have special performance characteristics when used in low temperature applications such as swimming pool heaters or heat pumps. Unglazed collectors have a greater sensitivity to environmental conditions and to operating flow rates. Also, the liquid heat transfer fluid may have a temperature lower than the ambient air. These characteristics need to be considered in developing test procedures for unglazed flat-plate solar collectors. Accordingly, a new standard, ASHRAE 96-80, Methods of Testing to Determine the Thermal Performance of Unglazed Flat-Plate Liquid-Type Solar Collectors [28], was promulgated. This standard closely follows ASHRAE 93-77, with the exceptions noted below. Accordingly, the new standard:

- has tighter requirements on collector test loop stability;
- requires greater instrumentation accuracy;
- restricts allowable environmental variables during the tests;
- requires that, during the tests, the wind does not exceed 1.3 m/s (3 mph);
- specifies that the range of ambient temperatures for all reported test points making up the efficiency curve must be less than 10°C (18°F).

Further differences between ASHRAE 96-80 and 93-77 are that ASHRAE 96-80 applies only to flat-plate non-concentrating collectors using liquid heat transfer media, while ASHRAE 93-77 applies to both liquid and air collectors, as well as concentrating and flat-plate collectors. These differences in scope made it possible to omit the requirement for determining the collector time constant from ASHRAE 96-80.

4.4 VERIFICATION AND EVALUATION OF ASHRAE STANDARD PROCEDURES

4.4.1 Round-Robin Test Using Interim Procedures

A round-robin test program was conducted at a number of test facilities in the United States to determine the comparability of thermal performance data for flat-plate liquid-heating solar collectors. When the test series was planned, ASHRAE 93-77 had not yet been adopted so that the NBS interim test procedure was specified for the round-robin. Some testing facilities, however, did use the more restrictive requirements set forth in the final standard (which was adopted during the course of the round-robin). The results of the round-robin series were reported in an NBS publication [29] on the "Results and Analysis of a Round-Robin Test Program for Liquid-Heating Flat-Plate Solar Collectors."

A total of 21 laboratories participated in the round-robin. These laboratories were located geographically as shown in figure 16. Two commercially available solar collectors were tested at each site. Collector No. 1 had two glass cover plates and a flat-black coated aluminum absorber plate assembled into a sealed unit which was attached to a sheet-metal box containing glass-fiber insulation, as shown in figure 17. Collector No. 2 consisted of a single glass cover plate and a steel absorber with a black chrome selective coating. The absorber was mounted on a thermal insulator, backed with glass fiber insulation. The entire assembly was mounted in a steel frame with a sheetmetal back and aluminum glazing frame, as shown in figure 18.

Each participant in the test series reported the test conditions for each data point and also plotted collector efficiency, as follows:

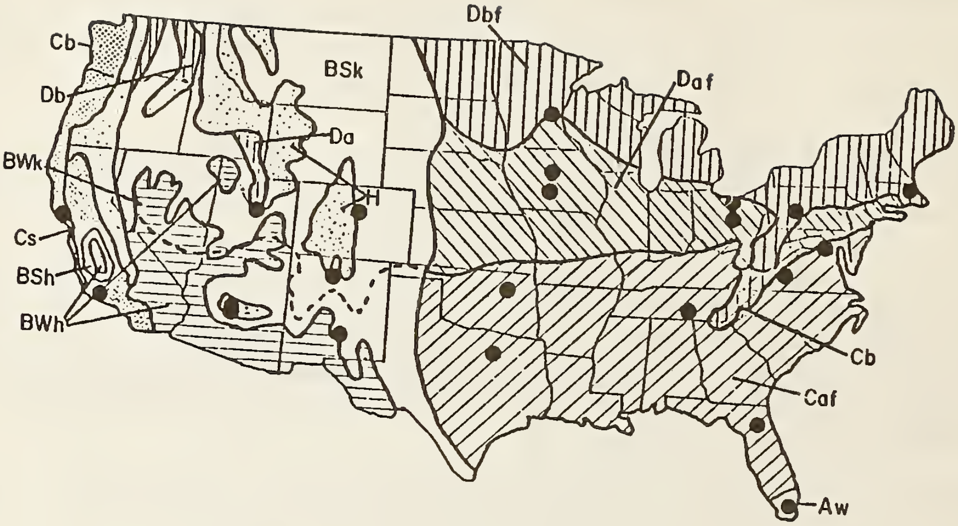
$$\eta \text{ versus } \frac{\frac{t_{f,e} + t_{f,i}}{2} - t_a}{I}$$

The data were used to determine values for the collector efficiency factors $F'(\tau\alpha)_e$ and for the collector heat removal factor $F'U_L$ by a first-order least-square fit to all measured data points. Mean and standard deviation values were calculated for these two parameters from each laboratory. This statistical analysis indicated important deviations, particularly for collector No. 2.

Figure 19 presents an indication of the spread and distribution of $F'(\tau\alpha)_e$ values for each collector. The greater frequency of values about the mean (smaller deviation) for collector No. 2 was attributed to the fact that more data were taken at smaller angles of incidence, than for collector No. 1.

The value $F'(\tau\alpha)_e$ showed a relatively large and unexpected standard deviation of 7.7 percent for collector No. 1. A major source of the deviation appeared to be the use of a "black and white" pyranometer by eight participants. Fewer participants used this pyranometer for collector No. 2. These data confirmed that "black and white" pyranometers are sensitive to tilt angle. Accordingly ASHRAE Standard 93-77 was modified to contain a requirement for using only a first class pyranometer or phyrheliometer as classified by the World Meteorological Organization (WMO) [13,30].

The statistical analysis also indicated a large deviation in values for $F'U_L$ for collector No. 1, apparently due to variations in insulation at the back and edges of some collector mountings, the use of different mass flow rates from that prescribed, and incidence angles greater than 45 degrees. A significantly lower overall loss coefficient observed for collector No. 2 appeared to be due to better thermal insulation for the absorber plate and the use of a selective coating. Data from the round-robin tests were also analyzed statistically to determine the effect of environmental conditions [31]. The data were examined



Aw - Tropical Savanna
BSh - Tropical and Subtropical Steppe
BSk - Middle Latitude Steppe
BWh - Tropical and Subtropical Desert
BWK - Middle Latitude Desert
Cs - Mediterranean

Cb - Marine West Coast
Caf - Humid Subtropical, no dry season
Da - Humid Continental (Warm Summer)
Daf - Humid Continental (Warm Summer), no dry season
Db - Humid Continental (Cool Summer)
Dbf - Humid Continental (Cool Summer), no dry season

Figure 16. Climatic location of testing facilities (from Ref. 29)

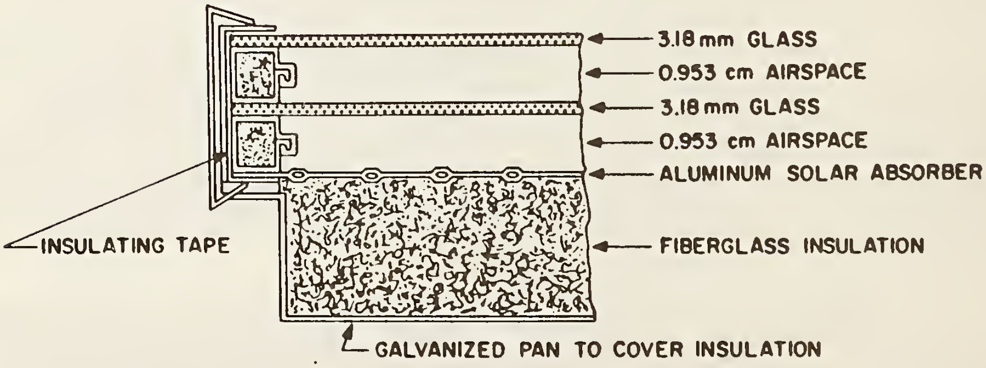


Figure 17. Schematic of flat-plate liquid-heating collector No. 1 (from Ref. 29)

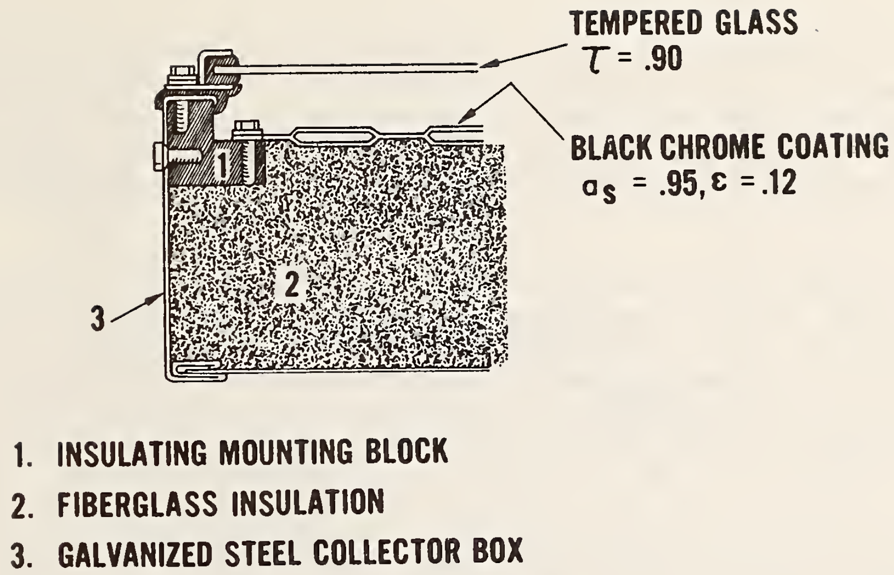


Figure 18. Schematic of flat-plate liquid-heating collector No. 2 (from Ref. 29)

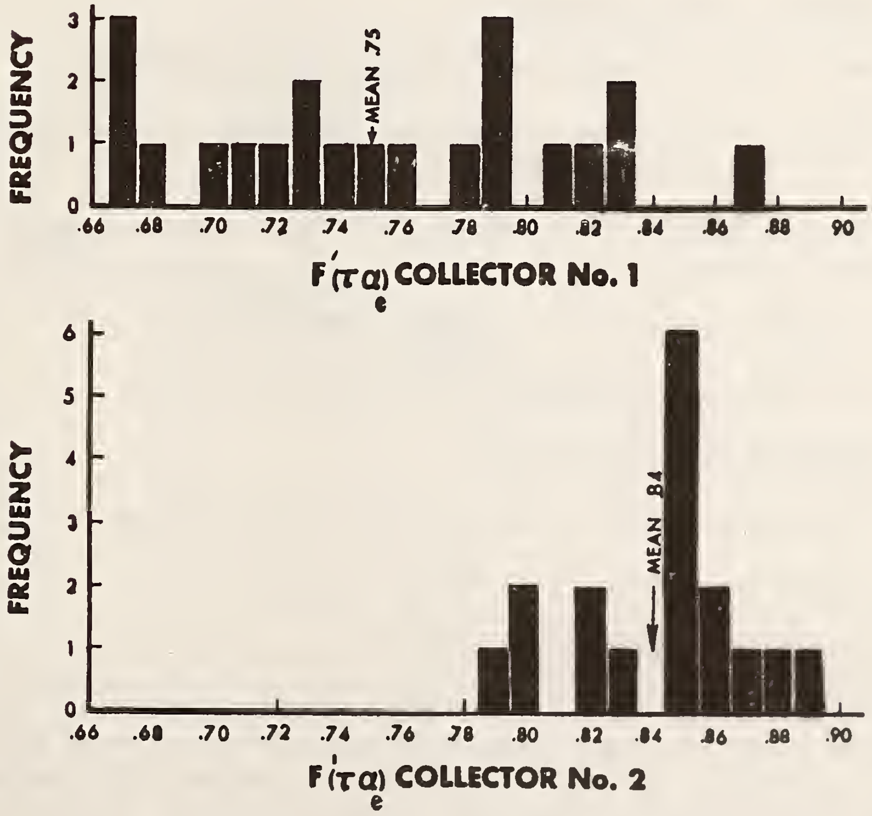


Figure 19. Frequency distribution of $F'(\tau\alpha)_e$ values for round-robin collectors (from Ref. 29)

to determine consistency across test conditions. The statistical analysis referenced all measured thermal efficiencies to a common set of environmental conditions by using analytical models for the two flat-plate collectors tested. The analysis indicated that the referencing of efficiencies to a common environment is feasible and significantly reduces the differences in measured efficiencies reported by the various participants.

Figures 20 and 21 show considerable scatter in the data, although the data for an individual facility were generally consistent and showed very little scatter. Correcting the data for differences in environmental conditions between facilities only reduced the scatter by about 30 percent. This small reduction appears to indicate that either the test requirements were not restrictive enough or that no accounting was made for systematic errors. B. D. Wood conducted a further analysis [29] on the effect of random and systematic errors. After analyzing the data from all test facilities, he concluded that the data scatter actually occurring (after correcting for operating and environmental conditions) among those facilities that reportedly adhered to the ASHRAE 93-77 procedures was much larger than should be expected. Based on the available data, he hypothesized that a combination of systematic errors resulted in data scatter. Possible sources of systematic error included:

- Systematic Facility Errors
  - Heat transfer between test apparatus and collector.
  - Reduced heat losses to ambient environment due to shielding of collector support stand.
  - Test apparatus not at steady- or "quasi-steady-" state condition during test.
  - Change in specific heat of the transfer fluid.
  - Inexperienced technicians conducting the tests.
- Systematic Instrument Errors
  - Conduction errors in thermocouple installations.
  - Pyranometer calibration error.
  - Flowmeter calibration error.

The significance of the variation in the reported performance for a particular collector was illustrated by calculating the expected system performance of two sample solar systems. The first sample was a residential, combined solar domestic hot water and space heating system in Madison, Wisconsin, with a hot water demand of 0.32 m^3 per day and an average monthly energy requirement for the year of about 1.7×10^9J. It was assumed to consist of 80 m^2 (861.14 sq. ft.) of collector No 1. In the second example, a solar domestic

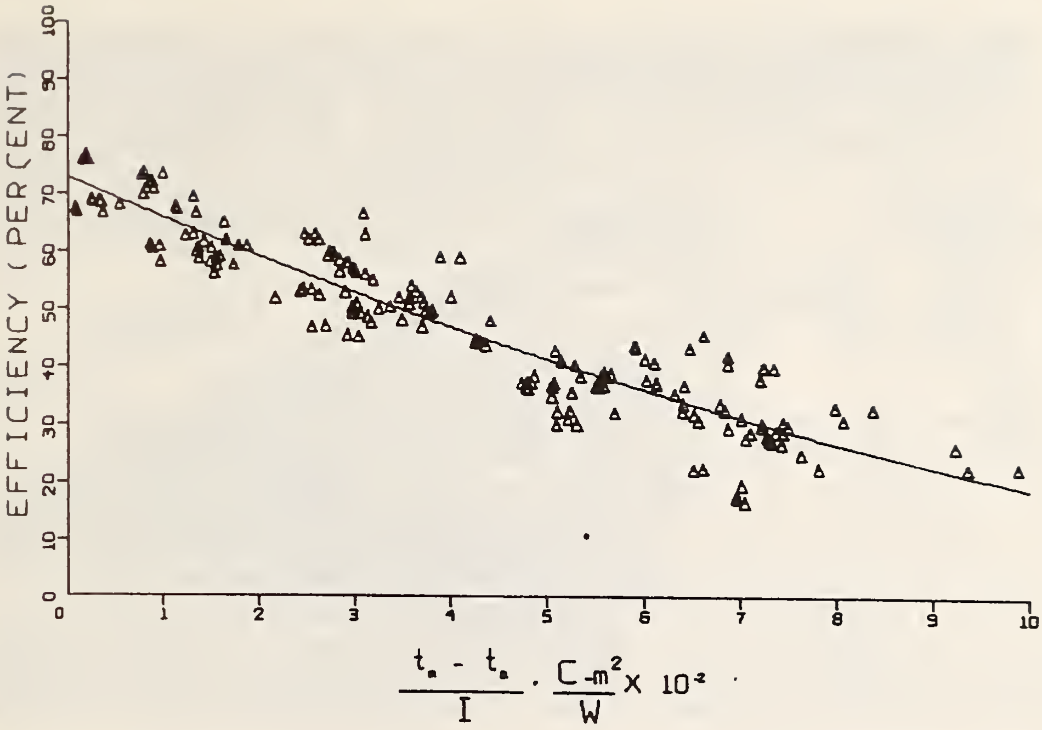


Figure 20. Uncorrected results from 12 facilities for collector No. 1 tests (from Ref. 29)

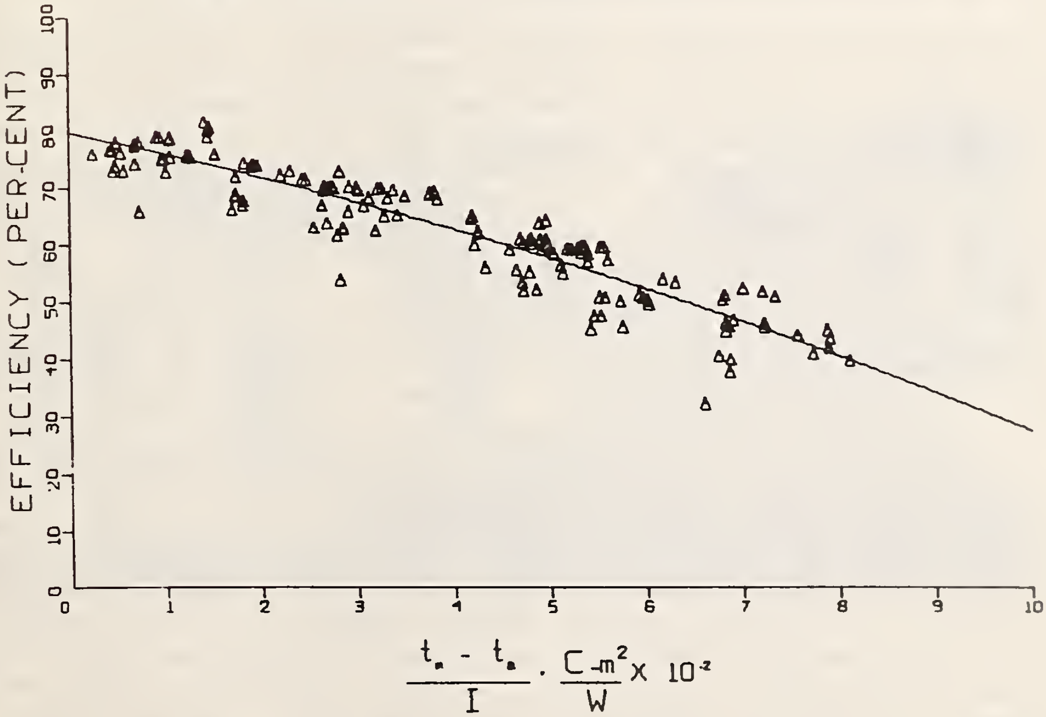


Figure 21. Uncorrected results from 10 facilities for collector No. 2 Tests (from Ref. 29)

hot water system was simulated in five different cities across the country. It was assumed that 5.37 m^2 (57.80 sq. ft.) of collector area No. 2 was installed.

The results of the analysis indicated that the use of the mean, "best", and "worst" values obtained in the round-robin test series resulted in a total spread of about 22.1 percentage points about the mean for the first example. For the second example, the maximum spread of 17.8 percent occurred in Washington, D.C.

In conclusion, data from the round-robin testing indicated that most of the reported differences in measured efficiency were due to experimental error or systematic differences between facilities. The data indicated that the preparation and mounting of collector No. 1 resulted in large variability in the test results. The results further indicated the importance of using a pyranometer which meets the class 1 requirements of WMO. In addition, differences in measured efficiencies between sites due to environmental conditions can be reduced by referencing all test results to a common environment using a straightforward analytical procedure. Finally, greater consistency in test results was observed for those participants who met the more restrictive ASHRAE 93-77 requirements.

4.4.2 Evaluation of ASHRAE 93-77

4.4.2.1 NBS Test Facility and Research

During the round-robin testing, NBS also constructed a facility for evaluating solar collector performance and assessing individual provisions of ASHRAE 93-77. The NBS test facility consisted of two test loops for evaluating liquid collectors and one for evaluating air collectors. The test equipment was located on an elevator which allowed the test facility to be exposed to the outdoor environment only when tests were run, and to conduct indoor tests of heat loss characteristics without disassembling any part of the equipment for the specimen mounting. Figures 22 and 23 show the facility in the process of being raised to ground level, and in the full raised condition, respectively. The details of the test loops and the specifications for the instrumentation are given in an NBS publication entitled, "Experimental Verification of a Standard Test Procedure for Solar Collectors" [30]. The use of solar simulators was not evaluated during this particular study.

Two separate, essentially identical test loops (see figure 24) were built for evaluating water heating collectors, so that it would be possible to test two individual collectors independently, and to make adjustments to one loop while not affecting the other. The collector mounting could be adjusted for tilt angles from 0 to 70 degrees, and for azimuth angles of 0 to 360 degrees. Figure 24 is a schematic drawing of the liquid collector test loop. This loop was similar to the closed loop shown in ASHRAE standard 93-77 [13] and was a development from the loop discussed in reference [25]. In the design of the test apparatus, particular care was given to the selection and installation of measurement instrumentation and controls for the temperature of the transfer fluid. Different flow meters were used for the two different loops.

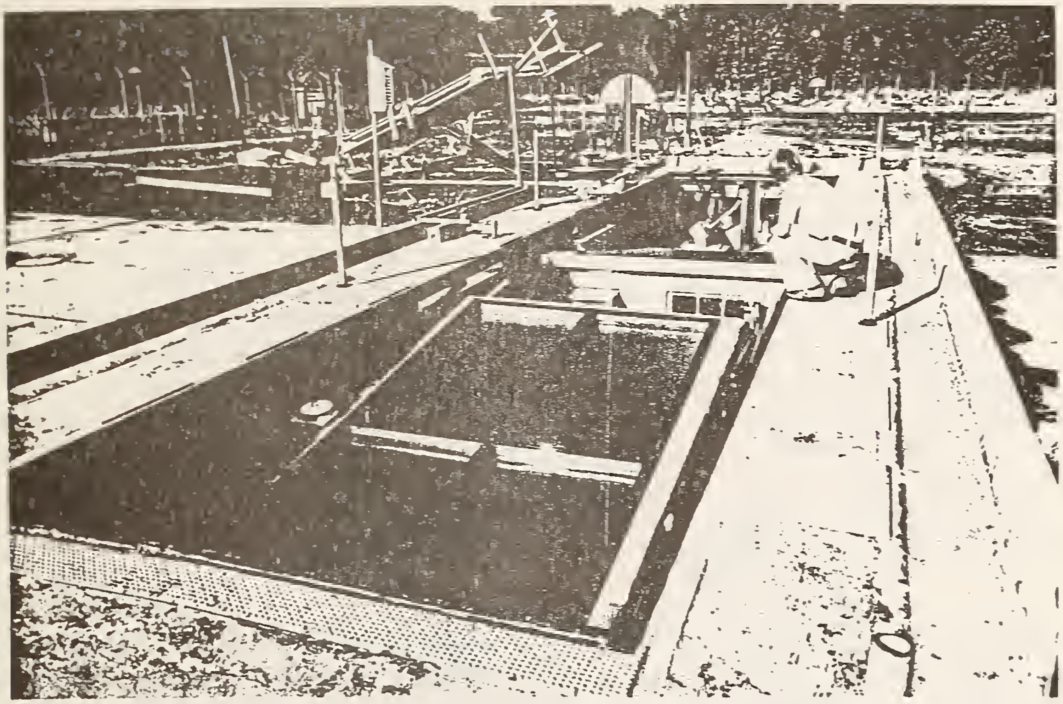


Figure 22. Solar collector testing equipment being raised to ground level at NBS, Gaithersburg, MD (from Ref. 30)

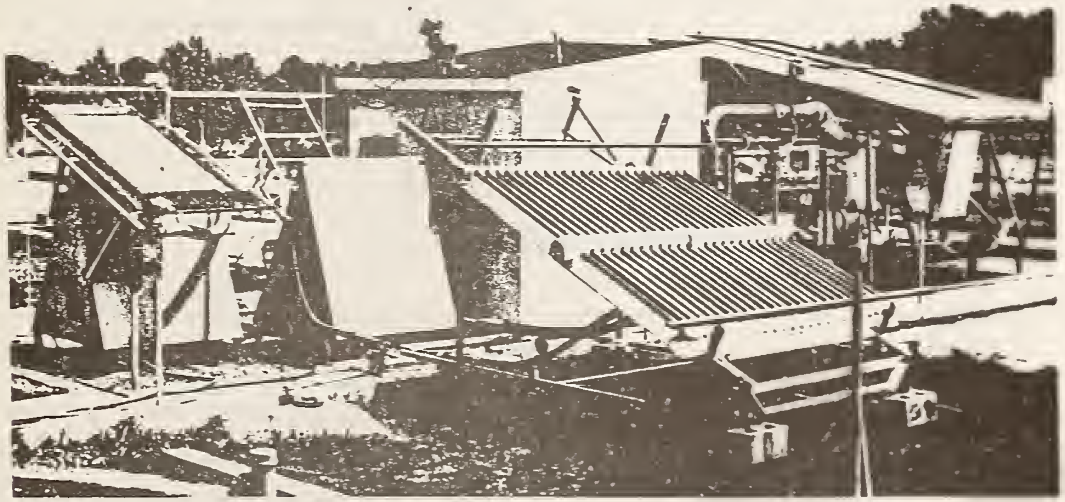


Figure 23. Solar collector testing equipment in place at NBS, Gaithersburg, MD. (Test stand with solar collector in middle foreground is not normally a part of the equipment) (from Ref.30)

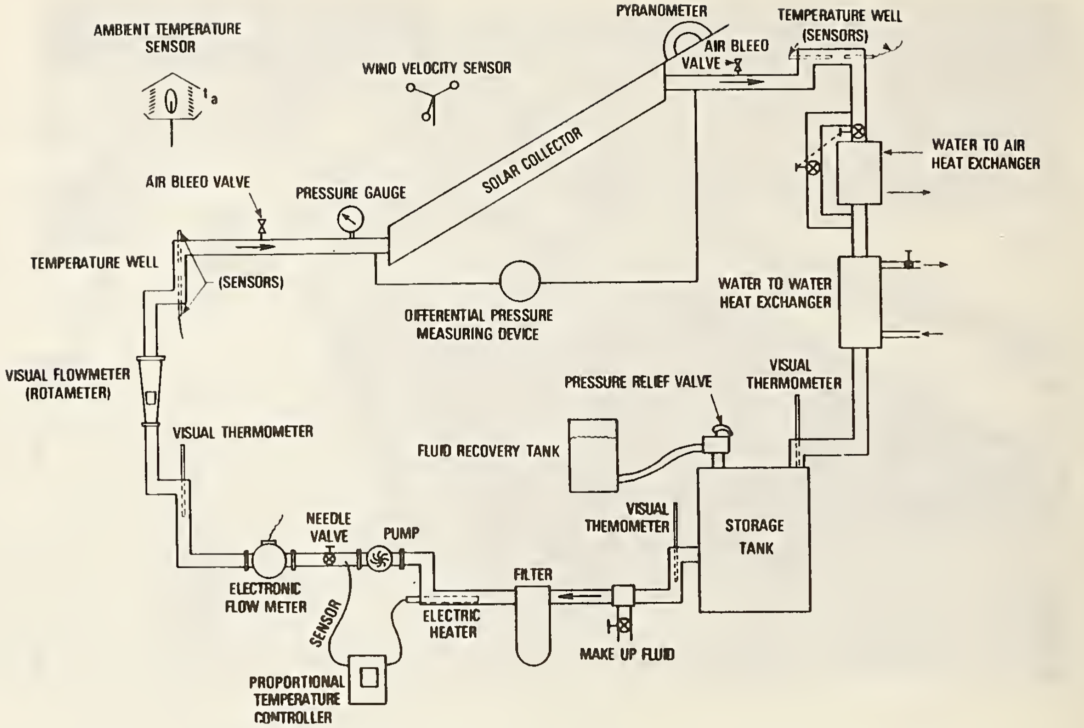


Figure 24. Schematic diagram of an NBS test loop for liquid-heating solar collectors (from Ref. 30)

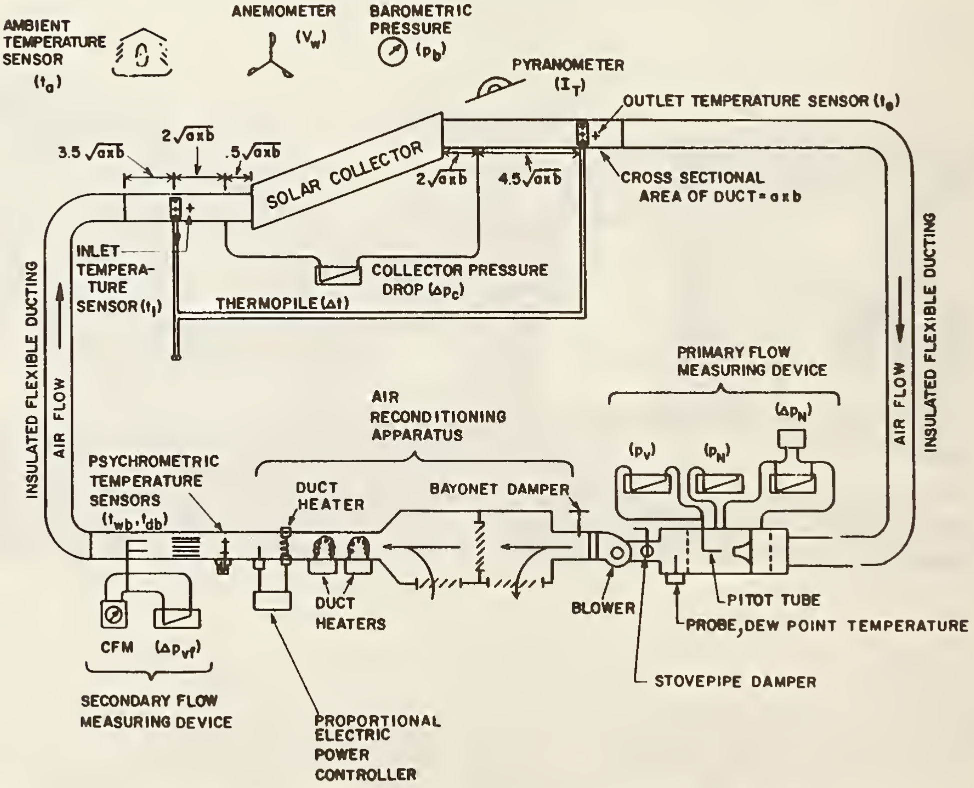


Figure 25. Schematic of the NBS test stand for air-heating solar collectors (from Ref. 30)

Only one test loop was built for assessing air collectors. It is shown in figure 25. The collector stand could accomodate collector arrays up to 10 m^2 in area. It could be tilted from 0 to 65 degrees and fully rotated for orientation.

As with the design and control of the test loops, the accuracy of the instrumentation used to make the meteorological measurements met, or exceeded, the requirements of ASHRAE 93-77. Ambient air temperature, wind speed, wind direction, total solar radiation, sky temperature, barometric pressure, and sun angle were measured. Originally a "black and white" pyranometer was used to measure total solar radiation, but this instrument was found to be sensitive to tilt angle. Errors of up to 7.4 percent were observed for typical collector tilt angles of 56 degrees, even though the same instrument agreed to within 1.5 percent in the horizontal position. This finding is consistent with those of other researchers. As a result, a first class pyranometer as classified by WMO, was substituted for the NBS testing and required in the ASHRAE standard.

To verify ASHRAE 93-77 experimentally, NBS tested one air-heating and five water heating solar collectors [30]. A major objective of these tests was the determination of whether the tests for time constant, the near-normal incidence efficiency, and the incident angle modifier, as specified by ASHRAE 93-77, could be carried out readily and accurately. It was found that all three tests could be conducted with little difficulty. In addition, a comparison of data from three all-day tests of collector efficiency showed good agreement with calculated efficiencies. Other conclusions reached by NBS included the following:

- The time constant can also be determined for concentrating collectors having a low concentration ratio. Method 1 of ASHRAE 93-77 is much easier to complete than Method 2.

- The incident angle modifier test as specified is applicable only to flat-plate collectors. An entirely different procedure, which depends on the optical characteristics of the collector, is required for concentrating collectors. Method 2 of ASHRAE 93-77 (section 8.3.3), involving an all-day test with the collector stationary facing south, is preferable to Method 1, which requires several test days and can produce erroneous results for collectors with large time constants.

- Thermal efficiency data must be collected symmetrically with respect to solar noon. Near-normal incidence efficiency data can and should always be collected to reduce scatter.

- Aperture of absorber area should be used instead of gross collector area.

- A class 1 pyranometer, as specified by WMO, is required for accuracy.

- Air leakage may be a significant source of error in tests of air-heating collectors. If the collector is tested under positive pressure, the air flow rate should be measured downstream of the collector; if under negative pressure, air flow should be measured on both sides of the collector. An open loop is preferable to a closed loop in testing air collectors.

- The all-day collector performance of flat-plate collectors on clear sunny days can be predicted with reasonable accuracy using test results obtained in accordance with ASHRAE 93-77.
- Tests on flat-plate collectors having a time constant of less than five minutes can be completed in six test days.

The recommendations for future work included the following:

- The feasibility of adapting the standard to concentrating collectors including procedures for determining incident angle modifiers for such collectors.
- The relationship between long-term collector performance in service and the performance indicated by tests.
- The combination of outdoor exposure for insolation/solar heating gain and indoor tests for heat loss should be examined, as it would reduce the time and cost of the tests. This concept was proposed by Smith [32], Symons [33], and by the German Solar Energy Industries Association [34].

4.4.2.2 Comparison of ASHRAE and BSE Procedures

One of the recommendations resulting from the NBS support work on ASHRAE 93-77 [13] as described by Hill, Jenkins, and Jones [30] was that a combination of outdoor exposure for insolation/solar heat gain and indoor tests for heat loss should be examined for glazed flat-plate liquid collectors. A procedure for such outdoor/indoor tests was developed by the German Solar Energy Association and adopted by the Bundesverband Solar Energy (BSE) [35]. Implementing this procedure, NBS conducted tests on five solar collectors (see table 2) using both the BSE and ASHRAE procedures [36], and compared the results. The NBS facility, described in reference [30], was particularly well-suited for this work, since it allowed the entire testing apparatus to be used both outdoors and indoors.

The BSE testing procedure prescribes a series of tests for determining collector efficiency by independently measuring optical efficiency and thermal losses through a combination of outdoor and indoor testing. These tests are described by Jenkins and Hill [36]. To determine the collector instantaneous efficiency according to BSE, the useful energy output and incident solar radiation are monitored on a collector installed outdoors. While the collector operates under quasi-steady operational conditions, the mass flow rate and temperature rise across the collector are measured. With the mean fluid temperature regulated to within ± 10°C of ambient air temperature, heat loss from the collector to the surrounding environment is negligible. (If the mean fluid

Table 2. Description of Collectors Used in Comparison of BSE and ASHRAE Test Methods (from Ref. 36)

	Collector No. 1	Collector No. 2	Collector No. 3	Collector No. 4	Collector No. 5
Manufacturer	Commercial Solar Energy	PPG Industries	Chamberlain Mfg. Company	Lennox LMSC 18-1	Commercial Solar Energy
Gross Area (m^2)	2.47	1.65	1.96	1.53	2.47
Aperture Area (m^2)	2.29	1.60	1.79	1.40	2.29
Glazing					
Material	Plate glass	Tempered glass	Tempered low-iron glass	Tempered low-iron glass with anti-reflective coatings	Polyfluoroethylene
Number	2	2	1	2	1
Solar Transmittance (single glass)	0.87	0.85	0.90	0.96	0.92
Absorber					
Material	Copper Foil	Aluminum Roll Bond	Mild Steel	Mild Steel	Copper Foil
Flow configuration	10 parallel risers	13 parallel risers	Pillow absorber completely wetted surface	10 parallel	10 parallel risers
Coating	Flat Lacquer	Flat Lacquer	Black Chrome Nickel Substrate	Black Chrome Nickel Substrate	Flat Lacquer
Solar Absorptance	0.95	0.94	0.94	0.94	0.95
I.R. Emittance	0.92	0.92	0.12	0.10	0.92
Insulation					
Material	Low Density Polyurethane	Glass fiber	Glass fiber	Fiberglass-board	Low Density Polyurethane
Thickness (cm)	6.35	7.62	7.00	7.9	6.35
*$F_R\ (\tau\alpha)_e$	0.58	0.74	0.80	0.72	0.63
*F_RU_L W/(m^2·°C)	-4.71	-5.14	-4.43	-3.62	-6.56
**F'	0.74	0.97	0.95	0.86	0.75
**U_L W/(m^2·°C)	6.06	5.44	4.63	4.24	9.10

* Derived from slope or intercept of ASHRAE 93-77 efficiency curve

** Determined from $F_R(\tau\alpha)_e$ and F_RU_L and MWB analytical formulations of $(\tau\alpha)_e$ and F' temperature is not within ± 10°C, a correction must be added.) The incident solar radiation absorbed by the absorber surface, Q_o, is then:

$$\dot{Q}_o = \frac{\dot{m}C_p \int_{\tau_1}^{\tau_2} (t_{f,o} - t_{f,i})\, d\tau}{\tau_2 - \tau_1}$$

where: $\dot{m}$ = mass flow rate through collector
C_p = specific heat of the collector working fluid
τ = time
$t_{f,o}$ = collector outlet fluid temperature
$t_{f,i}$ = collector inlet fluid temperature

The thermal losses are determined within a controlled indoor laboratory under zero solar irradiation. The working fluid is circulated in reverse through the collector over a range of operating mean temperatures above ambient at levels of 30°, 50°, 70° and 90°C, while the flow rate and temperature drop across the collector are monitored. The rate of thermal energy dissipated to the environment, Q_L, is then:

$$\dot{Q}_L = \frac{\dot{m}C_p \int_{\tau_1}^{\tau_2} (t_{f,o} - t_{f,i})\, d\tau}{\tau_2 - \tau_1}$$

Using the results of both outdoor and indoor tests, a family of efficiency curves can then be developed, as shown in figure 26.

The BSE and ASHRAE test requirements regarding environmental conditions, measurement uncertainties, and range of operating conditions are shown on table 3. The requirements for outdoor testing following the BSE and ASHRAE are nearly identical in all categories.

To compare the BSE and ASHRAE tests, it is essential that these results be presented in a common format. Since the BSE and ASHRAE procedures prescribe different formats for reporting these results, the BSE efficiency curves were transposed into an ASHRAE efficiency curve. In transposing the BSE data, each of the curves is based on the average outdoor solar irradiance experienced during the ASHRAE 93-77 test on the same collector.

The test loops used for both tests are essentially identical and are similar to those used for the tests described in BSS 117 [30]. Figure 27 shows a diagram of the closed-loop configuration, which was designed to control and stabilize the collector fluid inlet temperature to within ± 0.5°C (± 1.0°F) and the fluid flow rate to within ± 1 percent.

For conducting the BSE indoor tests, two types of wind simulators were used. The axial fan wind simulator is shown schematically in figure 28, and two

Table 3. Environmental Test Conditions Allowed Within the ASHRAE 93-77 and BSE Collector Test Procedures (from Ref. 36)

Environmental Parameter	ASHRAE Standard 93-77	BSE* η_o - Determination, Outdoor Testing	BSE* $\dot{Q}_L$ - Determination, Indoor Testing
Ambient air temperature	range < 30°C	no limits	15 - 25°C
Wind velocity across collector	should be $\leq$ 4.5 m/s	> 4 m/s	> 4 m/s
Total solar irradiance within collector plane	> 630 W/m^2	no minimum	< 1 W/m^2
Beam solar irradiance incident angle	< 30°	< 30°	-----
Foreground reflectance	< 0.20	< 0.20	-----
Apparent environmental radiance temperature	------	-----	< t_a ± 3°K

* BSE Guidelines and Directions for Determining the Usability of Solar Collectors, [35].

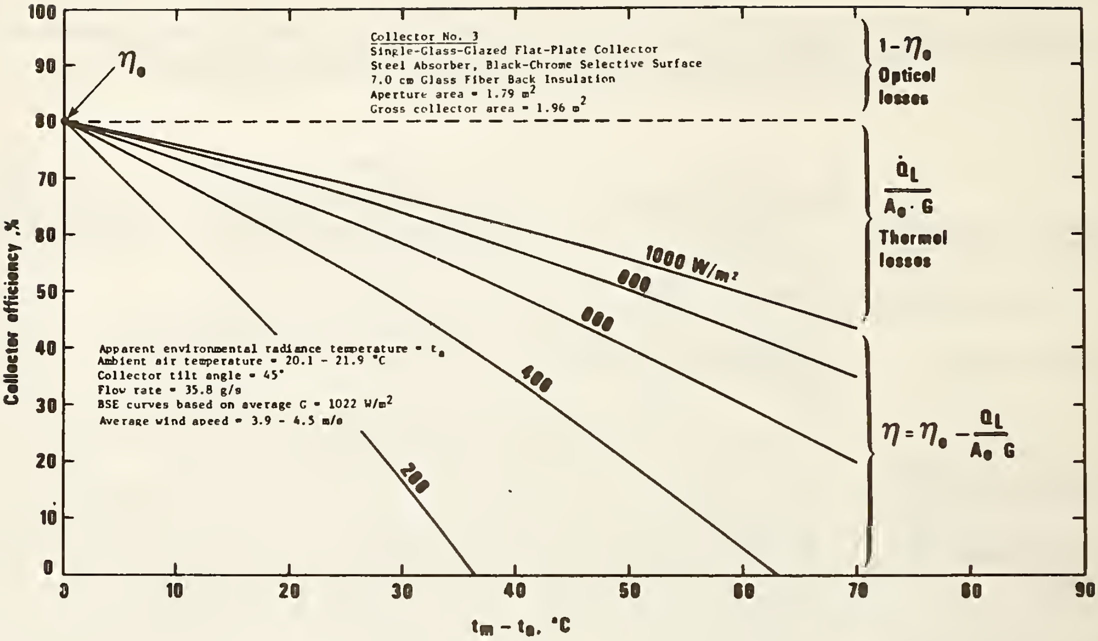


Figure 26. Collector efficiency using BSE procedure vs. the difference between collector mean fluid temperature, t_m, and ambient air temperature, t_a (from Ref. 36)

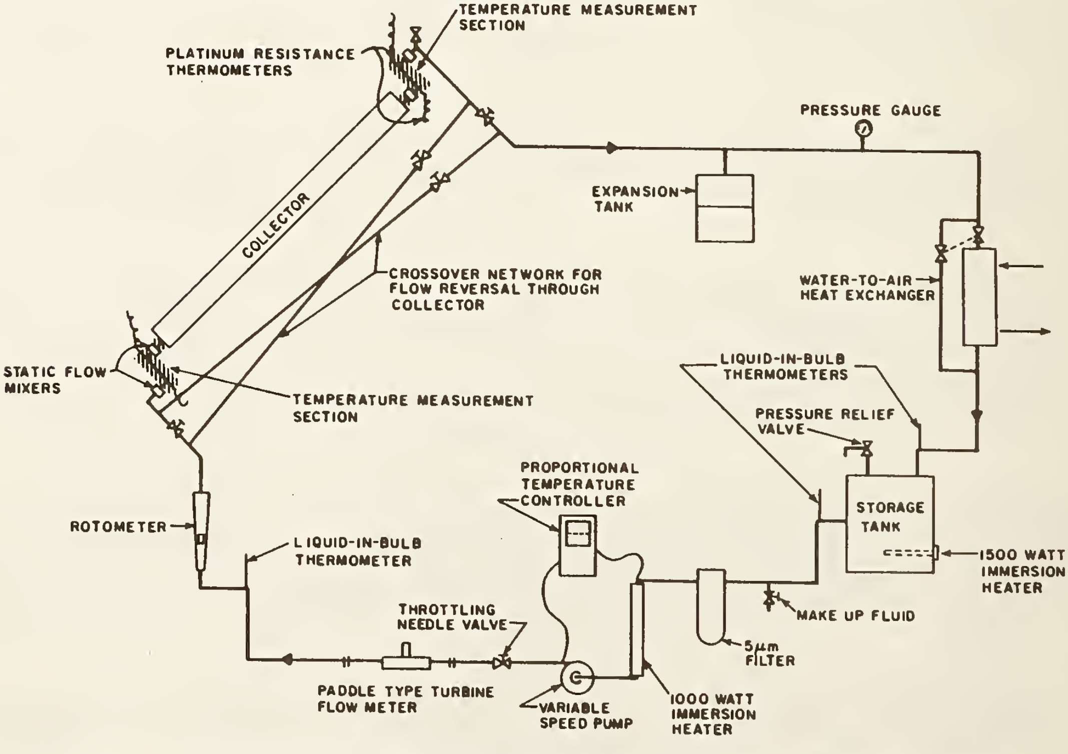


Figure 27. Closed-loop testing configuration for comparing BSE and ASHRAE test methods (from Ref. 36)

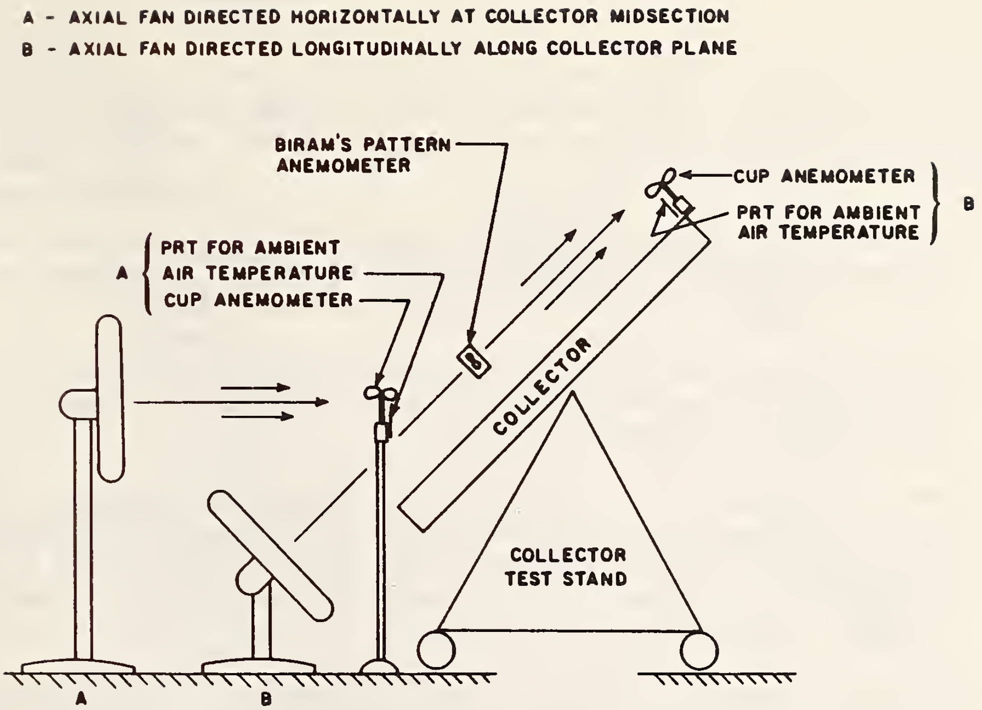


Figure 28. Schematic of axial fan wind simulator (from Ref. 36)

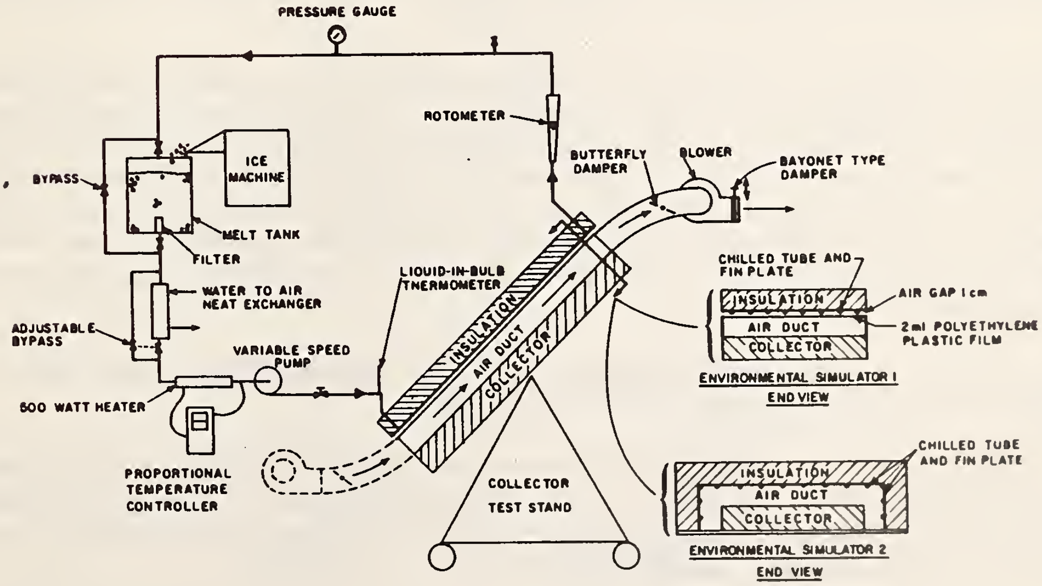


Figure 29. Environmental simulators (from Ref. 36)

environmental simulators are shown in figure 29. The environmental simulators provide a more uniform wind velocity across the collector, and permit the investigation of low "sky" temperature during indoor testing for thermal loss. The test results indicated that:

- For all five collectors tested, the differences between the efficiency curves determined according to BSE and ASHRAE procedures were less than the total uncertainties associated with ASHRAE Standard 93-77.
- Uncertainty in determining collector thermal efficiency is reduced and repeatability improved when using the BSE collector test procedure compared with the ASHRAE procedure.
- The determination of near-normal incidence instantaneous collector efficiency using the BSE procedure can be completed in two days, only one of which is dependent on outdoor environmental conditions. Four days of outdoor tests are normally required for ASHRAE tests using a fixed orientation stand.
- The environmental simulators were successful in increasing the uniformity of indoor environmental conditions. Axial fan wind simulators were also sufficient for simulating controlled wind conditions.

4.4.2.3 Evaluation of Unglazed Flat-Plate Collectors

NBS also conducted experiments to determine the differences in the thermal performance of unglazed flat-plate liquid solar collectors using both ASHRAE 96-80 [28] and BSE [35] test procedures.

The BSE procedures, unlike the ASHRAE, require both indoor (nonirradiated) and outdoor (irradiated) testing to determine collector optical efficiency and thermal loss characteristics independently. Instantaneous thermal performance for the expected operating conditions is calculated from these separately determined properties. Because the BSE procedure determines collector heat loss under zero-irradiance conditions, unlike the ASHRAE, it was not apparent that the thermal efficiency determined by the two separate procedures would be equivalent.

As a result, two unglazed flat-plate liquid heating collectors were tested using both BSE and ASHRAE procedures [37].

As with the earlier work, the tests were conducted at the NBS laboratories in Gaithersburg. The fluid test loop used in the tests is shown schematically in figure 30. Figure 31 gives a diagram of the two collector specimens which were tested by both ASHRAE and BSE procedures.

As mentioned in the previous section, the major difference between the ASHRAE and BSE procedures is that in the ASHRAE test, the collector heat loss is determined during outdoor exposure of the specimen, whereas in the BSE test, the heat loss is determined under controlled indoor conditions. Since unglazed

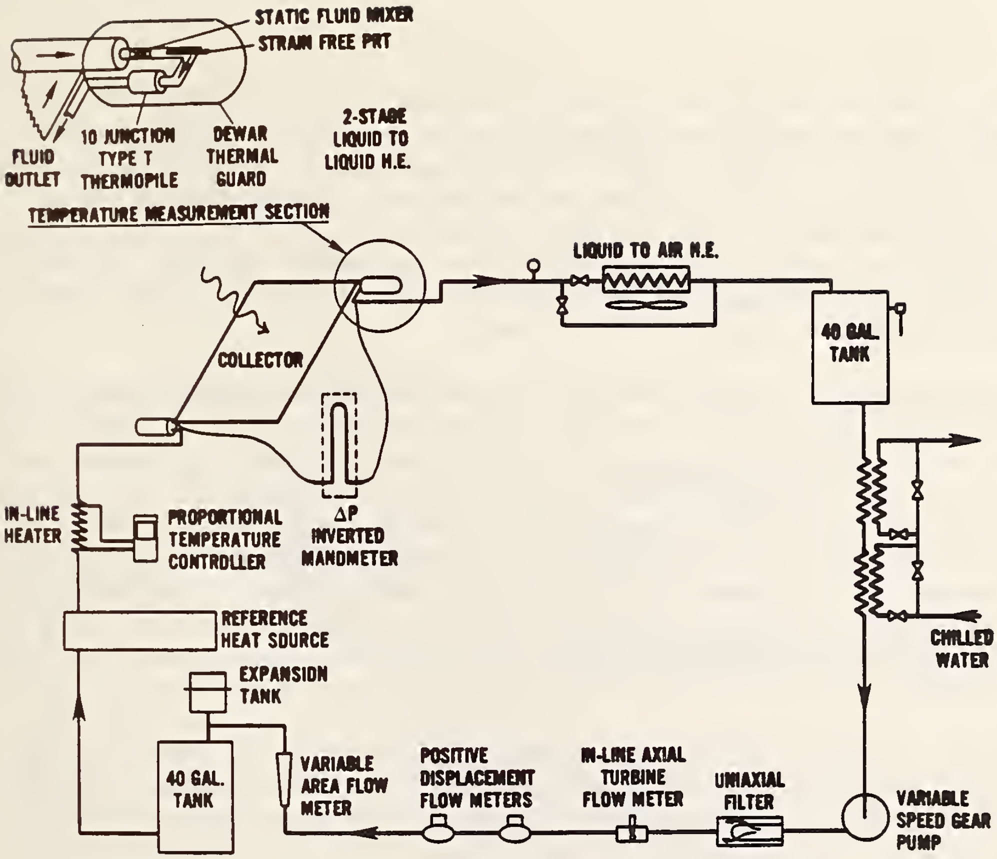


Figure 30. Schematic of fluid test loop used in experimental work on unglazed flat-plate liquid collectors (from Ref. 37)

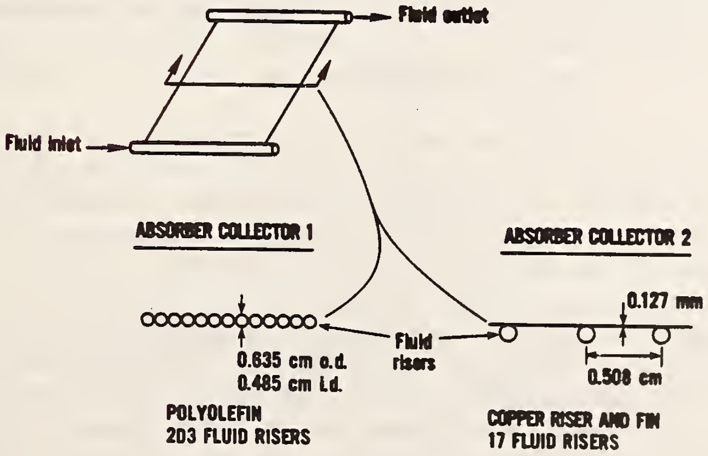


Figure 31. Diagrams of unglazed collector 1 and 2 absorbers (from Ref. 37)

collectors are more sensitive to the influence of wind, ASHRAE 96-80 restricts the average wind speed for each test to no more than 1.3 m/s (3.0 mph), a factor of three lower than the ASHRAE 93-77 requirement for glazed collectors. For the comparative tests, the BSE procedure was slightly modified to allow for direct comparison between the ASHRAE and BSE test results. Specifically, gross collector area instead of net aperture area was used, and the BSE wind speed specifications were changed to determine losses at several wind speeds from 0 m/s (still air) to 3.9 m/s (0 - 8.7 mph).

The test results again indicated that the differences between the thermal efficiency curves determined through the BSE and ASHRAE 96-80 procedures were less than the uncertainties associated with the curves. As can be seen in figure 32, the BSE-determined efficiency curves demonstrated the strong sensitivity of the unglazed collector thermal performance to wind. Although results from the two procedures were very similar, NBS concluded that the modified BSE procedure was preferrable to the ASHRAE method. The modified BSE procedure eliminates thermal loss uncertainties resulting from transient outdoor test conditions, permits thermal performance to be determined under selected environmental conditions, and is less time consuming.

Because of the strong dependence of test results on wind speed, and the results of the BSE investigation, it was suggested that wind simulators could also be used in outdoor tests. Although not tried in the reported test series, the use of such simulators could result in more controllable wind conditions during ASHRAE 96-80 tests.

4.5 DURABILITY AND RELIABILITY OF SOLAR COLLECTORS

4.5.1 Proposed Evaluation Criteria

The significance of collector durability and long-term performance is demonstrated by the 30 percent decrease in efficiency found in one U.S. collector system over a period of 18 years [38]. Such measurements of performance over time are quite rare, however. As a result, there was a great need to develop testing methods which would measure and simulate long-term performance.

The "Solar Heating and Cooling Demonstration Act of 1974," Public Law 93-409 [24] provided for the development of performance criteria and standard testing methods for use by industry in evaluating materials, components, and systems. In 1977, DOE instituted a comprehensive research program to provide an accurate data base for developing durability criteria and test methods.

One early step in the development of durability and reliability criteria was the publication in 1977 of a set of proposed test methods for evaluating solar collectors [39]. This publication, which was revised in 1978 [40], was intended to serve as a resource document in the development of consensus standards, a background document for organizations developing certification programs, and the basis for a testing program sponsored by DOE. The test methods and provisional rating criteria contained in it address issues of thermal performance, durability/reliability, structural integrity, and fire safety. In

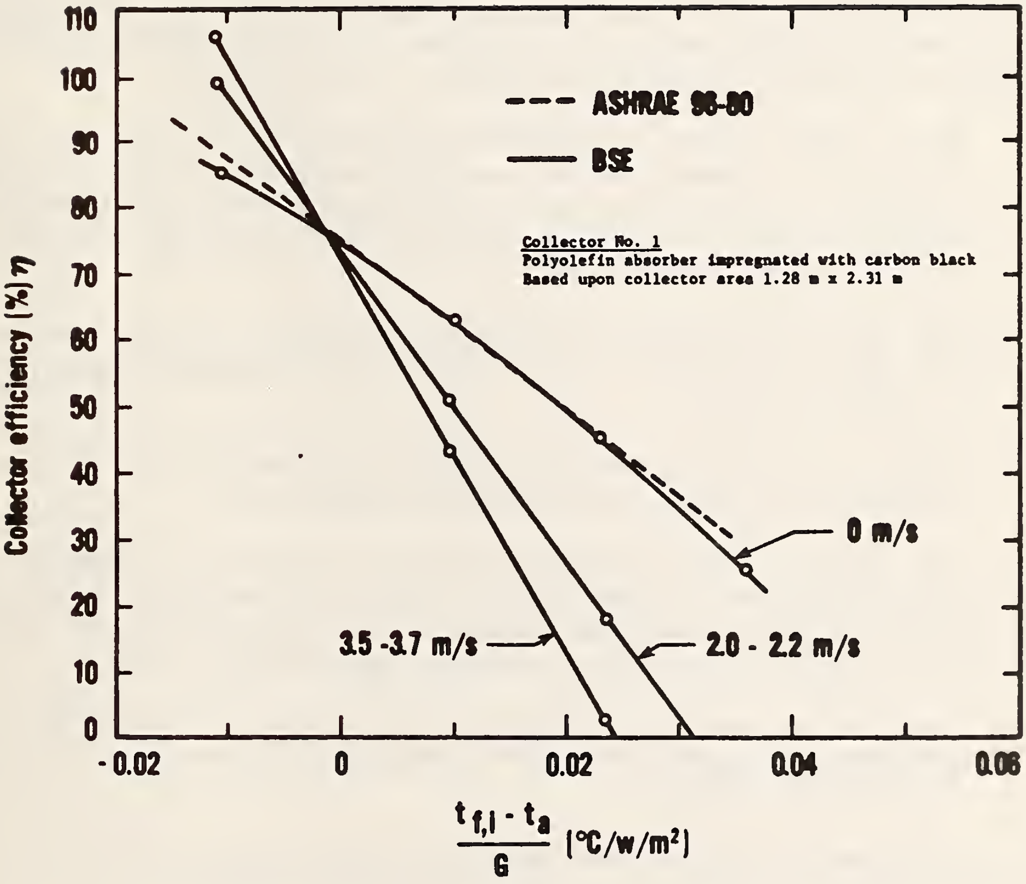


Figure 32. Comparison of ASHRAE Standard 96-1980 and modified BSE efficiency curves (for collector 1) (from Ref. 37)

the document, the selection of test methods was based on a review of over 400 consensus and other industry standards.

Individual test methods include thermal performance tests (in general accordance with ASHRAE 93-77), and calculation of all-day solar collector efficiency (see table 4). One modification to ASHRAE 93-77 is a revised preconditioning exposure. The thermal performance tests also include baseline and post-stagnation thermal performance tests. Other thermal performance tests include one for no-flow 30-day degradation to identify potential problems in collector materials or construction resulting from prolonged exposure to natural elements. Other tests are concerned with identifying potential durability/reliability and safety problems. They include:

1. Thermal Shock Tests--to determine the ability of a heated collector to withstand thermal shock caused by heavy rain, and to evaluate collector reliability after being subjected to thermal shock and boiling stresses induced by filling a hot collector with cool transfer fluid during start-up;

2. Rain Test--to determine collector resistance to water penetration when subjected to wind-driven rain. One recommended test is based on ASTM E 331 [41].

3. Thermal Cycling--to determine whether collectors will perform reliably after exposure to freezing conditions.

4. Live Loads--to determine the collector's ability to function after being subjected to snow loads, or positive, negative or combination wind loads with the loads being established according to ANSI A-58.1 [42], and the tests being conducted according to ASTM E 72 [43].

5. Longitudinal Loads--to determine the ability of the collector mountings to withstand cyclic loads in the plane of the longitudinal axis of the collector.

6. Hail Loads--to determine the ability of the cover plate to withstand the impact of hailstones and other flying objects.

7. Air Collector Rupture and Collapse Tests--to determine the ability of the air collector to meet the pressure requirements established by Underwriters Laboratories (UL) [44].

8. Static Pressure Leakage Tests--to determine the resistance of air collectors to air leaks using the UL procedures given above, and to determine the resistance of liquid filled collectors to static over-pressure using ASME hydrostatic and pneumatic tests [45].

9. Fire Resistance Tests--to determine the relative fire hazards created by roof-mounted solar collectors exposed to a fire sources using ASTM E 108-75 [46].

Table 4. Typical Computation of All-Day Solar Efficiency (from Ref. 40)

Calculation Steps	Hour of the day, solar time												Daily Total
	6-7	7-8	8-9	9-10	10-11	11-12	12-1	1-2	2-3	3-4	4-5	5-6	
1. Inlet fluid temp to collector, $t_{f,i}$, °C	49	49	49	49	50	50	51	52	54	54	54	54	
2. Ambient air temp, t_a, °C	10	10	10	13	15	16	16	22	24	24	18	18	
3. Incident radiation on collector plane, I_T, W/m^2, (Table A2, ASHRAE 93-77)	90	186	454	693	876	993	1031	993	876	693	454	186	7525
4. Collector thermal efficiency at normal incidence, determined in accordance with Sections 8.3.2 and 8.5 of ASHRAE 93-77 and using data from lines 1, 2, and 3.	—	.02	.15	.38	.42	.46	.46	.46	.43	.42	.18	.02	
5. Incident angle between the direct solar beam and outward drawn normal to the collector plane, θ.	90	75	60	45	30	15	15	30	45	60	75	90	
6. Incident angle modifier, determined in accordance with Sections 8.3.3 and 8.6 of ASHRAE 93-77 and using the value of θ from line 5.	—	.48	.82	.93	.97	1.0	1.0	.97	.93	.82	.48	—	
7. Energy output from the collector, W/m^2, (line 3) $\times$(line 4 + $[F_R\{\tau\alpha\}_{e,n}]$ $\times[\{$line 6$\}-1]$)	—	0	0	229	350	457	474	437	333	180	0	—	2460
8. Collector thermal efficiency, line 7/line 3													.33

The proposed rating criteria do not provide end-point criteria for thermal performance, but require that such performance be determined in accordance with ASHRAE 93-77, and that all-day collector efficiency be calculated and reported as shown in table 4. Measurements made after the 30-day no-flow degradation test are to be used to determine performance. For the 30-day no-flow degradation, the criteria limit the change in intercept or slope to that which would not cause a degradation in thermal efficiency of more than 10 percent.

The proposed criteria provide more specific guidelines for determining failure for durability/reliability, safety, and fire tests. For these tests, the major rating criteria include:

1. Thermal Shock (water spray/cold fill) Tests: No visual observation of catastrophic or structural failure, and no visual evidence of leakage.

2. Rain Tests: No visual observation of water penetration into the collector and no increase in collector weight greater than 1 percent.

3. Thermal Cycling Tests: No visual observation of catastrophic or structural failure.

4. Static Pressure Tests: For air collectors, the total volume of air is not to exceed 20 multiplied by the volume of the collector panel assembly for the test period. No pressure drop or visual observation of leakage for liquid collectors.

5. Wind Load Tests: For positive, negative, and combined loads, procedures are given for determining a "Design Load Rating" U, as follows:

$$U = R_m (1 - \alpha\nu)$$

   Where: R_m = Mean resistance (average maximum load resistance by collector),
   α = A factor dependent on the number of specimens tested, and
   ν = Coefficient of variation.

6. Longitudinal Load Test: No visual evidence of physical damage or permanent distortion.

7. Hail Load Test: Collectors which are not damaged by 4 cm (1-1/2 in.) diameter hailstones have a high probability of withstanding most hailstorms without damage. The reader is referred to the intermediate minimum property standards* to determine the mean annual days with hail in different regions of the U.S.

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* Intermediate Minimum Property Standards supplement, Solar Heating and Domestic Hot Water Systems, 1977 Edition, HUD 4930.2, prepared for HUD by NBS.

8. Air Collector Rupture and Collapse: No visual evidence of physical damage or permanent distortion.

9. Fire Performance: Meet Class C rating [46] for intermittent flame, spread of flame, and burning brand tests, except that only one series of tests needs to be performed. Meet ASTM E 84 guidelines for flame spread classification index for all insulation materials.

In addition, the provisional test procedures [39,40] provide guidelines for the selection and characterization of test specimens, as well as for shipment inspection. Recommendations are also given for test sequencing which considers technical considerations such as the need to induce degradation of materials before the appropriate test and minimize the probability that testing would damage a collector so that further testing would be impossible. Thus, the following sequence is suggested:

1. Static Pressure Leakage Test--to detect leaks in both air and liquid collectors.

2. Thermal Tests
    a. Preconditioning exposure
    b. Thermal Performance Baseline
    c. No-Flow 30-day Degradation -- (including d. and e.)
    d. Thermal Shock/Water Spray
    e. Thermal Shock/Cold Fill
    f. Post-Stagnation Thermal Performance

3. Rain Test.

4. Thermal Cycling including Positive Live Load; Negative and Combination Wind Loads; Longitudinal Load; and Hail Load; in any desired order following test No. 1.

5. Air Collector--Rupture and Collapse--To be done near the end of testing.

6. Fire Test--To be conducted at the end of testing since it will damage collector.

Throughout all collector testing, extensive documentation and calibration records are required.

4.5.2 Durability Research Program

4.5.2.1 Research Plan

The NBS research plan for determining collector durability is described in NBS TN 1136 entitled "NBS Solar Collector Durability/Reliability Test Program Plan" [47]. This research program was designed to correlate the results of laboratory, accelerated field, and simulated operational exposure tests with actual operating performance of collectors used for building heating and cooling applications.

The research described in [47] was designed to assess the influence of environmental exposure parameters that could affect the degradation of solar collectors and materials. Data obtained during the research program were intended to lead to more meaningful durability/reliability tests of collectors and materials. The testing program was designed to accomplish the following goals:

- Evaluate test procedures for predicting material deterioration rates and collector performance reliability;

- Evaluate the effects of collector material deterioration on collector thermal performance;

- Determine the influence of environmental exposure conditions on collector material deterioration;

- Compare thermal performance measurements of outdoor natural exposure with those obtained from exposure to solar simulators;

- Correlate data for tests from accelerated and normal operation of collectors and materials;

- Determine the influence of thermal shock and moisture penetration.

The research plan [47] describes the test procedures to be followed. Where possible, procedures using consensus standards outlined in [39,40] are to be followed. Table 5 identifies the tests for solar collectors, while tables 6 and 7 outline the exposure tests for cover and absorber materials, respectively. The plan also described the exposure conditions to be considered in the selection of outdoor tests sites. These include:

- Annual solar radiation and seasonal distribution,
- Humidity,
- Ultraviolet radiation in solar flux,
- Average and extreme high-low temperatures,
- Total seasonal precipitation,
- Average and maximum wind velocities,
- Pollutants, including particulate matter, oxidants, and acid gases.

Four sites were selected for testing solar collector performance based on desired environmental conditions and availability. These included: Phoenix, AZ (hot and dry); Cape Canaveral, FL (hot and humid); Palo Alto, CA (moderate and dry); and Gaithersburg, MD (moderate and humid).

Needed test procedures were identified for both the whole collector and collector materials to determine the influence of environmental exposure parameters. Tests results for the collector as a unit are discussed in section 4, while test results for collector materials and components are discussed in section 5.

Table 5. Summary Description of Field Test Series on Solar Collectors (from Ref. 47)

Test Series	Collector Performance Measurement	Conditions for Weathering Exposure	Properties of Test Series***
Series 1 "dry stagnation"	Initial measurement in accordance with ASHRAE 93-77. Performance re-test after 3, 15, 30, 60, 120 and 240 day exposures.*	Each collector pre-conditioned for each weathering exposure by purging with dry air to remove the remaining heat transfer fluid	1. Observation of collector performance and other characteristics for various weatherizing times. 2. Provide data for performance data. 3. Provide data for comparing collector.
Series 2 "no-flow stagnation"	Initial measurement in accordance with ASHRAE 93-77. Performance re-tests same as in Series 1.	Collectors same as in Series 1 except that Tests per NBSIR 78-1305A will be performed during Series 2 test collectors only.	1. Observation of effects of no-flow stagnation on collector performance and other characteristics. 2. Observation of effects of Thermal Shock Tests representing (a) filling a hot collector with cool heat transfer medium and (b) summer rain on a hot collector. 3. Observation of static pressure leakage after 30 and 120 days of exposure.
Series 3 "controlled flow"	Performance of test collectors measured in accordance with ASHRAE 93-77. Performance re-tests same as in Series 1.	During weathering exposure heat transfer for liquid.	1. Observation of effects of normal operation on collector performance and other characteristics.
Series 4 "dry stagnation with augmentation reflectors"	Initial measurement same as in Series 1. Performance re-tests same as in Series 1.	Pre-conditioning and weathering exposures same as in Series 1 except that a reflector** will be used on each collector during each day of weathering exposure*. Solar radiation measurements required both with and without reflector.	1. Observation of effects of dry stagnation on collector performance and other characteristics with solar radiation amplified by a reflector. 2. Obtaining temperature history within collectors for most severe exposure conditions.

* Individual days with solar radiation of 17,000 kJ/m^2·day or greater as measured in the plane of the collector aperture without the influence of a reflector.

** The reflector is described in reference 47.

*** All series include provision of data for comparisons between test series, test sites (climatic regions), collector designs, etc.

Table 6. Exposure Tests for Cover Materials
(from Ref. 47)

Exposure Conditions	Value of Range	Exposure Time
Temperature (indoor)	a) 70°C b) 90°C c) 125°C	500, 1,000 and 2,000 hr.
Temperature and Humidity (indoor)	a) 50°C and 98% RH b) 70°C and 95% RH c) 90°C and 95% RH	500, 1,000 and 2,000 hr.
Temperature and Radiation (indoor)	Xenon arc weathering machine a) 70°C b) 90°C	500, 1,000 and 2,000 hr.
Solar Simulator	a) Tungsten b) Xenon simulators with irradiance of ~950 W/m^2 and ~70°C	30, 60 and 120 cycles*
"Real Time" Outdoor	1 sun at ~60°C	80, 160 and 240 days**
Accelerated Outdoor	~6 suns at ~70°C	6, 12 and 24 equivalent months***

* Each cycle consists of 5 hrs. irradiation and 1 hr. cooling, as defined in reference 47.

** Radiant exposure must exceeded 17,100 kJ/m^2 for each day.

*** One equivalent month equals 6.625 x 10^8 J/m^2 (15,835 Langleys)

Table 7. Exposure Tests for Absorber Materials
(from Ref. 47)

Exposure Conditions	Value of Range	Exposure Time
Temperature (indoor)	a) 150°C b) 175°C	500, 1,000 and 2,000 hr.
Temperature and Humidity (indoor)	90°C and 95%	500, 1,000 and 2,000 hr.
Thermal Cycling (indoor)	-10°C to 175°C	5, 15 and 30 cycles
Temperature and Radiation (indoor)	Xenon arc weathering machine at 90°C	500, 1,000 and 2,000 hr.
Solar Simulator	a) Tungsten b) Xenon simulators with irradiance of ~950 W/m^2 and ~130°C	30, 60 and 120 cycles*
"Real Time" Outdoor	1 sun at ~140°C and ~160°C	80, 160 and 240 days**
Accelerated Outdoor	~6 suns at ~150°C	6, 12 and 24 equivalent months***

* Each cycle consists of 5 hrs. irradiation and 1 hr. cooling, as defined in reference 47.

** Radiant exposure must exceeded 17,100 kJ/m^2 for each day.

*** One equivalent month equals 6.625 x 10^8 J/m^2 (15,835 Langleys)

Five criteria were used to select collectors for testing. These included commercial availability and representativeness of the materials and construction practices commonly available. The collectors selected were flat-plate, aqueous-liquid types with one or two covers of glass, sheet plastic, or film, and selective or nonselective absorber coatings. Tracking concentrating collectors, collectors with nonaqueous or gaseous heat-transfer fluids did not meet the criteria, and so were not included in the testing. Table 8 outlines the key features of the eight collector specimens selected. Tables 9 and 10 present the cover and absorber materials included in the materials tests.

The testing program called for data to be collected on thermal performance, material properties, and environmental conditions. Computerized data reduction routines were advocated to deal with the large volume of data, and to identify correlations between relevant variables. The resulting data analysis would focus on three major areas of performance:

- Analysis of measured collector efficiency to correlate thermal performance changes with elapsed time and collector environment.

- Analysis of changes in material properties, including the correlation of property changes with exposure time and environmental conditions, and the effect of changes in material properties on collector thermal performance.

- Investigation of stagnation temperatures of collector materials. This includes the development of a mathematical model for predicting stagnation temperatures. Experimentally verified stagnation temperatures could then be used in developing accelerated aging procedures.

4.5.2.2 Statistical Uncertainty in Thermal Performance Data

The round-robin study of collector performance described earlier (4.4.1) demonstrated that corrections for environmental difference such as wind and solar irradiance reduced variability in the data between sites only slightly. It appeared that this variability was due more to systematic measurement problems arising from differences in instrument calibration, sensor installation, and general procedures.

As a result, NBS conducted a series of tests and analytical studies to determine the overall uncertainty in thermal performance data for solar collectors. This effort was designed to illustrate how the uncertainty in individual tests can affect the rating and selection of collectors, as well as to determine degradation with exposure or operating time [48,49]. Eight liquid flat-plate collectors representative of commonly used materials and construction types were selected for the tests (see tables 8 and 11). All collectors from each manufacturer were from the same production lot. The collectors were tested at four test sites representing climatological extremes.

Table 8. Solar Collector Test Specimen
(from Ref. 47)

Code	Cover Material[5]		Absorber Material[5]	
	Outer	Inner	Coating	Substrate
A	Glass[1]	---	Black Nickel	Steel
B	Glass[2]	Glass[2]	Black Velvet Paint	Copper
C	Glass[3]	FEP Film Heat Trap	Black Velvet Paint	Copper
D	Glass[2,4]	Glass[2,4]	Black Chrome	Steel (nickel flashed)
E	FRP - Type Ia	---	Flat Black Paint (lacquer primer)	Copper
F	Glass[1]	---	Copper Oxide	Copper
G	FRP - Type II	FEP Film	Porcelain Enamel	Steel
H	Polyester Film	FEP Film	Flat Black Paint (siliconized polyester)	Aluminum

[1] Water White Glass

[2] Low Iron Glass

[3] Ordinary Plate Glass

[4] Etched Anti-Reflection Treatment

[5] Obtained from collector manufacturer literature

Table 9. Cover Test Materials
(from Ref. 47)

Code[1]	Cover Material	Transmittance[3] (Controls)
E	FRP Type Ia	0.85
G	FRP Type II	0.84
H[2]	Polyester/FEP (outer) (inner)	0.85/0.96
J	Polycarbonate	0.88
K	Polyvinyl Fluoride	0.89
L	FRP Type Ib	0.84
M	FRP Type III	0.78
N	Polymethyl methacrylate (acrylic)	0.90
O[2]	Glass[4]/Polyvinyl Fluoride (outer) (inner)	0.86/0.89

[1] Code letters E, G and H indicate materials coupon specimens cut from solar collectors E, G and H. Codes J, K, L, M, N and O tested at the materials level only.

[2] Materials to be exposed as a combination in the cover mini-boxes and in the accelerated weathering machine.
Materials to be exposed individually in all other tests. Glass and FEP materials not to be used for individual tests because of proven stability.

[3] These properties are dependent on the formulations and manufacturing processes used. Other products within a generic class of materials may have significantly different properties.

[4] Ordinary plate glass.

Table 10. Absorber Test Materials
(from Ref. 47)

Code[1]	Absorber Material		Optical Properties[2]	
	Coating	Substrate	Absorptance[3]	Emittance[3]
A	Black Nickel	Steel	0.87	0.13
C	Flat Black Paint	Copper	0.98	0.92
D	Black Chrome	Steel (nickel flashed)	0.97	0.07
E	Flat Black Paint	Copper	0.95	0.87
F	Copper Oxide	Copper	0.96	0.75
G	Black Porcelain Enamel	Steel	0.93	0.86
H	Flat Black Paint	Aluminum	0.95	0.89
I	Black Chrome	Stainless Steel	0.88	0.19
J	Black Chrome	Aluminum	0.98	0.14
L	Lead Oxide	Copper	0.99	0.29
M	Oxide Anodized	Aluminum	0.94	0.10
N	Oxide Conversion Coating	Aluminum	0.93	0.51
P	Black Chrome	Copper	0.96	0.08

[1] Code letters A through H indicate materials coupon specimens cut from solar collectors A through H. Codes I through P tested at the materials level only.

[2] These properties are dependent on the formulations and manufacturing processes used. Other products within a generic class of materials may have significantly different properties.

[3] Average values based on a minimum of ten test specimens.

Table 11. Test Collector Specimen Description (from Ref. 48)

Collector Code	Cover Material			Absorber Material			Average Area*	
	Outer	Inner	Solar Transmittance	Material	Solar Absorptance	Emittance	Gross (m^2)	Aperture (m^2)
A	Water White Glass	---	0.90	Black Nickel	0.87	0.13	2.150	1.831
B	Low Iron Glass	Low Iron Glass	0.88	Black Velvet Paint	0.97	0.96	1.732	1.602
C	Plate Glass	Thin Film Heat Trap	0.86	Black Velvet Paint	0.98	0.92	2.589	1.924
D	Etched Glass	Etched Glass	0.96	Black Chrome	0.97	0.07	1.655	1.402
E	FRP (Type I)	---	0.85	Lacquer Primer	0.95	0.87	1.892	1.720
F	Water White Glass	---	0.90	Copper Oxide	0.96	0.75	1.922	1.769
G	FRP (Type II)	FEP Film	0.84 0.96	Porcelain Enamel	0.93	0.86	2.563	2.188
H	Polyester Film	FEP Film	0.85 0.96	Siliconized Polyester Paint	0.95	0.89	2.916	2.641

* Average of values reported by four test sites.

Two categories of uncertainty were identified in the thermal performance data for solar collectors. These included:

- Measurement uncertainties related to the individual and cumulative instrument calibration and operational errors. Measurement accuracy problems were identified for solar irradiance, fluid flow rate, temperature and working fluid properties, and the data acquisition system.

- Meteorological uncertainties related to variations in the site environment including ambient air temperature, wind speed, total solar irradiance, beam solar irradiance incident angle, and reflected solar irradiation.

The data analysis was performed using the statistical concepts and terminology recommended by ASTM [50]. This analysis was performed for both thermal efficiency and incident angle modifier (IAM) measurements. Variability was calculated for measurements made "within" a single test site and "between" various test sites. Tables 12 and 13 present the intercept, mean, standard error of the mean, standard deviation, and coefficient of variation for the intercept and slope respectively for data obtained "within" and "between" test sites. As might be expected, the "between" standard deviations are somewhat larger than those for "within" site data.

Figure 33 illustrates the calculated measurement uncertainty. The solid curves represent the difference in calculated thermal performance for a single glass-cover, selective-absorber type collector exposed to the allowed extreme environmental conditions. (Calculations are given in reference [29].) Experimental verifications performed with a Xenon arc solar simulator [49] are indicated by black squares bracketing the curve for average outdoor data. Table 14 presents the incident angle modifier data.

Based on the results of the experimental tests and statistical analysis, it was concluded that the total experimental uncertainty is about the same as the random error predicted by ASHRAE 93-77. Furthermore, measurement error was believed to be the major contributor to the "within" site variability, while environmental effects appeared to be a significant factor affecting the loss coefficient data obtained "between" sites (reproducibility). Heat loss coefficient data were analyzed before and after testing to examine degradation problems. This analysis indicated that application of uncertainty values for thermal performance data can have significant impact on evaluating collector degradation, collector rating, and seasonal efficiency. The following conclusions were drawn:

- Material degradation is about equivalent to a 0.10 change in cover plate transmittance or absorber solar absorptance and emittance.

- Collector all-day thermal output varies from ± 17 to ± 68 percent for specific winter operation conditions, which results in significant ranking changes.

Table 12. Standard Deviation and Coefficient of Variation of Intercept Within and Between Test Sites (from Ref. 48)

Collector	Intercept Mean	Standard Error of Mean		Standard Deviation and Coefficient of Variation			
				Within		Between	
		Value	Percent	s_r	$\%cv_r$	s_R	$\%cv_R$
A	0.610	0.0061	0.99	0.0159	2.60	0.0176	2.88
B	0.652	0.0073	1.11	0.0105	1.60	0.0167	2.56
C	0.537	0.0042	0.78	0.0146	2.71	0.0146	2.71
D	0.643	0.0036	0.56	0.0125	1.94	0.0215	1.94
E	0.603	0.0039	0.56	0.0118	1.94	0.0119	1.97
F	0.651	0.0066	1.01	0.0155	2.37	0.0181	2.78
G	0.560	0.0101	1.80	0.0120	2.13	0.0222	3.98
H	0.632	0.0053	0.83	0.0080	1.25	0.0123	1.94

Average Coefficient of Variation Within ($\overline{\%cv_R}$) = 2.07%

Average Coefficient of Variation Between ($\overline{\%cv_R}$) = 2.39%

Table 13. Standard Deviation and Coefficient of Variation of Slope Within and Between Test Sites (from Ref. 48)

Collector	Slope Mean (W/°C·m^2)	Standard Error of Mean		Standard Deviation and Coefficient of Variation			
				Within		Between	
		Value	Percent	s_r	$\%cv_r$	s_R	$\%cv_R$
A	4.531	0.236	5.20	0.375	8.22	0.556	12.3
B	5.535	0.078	1.41	0.267	4.87	0.267	4.87
C	4.287	0.120	2.81	0.233	5.48	0.307	7.12
D	3.095	0.216	6.98	0.238	7.71	0.471	15.26
E	6.439	0.167	2.59	0.466	7.22	0.500	7.80
F	5.996	0.254	4.51	0.363	6.07	0.613	10.20
G	5.405	0.145	2.69	0.278	5.16	0.363	6.77
H	5.661	0.145	2.56	0.153	2.70	0.312	5.54

Average Coefficient of Variation Within ($\overline{\%cv_R}$) = 5.93%

Average Coefficient of Variation Between ($\overline{\%cv_R}$) = 8.37%

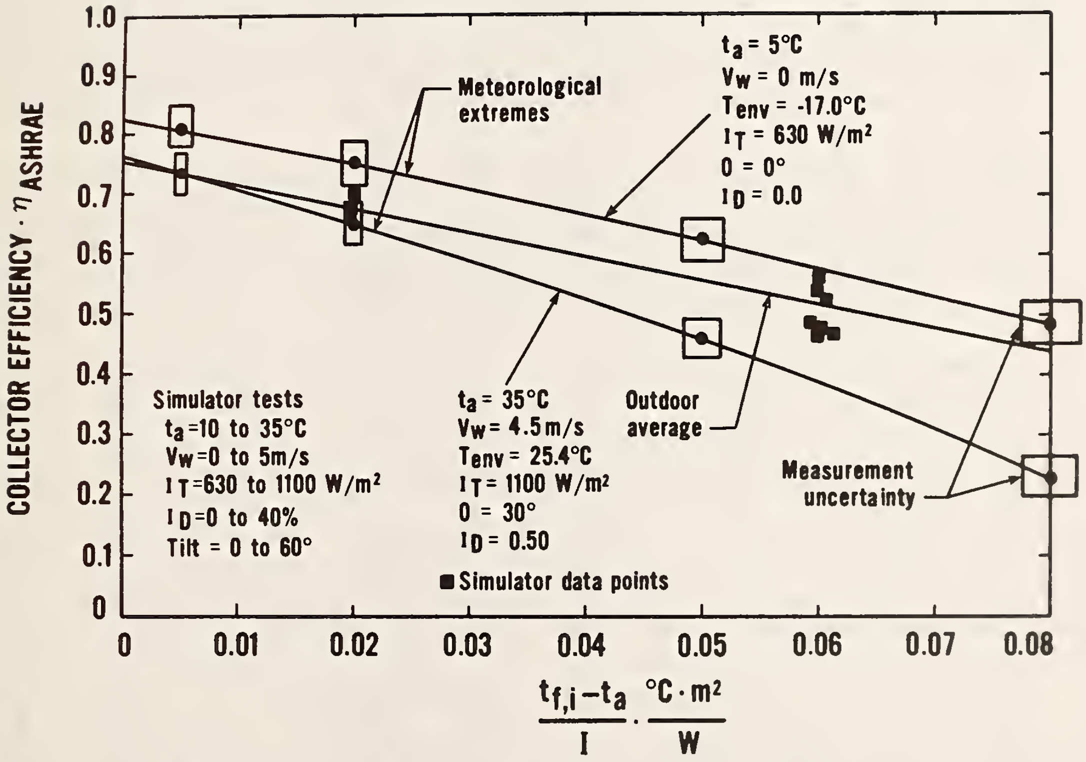


Figure 33. Uncertainty associated with the ASHRAE 93-77 efficiency measurements for a single-glazed selective absorber-type collector (from Ref. 48)

Table 14. Incident Angle Modifier Standard Deviation Values Within and Between Test Sites (from Ref. 48)

Data Source	Parameter	Collector Type								Average %cv
		A	B	C	D	E	F	G	H	
Test Site #1	Mean	0.040	0.106	0.248	0.170	0.168	0.078	0.203	0.127	
	Standard Error	0.013	0.003	0.028	0.024	0.030	0.015	0.053	0.030	
	Standard Deviation	0.022	0.005	0.048	0.041	0.052	0.026	0.091	0.051	
	$\%cv_r$	55	4.2	19	24	31	33	45	39	$\%\overline{cv_r} = 31$
Test Site #2	Mean	0.100	--	0.270	0.135	--	0.090	0.130	--	
	Standard Error	0.010	--	0.020	0.025	--	0.020	0.020	--	
	Standard Deviation	0.014	--	0.028	0.035	--	0.028	0.028	--	
	$\%cv_r$	14	--	10	26	--	31	22	--	$\%\overline{cv_r} = 20.6$
Test Site 1, 2 & 3	Mean	0.094	0.125	0.261	0.165	0.165	0.113	0.173	0.118	
	Standard Error	0.029	0.019	0.014	0.017	0.021	0.032	0.028	0.023	
	Standard Deviation	0.052	0.027	0.036	0.040	0.043	0.057	0.069	0.045	
	$\%cv_R$	57	22	14	24	26	51	40	38	$\%\overline{cv_R} = 34$

- Residential annual heating and domestic hot water solar fraction can vary by as much as ± 6 to 7 percent annually.

The analysis of uncertainty in solar collector data indicated that variability collector performance continues to be a real problem.

4.6 FLAMMABILITY OF SOLAR COLLECTORS

As part of the DOE collector test program (section 4.5.1), research was initiated to evaluate the flammability of solar collectors to determine applicable test methods. As a possible rating basis, references 19 and 20 suggested that solar collectors meet Class C rating for intermittent flame, spread of flame, and burning brand tests of ASTM E 108 "Fire Tests of Roof Coverings" [46].

NBS directed an experimental program at two different laboratories to: (1) evaluate the use of ASTM E 108 as a means for determining the influence of roof-mounted collectors on the fire characteristics of roof coverings; (2) determine modifications in the test procedure that might be required to make it applicable to roof mounted collectors; and (3) determine the influence the flat-plate solar collectors constructed of various materials might have on the fire characteristics of roof coverings [51]. The study did not include the rating of collectors tested, potential self-ignition of collectors, or the fire resistance of roof assemblies with solar collectors when exposed to interior fires.

The experimental work was conducted at two private testing laboratories. The tests were conducted on 11 collector designs as outlined in table 15 and the four mounting configurations as shown in figure 34. The test roofs were wood decks covered with Class C asphalt-impregnated organic-felt shingles. Burning brand, intermittent flame, and spread of flame tests were conducted.

For the burning brand tests, Class A, B, or C brands were placed on the collector covers and, for collectors mounted on standoffs, the brands were placed beneath the covers directly on the roof surface. For the intermittent flame test, the test deck (including collector) was subjected to a luminous gas flame--of a temperature of 700° to 760° C ± 30°C (1300° to 1400° F ± 50°F) depending on class---approximately the width of the deck, which uniformly bathed the surface. The flame was applied intermittently for a specified period ranging from 1 minute on and 2 minutes off to 2 minutes on and 2 minutes off, in 3 to 15 cycles. For the spread of flame test, the same type of flame was applied continuously for 10 minutes for Classes A and B and for 4 minutes for Class C. Figure 35 shows a schematic drawing of the test apparatus.

The Class C brands ignited the one collector cover with acrylic glazing and destroyed the collector, but had no effect on either tempered or annealed glass and caused only a small area of blackening on fiber reinforced plastic (FRP) covers. Both Class A and B brands readily ignited FRP covers, shattered tempered glass glazing and broke annealed glass, but the absorber plate prevented further fire penetration of the collector.

Table 15. Fire Test Collector Description (from Ref. 51)

Collector Code	Materials					Approximate Dimensions Length × Width × Depth
	Case Sides	Case Back	Glazing	Insulation	Absorber	
29-L	Aluminum	Aluminum	Glass (tempered)	Foam plastic[1]	Aluminum	259 × 127 × 17.7 cm (102 × 36 × 3 1/2 in)
32-L	Wood	Plywood	FRP[2]	Fiberglass	Aluminum	305 × 127 × 17.7 cm (120 × 48 × 5 in)
41-L	Wood	Plywood	Double Glass (tempered)	Urethane foam	Copper	239 × 91 × 8.6 cm (94 × 36 × 3 3/8 in)
43-L	Molded FRP	Molded FRP	FRP	Urethane foam	Copper	244 × 91 × 14.6 cm (96 × 36 × 5 3/4 in)
45-L	Aluminum	Aluminum	FRP	Foam plastic	Aluminum	300 × 96 × 7.6 cm (118 × 37 3/4 × 3 in)
46-L	Wood	Hardwood	Glass (tempered)	Isocyanurate foam	Copper	236 × 89 × 8.9 cm (93 × 35 × 3 1/2 in)
54-L	Wood	Plywood	Glass (annealed)	Fiberglass	Aluminum	251 × 126 × 8.9 cm (99 × 49 3/4 × 3 1/2 in)
103-L	Aluminum	Aluminum	Acrylic	Polystyrene (loose fill)	Aluminum	244 × 122 × 19.1 cm (96 × 48 × 7 1/2 in)
108-L	Steel	Steel	FRP	Fiberglass	Steel	220 × 102 × 7.6 cm (86 1/2 × 40 × 3 in)
126-L	Aluminum	Aluminum	Glass (tempered)	Fiberglass	Copper	196 × 89 × 12.7 cm (77 × 35 × 5 in)
78-L	Aluminum	Aluminum	FRP	None	Aluminum	500 × 61 × 18.4 cm (196 3/4 × 24 × 7 1/4 in)

[1] Rigid foam plastic, type unknown

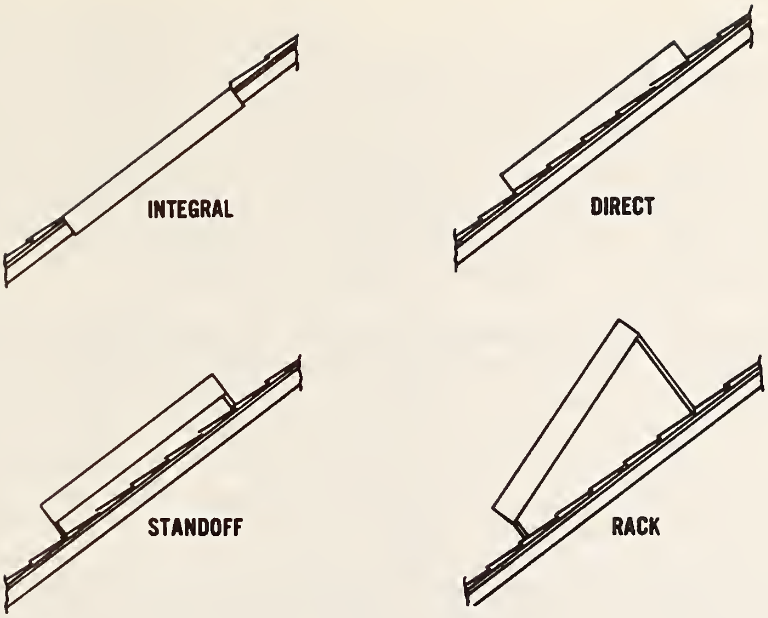


Figure 34. Collector mounting configurations (from Ref. 51)

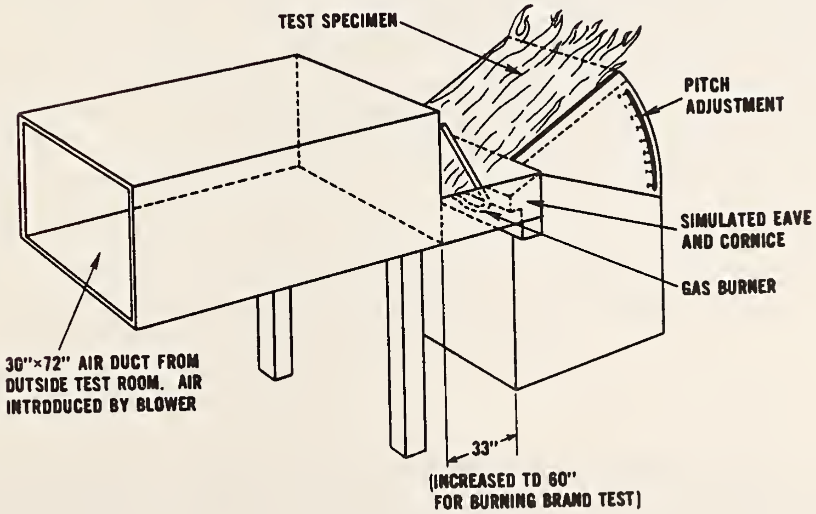


Figure 35. Schematic of fire test apparatus (from Ref. 51)

In the intermittent flame tests conducted on three collectors constructed of FRP, wood, and aluminum, neither the shingles nor the collector were ignited.

During the flame spread tests, both FRP and acrylic collector covers were ignited within less than 4 minutes. The spread of flame under collectors was shown to be primarily a function of separation or standoff distance between the collector and the roof covering. The rate of flame travel did not depend on the material (wood, steel, aluminum) of the collector.

From the test results, it was concluded that the burning brand test of ASTM E 108 could be applied with only minor modifications to solar collectors. It was also determined that collectors meeting the burning brand test and the spread of flame test also met those for the intermittent flame test. The presence of the collector on the roof appears to have the most significant impact on the flame spread test. The results indicate that collectors mounted on roofs with a standoff greater than approximately 4 cm (1-1/2 inch) above a Class C roof covering will result in flame travel under the collector greater than that allowed by the test criteria, regardless of collector construction. The results also indicate that collectors with combustible glazing could provide a path for rapid flame spread from one area of roof to another. This could be a particular problem for thermoplastic materials.

The researchers suggested that further investigations should be conducted to determine the suitability of small-scale flammability tests such as ASTM D 635 for evaluating the combustibility of glazing materials. In addition, the possibility of fire penetration into the building air duct system from burning collector covers should be investigated.

5. COLLECTOR MATERIALS RESEARCH

The preceeding section summarized various evaluations of the performance of a solar collector as a unit. Collector performance can also be analyzed in terms of the performance of individual materials such as glazing or insulation. In section 5, research and test methods for cover plates, absorber materials, collector insulation, gaskets and sealants, rubber hose, containment materials, and heat transfer fluids are reviewed. The bulk of this research dealt with issues such as durability and stability over time, rather than thermal performance, with the majority of the resulting standards being promulgated by ASTM rather than ASHRAE. Yancey [52] summarized NBS materials research activities in a companion document.

5.1 COVER PLATES

5.1.1 Introduction

In a flat-plate solar collector, cover plates perform a number of important functions. They minimize heat losses from the front surface of the solar collector, while protecting the internal components of the collector from adverse weather conditions such as rain, snow, and hail. The cover plates must also maintain the maximum possible transmittance of incident solar radiation.

The properties of most commonly used cover plate material, glass, are well-known and understood. Glass is subject to breakage, relatively heavy, and costly, so that alternative materials such as plastics have been used. Plastics are generally less costly, lighter in weight, easier to fabricate, and can have higher impact resistance. On the other hand, the long-term durability of plastic is not well documented. Exposure of plastic to sunlight, airborne abrasives, and aging can reduce transmittance and induce brittleness. As a result, a number of research studies were performed at NBS and elsewhere of documented field problems [53, 54, 55, 56] to determine methods for evaluating the optical and mechanical properties of cover plates, as well as durability and resistance to adverse weather such as hail. The studies reviewed in section 5.1 [62, 63, 64, 65] formed the technical basis for ASTM Standards E 765-80 [57], E 782-81 [58], E 881-82 [59], and E 822-81 [60], as well as a set of proposed revisions to ASTM E 424-71 [61].

5.1.2 NBS Research on Cover Plates

In 1976, NBS initiated a series of laboratory and field studies to determine the optical, mechanical, and durability properties of different cover plate materials [62]. This research was designed to assess the performance requirements for cover plate materials, identify test methods for assessing performance, collect data on performance, and prepare draft standards for consideration by ASTM Committee E-44 on Solar Energy Conversion.

NBS conducted research in several areas: cover plate performance after natural and accelerated weathering [62, 63]; determination of cover plate properties including stability, warpage, and mechanical response [62]; measurement of optical properties [64]; and determination of procedures for assessing hail impact on the durability of cover plate materials [65].

In the first study [62], researchers identified field problems, determined performance requirements for and properties of cover plate materials, and identified degradation factors. The following potential problems with different cover plate materials were identified: breaking, rupturing, and cracking caused by thermal stresses, accidental impact, and environmentally induced embrittlement; impact damage from hail, accidents, or vandalism; loss of solar transmittance due to yellowing, mechanical distortion, dirt, or moisture condensation on either surface of the plate material. These problems were then evaluated through research which determined the properties of cover plate materials and their response to various degradation factors. Laboratory and field exposure tests were conducted on selected typical cover plate materials commercially available in 1976.

Primary cover plate properties include solar transmittance, dimensional stability, tensile properties, and hail impact resistance. Secondary properties include the transmittance of long wavelength radiation, abrasion resistance, and static electric charge build-up (which could attract and hold dust or dirt particles, thereby reducing solar transmittance.) The most important degradation factors include solar radiation (primarily ultraviolet (UV) radiation) and elevated temperatures. In addition, synergistic reactions from a combination of solar radiation, high temperatures, and moisture, appear to be significant factors in the degradation of plastic materials. Furthermore, thermal cycling, moisture, and air pollution may cause surface degradation.

The materials were subjected to aging procedures which simulated common degradation factors. These aging procedures included: heat stability aging given in ASTM D 794 [66], artificial weathering with xenon arc lamp (ASTM D 2565) [67], and natural weathering exposure. For natural weathering, insulated wooden "mini-collectors" were used in tests conducted in Gaithersburg, MD; Miami, FL; and New River, AZ. After exposure, the specimens were tested for solar energy transmittance, linear dimensional stability, and warpage. One objective of the tests was the comparison of results from screening tests for solar energy transmittance using two different procedures recommended in ASTM E 424 [61]. The various tests were conducted on ten materials, including glass, plastic films, and plastic sheets.

The results from the laboratory and field studies [62] indicated that:

- Accelerated laboratory testing procedures offer an effective means of screening cover plate materials.

- Heat aging at 150°C (302°F) for 500 hours is an effective means of identifying materials which will develop problems in outdoor weathering.

- The mini-collectors provide useful data on outdoor exposure.

- Factors which contribute to solar energy transmittance losses include solar radiation, moisture, and air pollutants, as well as dust and dirt retention. Solar radiation dosage, however, appears to contribute to decreases in the mechanical and physical properties of materials.

- Method A of ASTM E 424, which uses a spectrophotometer, has better precision and reliability than Method B, for determining solar energy transmittance of cover plate materials.

5.1.2.1 Calculation of Solar Transmittance

NBS also conducted a parametric study of the procedures for measuring the spectral transmittance of cover plate materials [64]. Method A of ASTM E 424 allows two procedures for calculating the spectral transmittance of a solar collector cover from data obtained with an integrating sphere spectrophotometer. The obtained data may be integrated using the weighted ordinate method or the selected ordinate method. The NBS results indicate that these two methods do not yield identical results, with the weighted ordinate method producing higher solar transmittance values than the selected ordinate method (up to one percent higher.)

Method A also assumes that the solar energy spectral distribution or air mass is equal to 2.0 (the value obtained when the sun reaches an angle of 60 degrees between the zenith and the line of sight). Most solar collectors, however, are exposed to more hours of radiation that approximates air mass 1.5. As a result, Roberts, Masters, and Clark [64] assessed the effect of varying air mass value upon the transmittance and reflectance values of typical materials. They determined that the three values of air mass studied, 1.0, 1.5, and 2.0, could vary the obtained transmittance values by as much as 4 percent. This effect is greatest for those materials with the least transmittance in the ultraviolet range.

Consequently, NBS recommended to ASTM Committee E44 that ASTM E 424 be revised to specify only one integration method for calculating transmittance, since the two calculation methods do not agree. It also recommended that the solar energy distribution used in Method A be changed to air mass 1.5, as this appears to be a more representative value.

5.1.2.2 Determination of Impact Resistance

In addition, NBS studied the effect of simulated hail impact on solar collectors [65,68]. These studies were concerned with estimating the maximum size of hail [68], hail impact loadings and stresses, simulating hail by ice balls, and selecting launching equipment. They identified means of mounting cover plate test specimens, determining suitable points of vulnerability, predicting appropriate ice ball velocity and direction, and assessing damage to the collector cover plate. These experiments confirmed the feasibility of using ice balls propelled from a compressed-air launcher to simulate hail.

5.1.3 ASTM Standards

Based on the laboratory and field studies, NBS drafted several proposed methods for evaluating cover plate materials and submitted them to ASTM Committee E44. The committee promulgated the four standard practices described below, which closely follow the draft proposals. It is currently considering revisions to ASTM E 424 in line with NBS test results. Each of the four standards will be reviewed below in some detail to provide an indication of the kinds of information covered by the standard.

5.1.3.1 ASTM E 765-80

Standard Practice for Evaluation of Cover Materials for Flat Plate Solar Collectors -- ASTM E 765-80 -- provides evaluation procedures for measuring the primary properties of cover plate materials and for assessing the durability of cover plates by comparing initial property measurements with those obtained after exposure to aging procedures [57].

The standard specifies the number and geometry of the test specimens. It indicates that tension test specimens should be cut from the same piece of material that was subjected to the aging procedures. It states further that optical property tests should not be performed on specimens damaged from the physical property tests. The specimens should be conditioned for at least 40 hours prior to testing. Both conditioning and testing should occur at 23 ± 2°C and 50 ± 5 percent relative humidity.

The property measurement tests for ASTM E 765-80 involve measurement of solar energy transmittance, effect of dirt retention on solar transmittance, dimensional stability, tensile properties, and impact resistance. Four measurements of solar energy transmittance are to be made by the appropriate method from ASTM E 424. Dirt retention is determined by measuring solar energy transmittance after exposure to natural weathering. The specimen is first measured, then cleaned, and then remeasured. The difference in solar transmittance before and after cleaning is a measure of the dirt retained during natural weathering. Linear dimensional stability is measured by ASTM Method D 1042 for rigid and semi-rigid materials, and by ASTM D 1204 for non-rigid materials. Warpage for rigid and semi-rigid materials is measured by D 1181. Tensile properties, which must be measured only after careful conditioning, include tensile strength, percent elongation at yield and at break, and elasticity. Method ASTM D 638 is specified for use with rigid and semi-rigid plastic materials, and ASTM D 822 for flexible membrane materials. Finally, impact resistance is to be measured by ASTM E 822 (which was only a draft standard when E 765 was adopted.)

Aging procedures include heat stability, natural weathering, and optional accelerated weathering procedures. Heat stability is measured separately for outer and inner cover materials using Practice D 794 for 240 hours. The test temperature is 75 ± 2°C for outer and 125 ± 2°C for inner cover materials. To measure natural weathering, the cover test specimen is exposed to natural conditions for at least 12 months using Practice E 782. Although accelerated weathering should not be substituted for natural weathering tests, it may be used as a screening tool. (If accelerated weathering test results can be shown to correlate with natural weathering data, then accelerated weathering may be effective for obtaining long-term durability information in a short time.) Two different procedures may be used for accelerated weathering--a laboratory procedure or an outdoor procedure with concentrated natural solar radiation. For the laboratory procedure, specimens are exposed according to Procedure A of ASTM practice D 2565. Three increments of exposure length are specified, and vary from 700 to 3800 hours. Moisture conditions should be simulated by a water spray for 30 minutes following 90 minutes of light exposure. In the outdoor exposure, specimens are exposed to concentrated natural solar radiation machines such as referenced in ANSI Z97.1-1975, until they have received a specified level of total incident radiant exposure. Again, the application of a water spray at specified levels and intervals is recommended for materials exposed to moisture in service.

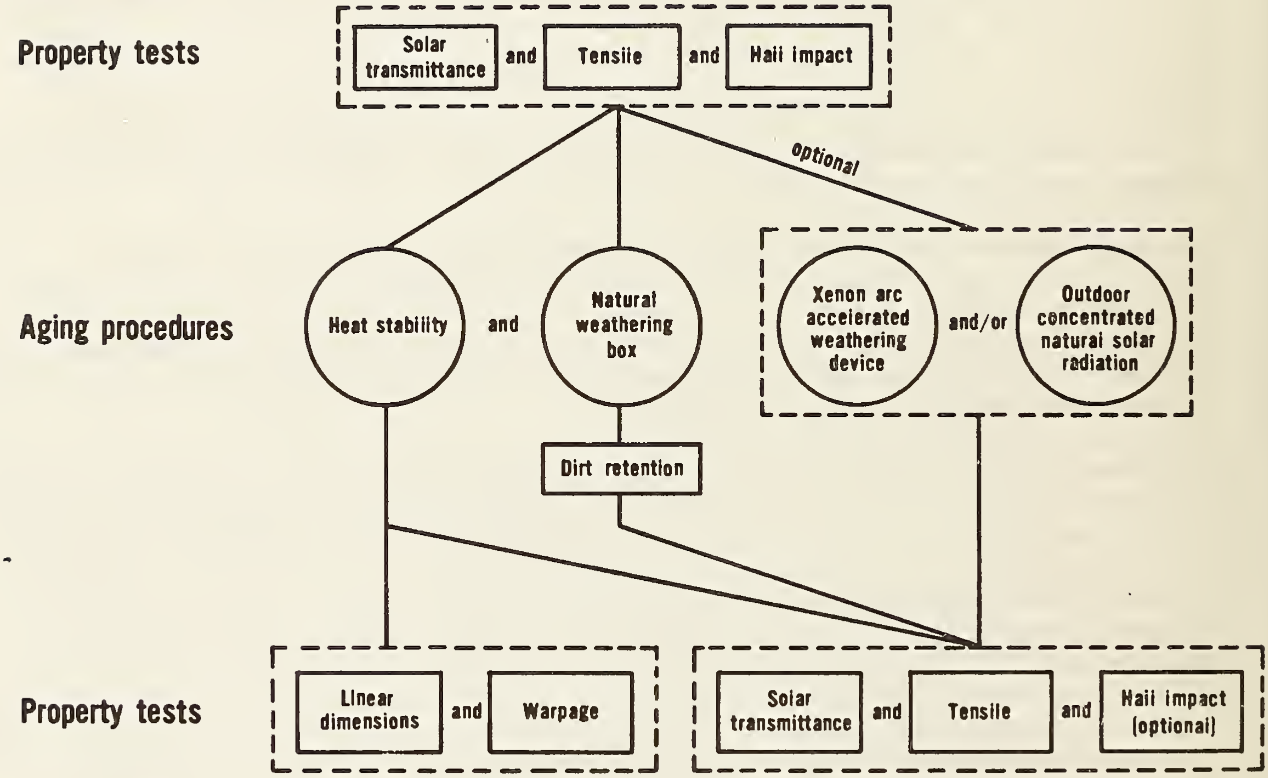
Determination of cover plate properties includes measurement of solar transmittance and effect of dirt on solar transmittance, as well as determination of dimensional stability, warpage, tensile properties, and hail impact resistance. Measurement of durability is specified by aging procedures, such as heat stability, natural and accelerated weathering, and outdoor exposure to concentrated natural solar radiation.

The standard also specifies procedures and sequencing for the various property measurement tests. Solar transmittance, tensile strength, impact resistance, initial warpage, and initial linear dimensions are to be measured before aging. After aging, solar transmittance, tensile strength, effect of dirt retention, warpage, and final linear dimensions are to be measured. Impact resistance should be measured after aging unless sample size limitations prevent this measurement. Solar transmittance, impact resistance, dimensional stability, and dirt retention should be measured on a minimum of three separate specimens at each exposure increment for each aging procedure. Table 16 provides a flow chart of the sequence for testing both properties and response to aging. The standard also requires the development of a test report which documents the solar collector cover plate materials, and the data obtained from the various testing procedures.

5.1.3.2 ASTM E 782-81

Standard Practice for Exposure of Cover Materials for Solar Collectors to Natural Weathering under Conditions Simulating Operational Mode [58] sets forth a procedure for evaluating cover plate materials, including both glass and plastics, that are exposed to natural weathering conditions which approximate normal operating (rather than stagnation) conditions. It outlines the use of a weathering box test fixture to elevate cover plate temperature (similar to the "mini-collectors" used by NBS [62]). Elevated temperatures are used with solar radiation since this combination may cause some cover plate materials to degrade more rapidly, thus allowing a more realistic assessment of material stability. The practice also provides guidelines for fabricating the weathering box to provide uniform exposure to minimize unwanted variation. The weathering box should be made of corrosion resistant metal with a weep hole for drainage. The interior should be coated with a flat black nonselective coating. Organic

Table 16. Flow Chart of Sequence for Testing Response to Aging (from Ref. 62)



materials should be eliminated from the interior to minimize outgassing. Mounting procedures are given for rigid and semi-rigid glazing, as well as films. Assembly procedures for the weathering box are also given.

The weathering boxes are to be mounted on weathering racks such as those described in ASTM Practice D 1435. The racks should be capable of angular adjustment with the axis of rotation on an east-west line. Rack tilt should be adjusted seasonally (at least four times a year) to maximize incident solar radiation. Although a period of exposure is not specified, the standard notes that repeated exposure at different seasons over a period of more than 1 year is needed. ASTM E 765 is referenced as a means of evaluating weathering effects.

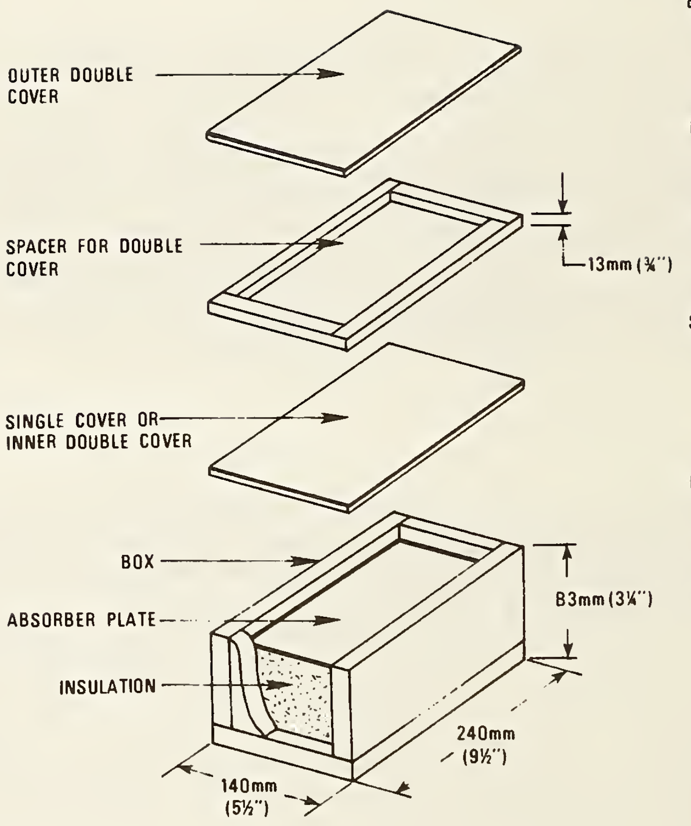
The practice also provides a procedure for mounting the weathering boxes on weathering racks capable of adjustment to variable angles throughout the year. Finally, it outlines the data to be collected by the weathering box procedure. These include identification of the collector plate material, material test configuration, mounting procedures, geographical and climatic factors, exposure duration, radiant exposure, monthly temperature mean and range, visual inspection data, and description of control specimens. Additional, optional data include monthly relative humidity range and mean, monthly and daily rainfall or dew, daily radiant energy and temperature range, wind direction and velocity, atmospheric conditions including air pollution, ultraviolet radiation, and maximum absorber plate temperature. Again, the reporting procedures are specified.

5.1.3.3 ASTM E 881-82

Standard Practice for Exposure of Solar Collector Cover Materials to Natural Weathering Under Conditions Simulating Stagnation Mode [59] provides a procedure for evaluating cover plate materials exposed to natural weathering at elevated temperatures approximating stagnation conditions. As such, it is a companion document to ASTM E 782-81, for evaluating both plastic and glass materials under normal operating conditions. It also uses a weathering box technique similar to that described in E 782-81. The practice sets forth the configuration for the weathering box, including a detailed appendix for determining the back and edge loss coefficient. Figure 36 presents a sketch of the weathering box. Procedures for natural weathering (under stagnation conditions) are given along with another appendix for calculating variable angle exposure schedule.

5.1.3.4 ASTM E 822-81

Standard Practice for Determining Resistance of Solar Collector Covers to Hail by Impact with Propelled Ice Balls [60] describes a procedure for assessing the ability of collector cover plates to withstand the impact of falling hail. Propelled ice balls are used to simulate hail. The data obtained by using the practice can be used to evaluate the impact resistance of a single material or collector, or to compare several collector covers, or to provide common data for selecting covers in a particular area. They can also be used to assess the effects of environmental conditions on changes in impact resistance.



MATERIALS:

BOX AND SPACER:

19mm (¾") WOOD PAINTED
WHITE ON OUTSIDE

INSULATION:

50mm (2") FIBERGLASS BLANKET

ABSORBER:

BLACK PORCELAIN ENAMEL
ON STEEL, $\alpha = .93$, $\epsilon = .85$

SEALANT:

RTV SUITABLE FOR OUTDOOR
EXPOSURE.

NOTE:

VENT HOLES WERE DRILLED
IN THE BOTTOM OF THE BOX
AND THE END OF THE SPACER
TO MINIMIZE MOISTURE
ACCUMULATION

Figure 36. Sketch of mini-collector (weathering box) for natural weathering exposure (from Ref. 62)

Standard Practice E 822-81 applies to rigid, semi-rigid, and flexible cover plate materials. It describes use of a launcher to propel an ice ball at a desired, calculated velocity with an accuracy of within ± 2.5 cm of the intended impact point. A test specimen may consist of a complete glazing assembly, complete solar panel, or section of cover plate material. Test base material and arrangement are specified. A pre-conditioning period of not less than 24 hours at 23 ± 2°C and 50 ± 5 percent relative humidity is specified for test materials. Testing must occur within one hour of preconditioning.

Ice ball size should correspond to hail size typical of a given location (as determined from local weather records or various publications referenced in the standard). Uniform, spherical, crack-free ice balls are made in molds stored in a freezer maintained at -12 ± 5°C. The velocity used in launching the ice ball must correspond to the ice ball diameter, however. A formula is given for calculating the resultant velocity. The launcher should be positioned so that the path of the ice ball will be essentially perpendicular to the cover plate material. Four impact points are specified, each in a corner 15 cm from both supporting edges. The test should be terminated when the cover plate material is totally destroyed. Launch velocity, iceball weight and diameter, and all observable effects should be recorded.

5.1.3.5 Proposed Revisions to ASTM E 424-71

Standard Test Methods for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials [61] specifies the procedures for measuring the solar energy transmittance and reflectance of materials in sheet form by two measuring instruments--a spectrophotometer and a pyranometer. Revisions to the calculations performed on the data collected with the spectrophotometer have already been discussed. These revisions are currently being considered by the E44 committee.

5.2 ABSORBER MATERIALS

5.2.1 Introduction

Absorber materials in solar heating and cooling systems are used to absorb radiant energy from the sun and convert it into thermal energy. For maximal efficiency, absorber materials should have high absorptance and low emittance, not only when first installed, but throughout the life of the solar collector.

Significant problems with absorber materials occurred in the solar demonstration programs conducted by the HUD and DOE. Field inspections by NBS personnel also revealed various problems [53]. Many of these problems can be attributed to prolonged exposure at stagnation conditions, as well as to thermal cycling, high levels of ultraviolet radiation, and moisture. As a result, NBS conducted a series of studies [69] which evaluated methods for assessing and screening absorber materials.

In these studies, Masters, Seiler, Embree, and Roberts [69] identified the prime performance requirements for absorber materials as:

- High absorption in the wavelength range of 0.3-3.5 nm
- Ability to maintain high absorption over extended time-periods
- Resistance to degradation resulting from:
  - --elevated temperatures
  - --temperature cycles
  - --ultraviolet radiation
  - --moisture
- Chemical and physical compatibility with other materials.

Degradation products should not affect performance of other collector materials.

The functional key properties of absorber materials include solar absorptance (α) and infrared emittance (ε). Key degradation factors include elevated temperature, temperature cycling, ultraviolet radiation, and moisture. Secondary degradation factors include freezing, oxygen, ozone, and airborne contaminants. These latter degradation factors were not included in the NBS research, however.

5.2.2 NBS Research

In the evaluation of performance requirements for absorber materials, NBS conducted laboratory (accelerated) and field (stagnation) weathering tests on 12 absorber materials used in solar applications [69]. These materials included:

- Nickel coated foil
- Anodized aluminum
- Copper oxide
- Black chrome
- Polyvinylidene fluoride (2 samples)
- Urethane
- Alkyd
- Silicone
- Modified polyester
- Epoxide
- Porcelain enamel

Substrates included steel, copper, and aluminum, but not all absorber materials were tested on all substrates. In the testing phase, properties of the materials were measured before and after a series of aging (conditioning) tests. The optical reflectance and absorptance of the absorber materials were determined by ASTM E 424-71 Method A [61]. Total normal infrared emittance was measured using ASTM E 408-71 [70]. These measurements were complemented with visual inspections.

The accelerated laboratory exposure tests assessed the effects of elevated temperature, thermal cycling, ultraviolet radiation, and moisture on absorber material performance. The results of oven aging at 150°C (302°F) for up to 14 weeks showed little effect on the absorptance of all absorber materials except for copper oxide and black chrome on copper. Exposure at higher temperatures (200° and 250°C) resulted in greater changes in absorptance and emittance for some specimens. Nine out of 26 specimens showed emittance changes of more than 0.01 unit (8 decreased, while 1 increased--polyvinylidene fluoride). One material--epoxide--decomposed on a copper/aluminum substrate but not on a steel substrate. After 12 weeks of exposure to 250°C, 10 specimens exhibited little or no change in absorptance, but 13 exhibited degradation or loss of adhesion. The three remaining specimens showed degradations in absorption, and two exhibited substantial degradation in emittance.

After 84 cycles of thermal cycling, a moderate reduction in absorption was observed in two specimens (copper oxide and black chrome on copper) and failure in nine specimens. Accelerated UV radiation of more than 2000 hours had little, if any, effect on the optical properties of the absorber materials.

It appears that both moisture tests--continuous exposure at 92° C and 97 percent relative humidity exposure to a moisture condensation cycle--induced the same degradation mechanisms, but that the condensation cycle was less severe. In neither test was the degradation in absorptance and emittance severe. However, the visual appearance of several specimens changed, due to surface corrosion. In one specimen, the coating lost adhesion after 21 weeks at 92°C and 97 percent relative humidity.

The cumulative exposure test was designed to study the effect of sequential exposure of the same specimen to oven aging, thermal cycling, UV radiation, and moisture. This test, however, was terminated after 28 thermal cycles because of the large number of failures. After 28 cycles, only specimens of anodized aluminum, copper oxide, black chrome on steel and on copper, polyvinylidene fluoride on steel and on aluminum remained intact. All other specimens had delaminated.

A second series of tests measured the effects of outdoor exposure on absorber materials. At all three sites studied, only small changes in absorptance and emittance were measured after outdoor exposure periods of up to five months. These data suggested that the laboratory tests provided more severe conditions. A test for outgassing showed that outgassing appeared to affect the transmittance of the cover glass only with polyvinylidene fluoride, urethane, and alkyd absorbers at 0.4, 1.8 and 5.5 percent, respectively.

The data collected in the NBS tests showed that elevated temperature, thermal cycling, and moisture can degrade some materials used as absorbers. Where specific degradation factors such as high temperature, thermal cycling, and moisture are likely to occur, the data indicated that accelerated aging tests can be used effectively in evaluating and screening absorber materials. The tests also indicated that degradation which can be observed visually does not always result in a change in absorption or emittance. Finally, little change was observed in the absorptance, emittance, and appearance of most test specimens exposed to outdoor weathering at three sites, since these conditions appeared to be less severe than the accelerated laboratory exposures. Exposure to elevated temperatures above 150°C (302°F) can identify polymeric materials that are susceptible to degradation from thermal decomposition. Thermal cycling can identify potential adhesion problems due to expansion and contraction. Cumulative exposure testing is a more severe test than exposure of test specimens to a single aging procedure. The data also indicate that the substrate to which the material is applied can affect its resistance to the exposure conditions.

Masters, Seiler, and Roberts [71] continued the evaluation of the performance of selected absorptive coatings for outdoor exposure at three sites. This study was designed to obtain additional data on the effects of stagnation conditions on absorptive coatings. Results from the additional outdoor exposure were compared with data from accelerated laboratory exposures reported earlier [69].

In the follow-on NBS research, test specimens (of both selective and nonselective absorptive coatings) were exposed outdoors at three sites with different climate conditions for about 24 months. Solar absorptance and infrared emittance were measured before exposure and at approximately four-month intervals. The same test materials were studied as in the earlier study. Three specimens of each material were exposed in the NBS mini-collectors, mentioned earlier. Again, tilt angle was adjusted seasonally, to expose the test materials to maximum solar radiation.

The authors found that the outdoor exposure data indicated that simulation stagnation conditions do degrade some materials used as absorber coatings. Degradation of optical properties and appearance was similar during both outdoor exposure and accelerated weathering. Some changes in properties for some coatings were observed during accelerated laboratory weathering, but not during outdoor exposure. These included moisture exposure, oven aging, and thermal cycling. The authors concluded that the accelerated laboratory procedures produce more severe conditions than the outdoor exposures. These data confirm that ASTM E 781-81 adequately addresses the problem of measuring the response of absorber coatings to outdoor weathering conditions.

5.2.3 ASTM Standards

5.2.3.1 ASTM E 744-80

Based on the results from the laboratory and field exposure tests, NBS submitted drafts for two proposed standards to Committee E44. The drafts contained methods for evaluating solar absorptive materials for thermal applications (E 744-80) and a procedure for determining the effect of outgassing on the transmittance of glass test plates (No ASTM Designation).

Standard Practice ASTM E 744-80 [72] provides a methodology for evaluating absorptive materials used in flat-plate or concentrating collectors with concentration ratios not to exceed 5. The practice does not apply to absorptive surfaces directly in contact with the heat transfer fluid, used in evacuated collectors, or in collectors without cover plates. The practice includes test methods for determining properties such as absorptance, emittance, and appearance, as well as aging tests for primary degradation factors as solar radiation, elevated temperatures, temperature cycles, and moisture. (In some geographical locations other factors, such as salt spray or dust erosion should be considered.) The practice includes two alternative testing methods: Method A, consisting of a series of laboratory tests to simulate various outdoor exposure conditions; and Method B, a single test for actual outdoor exposure. Either method may be used. Equivalency of the two methods through correlation of laboratory performance with actual in-service performance was not established, however. Figure 37 shows an outline for the two test method options. Both methods require that before and after the aging tests, absorptance, emittance, and appearance of the specimens be determined by ASTM E 424-Method A, by ASTM E 434, and by ASTM B 537, respectively. The aging tests in Method A consist of:

- A heating aging test at stagnation temperature for 500 hours.
- A temperature cycling test with stagnation temperature as maximum and -10°C as minimum. Thirty cycles at three hours are required.
- A moisture test by storing the specimens for 30 days at 90 ± 5°C and 95 ± 5 percent relative humidity.
- Exposure to ultraviolet light, using either outdoor exposure to direct sunlight reflected from a Fresnel concentrator, or a xenon arc or a filtered carbon arc lamp. Table 17 establishes the test conditions for the exposures.

These individual tests are conducted on separate specimens.

The aging test in Method B consists of exposure of the specimen for a minimum of 12 months to the outdoor environment in a unit simulating stagnation conditions for collectors with cover plates. This test is to be evaluated using ASTM E 781-81, to be discussed in the next section. Again, absorptance, emittance, and appearance are to be measured both before and after aging.

NBS also drafted a "Proposed Standard Practice for Determining the Effect of Outgassing on the Transmittance of Glass Test Plates Which Simulate Solar Collectors." This draft is discussed in references [69] and [74].

5.2.3.2 ASTM E 781-81

Although NBS did not develop a draft of ASTM E 781-81 [73], the research conducted by Masters, Seiler, and Roberts [71] was done specifically to provide a validation of the procedures described in Standard Practice for Evaluating Absorptive Solar Receiver Materials When Exposed to Conditions Simulating Stagnation in Solar Collectors with Cover Plates. Since the research demonstrated that the test procedures were, in fact, valid, they will be discussed in some detail here.

The practice provides a test procedure for evaluating absorptive solar receiver materials and coatings used in flat-plate collectors where maximum stagnation temperatures reach 200°C (392°F). It is intended to be a screening test for

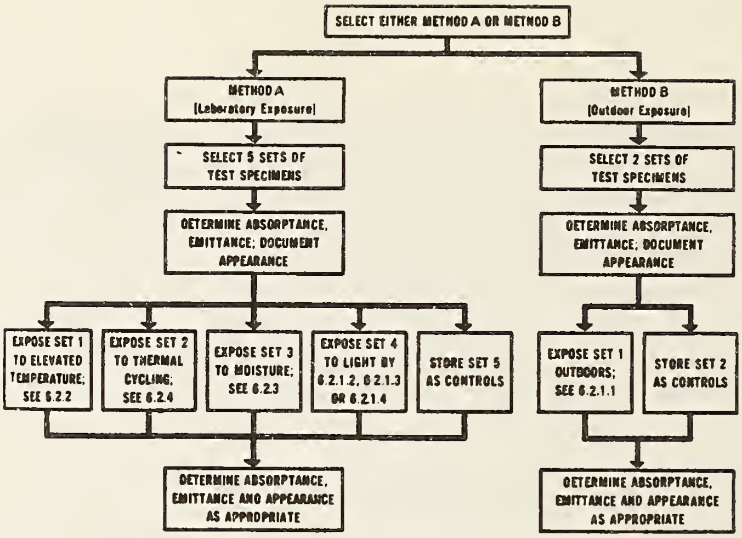


Figure 37. Outline of test method options (from Ref. 72)

Table 17. Exposure Test Conditions (from Ref. 72)

Conditions	Outdoor * exposure	Xenon Arc exposure	Carbon Arc exposure
Radiation Source	Concentrated Sunlight	Xenon Arc	Carbon Arc
Standard Practice (ASTM)	-----	G26	G23
Method	-----	A	A
Apparatus Type	Fresnel Mirror (8x)	A, AH, B, BH	E$^{(1)}$, EH
Filters	-----	Borosilicate$^{(2)}$	Borosilicate$^{(2)}$
Irradiance at 340 nm, Wm^2	-----	.55	-----
Radiant Energy Interval	Uncontrolled	Continuous	Continuous
Black Panel Temperature, °C	90 ± 5	90 ± 5	90 ± 5
Relative Humidity	Uncontrolled	Uncontrolled$^{(3)}$	Uncontrolled$^{(3)}$
Irradiation at 340 nm, kJ/m^2	-----	2970	-----
Exposure Interval, hours	1100	1500	1200

* using Fresnel concentration
(1) Water or air heaters may be required to maintain temperatures.
(2) Corning 7740 glass for Xenon Arc and 7058 glass for Carbon Arc is satisfactory.
(3) Operate with humidifier turned off.

absorber materials under conditions with single cover plates. It differentiates between test methods for selective and non-selective absorber materials.

The practice specifies a test apparatus, including an exposure box and conditions for its pre-exposure. It specifies characteristics for cover plates, seals, insulation, sample mounting plates, and condensation control. The practice provides guidelines for actual testing using two options. Option A allows test specimens to be removed, measured, and then returned to the test site. Option B calls for providing enough test specimens that can be replicated to permit withdrawals at preselected intervals without replacement. The standard notes that the cover plate should be cleaned if outgassing occurs.

The practice specifies mounting angles as a function of test site latitude. It also specifies that test specimens be exposed to a minimum total solar irradiation of 6.2×10^9 J/M^2 (essentially a 12-month period of normal solar radiation.) Solar absorptance, emittance, and general appearance are to be measured prior to exposure and at preselected intervals. Other measurements include daily temperature, total incident irradiation using a pyranometer, and cover plate spectral transmittance, solar absorptance of the test specimen, and appearance at specified intervals. The practice also calls for periodic maintenance of the test fixture.

The NBS research, as noted earlier, confirmed that the procedures given for exterior weathering appear to predict the performance of solar absorptive materials adequately.

5.3 COLLECTOR INSULATION

5.3.1 Introduction

Insulation for flat-plate solar collectors is designed to minimize heat loss from the back and sides of the collector enclosure. To do this, the insulation should have low thermal conductivity, dimensional stability, and chemical compatibility under environmental conditions which include variations of temperature, humidity, and solar radiation. The insulation must also not adversely affect other collector materials with which it is in contact or which it may otherwise affect.

Although there are many test methods for evaluating the performance of thermal insulation under normal conditions in buildings or industrial applications, Skoda and Masters [53] determined that the problems which occurred with insulation for solar collector materials were different from those commonly encountered in building applications. As a result, NBS conducted research to identify the critical in-service operating conditions and performance requirements, to determine appropriate test methods for evaluating representative insulation materials, and to draft procedures for screening insulation materials used in solar collectors.

Godette, Lee, and Fearn [75] identified the critical in-service conditions under which collector insulation must perform as the following:

- Sustained high or low temperatures, which vary from as high as 260°C (500°F) to as low as -40°C (-40°F).

- Diurnal temperature - humidity cycling.

- Condensation or accumulation of water within the collector.

- Continuous contact between the insulation and the components of the collector system.

The key properties of sucessful collector insulations were identified as: mass, size, density, water absorption, moisture absorption, thermal conductivity, and friability. The degradation factors were identified as: high and low temperature, water, high relative humidity, mold, and vibration. In addition, contact compatibility is an important factor.

5.3.2 NBS Research

To identify test methods that are most appropriate for evaluating commonly used insulation materials, particularly in terms of degradation, NBS studied 21 insulation materials using seven ASTM and four non-standardized tests [75]. The materials covered were:

- Mineral fibrous materials (glass, slag, rock, wool), in both batt and board form.

- Mineral cellular materials (calcium silicate, foamed glass, perlite, vermiculite), in performed tubular and in board form.

- Organic fibrous materials (cellulose, wood fiber), as loose fill and board.

- Organic cellular materials (polystyrene, polyurethane, ureaformaldehyde foams), as board, preformed tabular, and foamed-in place.

The following ASTM tests were conducted:

- C 167: "Thickness and Density of Blanket-or Batt-Type Thermal Insulating Materials."

- C 209: Section 13: "Testing Insulation Board (Cellulosic Fiber), Structural and Decorative: Water Adsorption."

- C 553: Section 15: "Mineral Fiber Blanket and Felt Insulation (Industrial Type): Moisture Adsorption."

- C 518: "Steady-State Thermal Transmission Properties by Means of Heat Flow Meter."

- C 411: "Hot Surface Performance of High-Temperature Thermal Insulation."

- C 356: "Linear Shrinkage of Preformed High-Temperature Thermal Insulation Subjected to Soaking Heat."
- D 3273: "Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber."

Non-standard tests were conducted for:

- Thermal cycling
- Outgassing
- Corrosion
- Friability (breaking up of material)

The test results indicated that, for the types of materials included, not all of the above 11 tests were appropriate for screening insulation materials. Those tests which are appropriate include the ASTM tests for: water absorption, thermal conductivity, linear shrinkage, and hot surface performance; and the newly developed tests for: corrosion, outgassing, and thermal cycling. The tests for density, moisture adsorption, resistance to mold growth, and friability were not found to be necessary, as these characteristics do not appear to be principal factors in the degradation of insulation.

5.3.3 ASTM E 861-82

Based on the laboratory research, NBS drafted a set of procedures for screening insulation materials for solar collectors. ASTM promulgated Standard Practice for Evaluating Thermal Insulation Materials for Use in Solar Collectors (ASTM E 861-82) [76], which relies heavily on the NBS draft procedure. This ASTM practice provides a methodology for screening solar collector insulation materials, in terms of their level of performance and relative stability under simulated in-service conditions. The test methods provide for the assessment of both the fundamental properties of the insulation, and the response to aging (degradation of test materials). The methods, which are designed to apply to all types of insulation, assess the effects of elevated temperatures, temperature cycles, and moisture on the degradation of insulation materials.

The practice stipulates the use of at least three representative specimens. These are to be maintained in a conditioned space at 24°C ± 2°C (73 ± 5°F) for at least 48 hours before testing. The practice provides a set of 10 tests for evaluating the degree of degradation of the insulation materials after exposure to simulated in-service conditions. These tests include methods for determining pH, surface burning characteristics, moisture adsorption and moisture absorption, thermal resistance, linear shrinkage, hot surface performance, chemical compatibility with adjoining material, outgassing, and durability.

Table 18 lists the tests and procedures to be followed. The purpose of this standard is to present various tests by which the performance of different insulation materials may be screened and compared. As a result, no criteria for performance levels are given.

Table 18. Tests and Procedures for Evaluating Thermal Insulation Materials for Solar Collectors [from Ref 76]

Preparation

Select 3 representative specimens for each sample
Condition at 24°C and 50 ± 5 percent relative humidity for 48 hours

Procedure (no sequence required)

1) Measure pH
2) Determine flame spread and smoke developed classifications
3) Determine moisture adsorption
4) Determine water absorption
5) Determine thermal resistance
6) Determine linear shrinkage (expansion) - at expected maximum in-service temperatures (including stagnation)
7) Determine hot-surface performance
8) Determine chemical compatibility with adjoining material following exposure to 49°C and 95 ± 3 percent relative humidity for 96 hours
9) Inspect for outgassing (no test method available)
10) Evaluate durability by determinng thermal resistance before and after accelerated aging
11) Examine specimens and note visible changes such as cracking, warpage, delamination, decomposition, and dimensional variation, as a function of aging.

5.4 GASKETS AND SEALANTS

5.4.1 Introduction

The primary function of rubber seals in solar energy systems is to seal or weatherproof joints between materials or components, and to do this over the design service life. Seals and gaskets must perform under exposure to elevated and depressed temperatures, temperature cycles, solar radiation, oxygen, ozone, and airborne pollutants. These seals must maintain sufficient elasticity and adhesion to substrates, and must not affect the performance of other materials which they contact.

While there are numerous test methods for sealants used in conventional building construction, none of these is totally adequate for the high temperatures encountered in solar energy applications. Existing standards seldom consider temperatures of building seals above 70°C. Yet, the temperature of solar collector materials can range from 150° to 250°C. Current standards also do not cover hydraulic seals exposed to certain heat transport and storage liquids at elevated temperatures. Skoda and Masters [53] observed rubber seal failures, such as loss of elasticity, bond failure, and outgassing, in numerous operational solar energy systems.

5.4.2 NBS Research

NBS conducted a study [74] to identify the performance requirements for rubber seals in solar energy systems. This study was also designed to: identify and assess existing test methods and develop new ones as needed; evaluate commercially available rubber seal materials; and draft proposed standard test methods, specifications, or practices for rubber seals for submission to ASTM for consideration as consensus standards.

The NBS research into the performance of sealants identified the following key properties and applicable ASTM test methods:

- Ultimate elongation - D 412
- Compression set - D 395, D 1229
- Hardness - D 1415, D 2240
- Tension strength - D 412
- Low temperature flexibility - C 711, C 734, C 765, D 2137
- Volatile content, condensible volatiles - D 865
- Adhesion - C 719

The key factors that affect the above properties and applicable ASTM test methods were identified as:

- Elevated temperatures - C 771, C 792, D 865
- Depressed temperature - D 1229, D 2137
- Ozone - D 1149
- Ultraviolet radiation - C 732, C 793
- Cyclic joint movement - C 719
- Contact with liquids - D 471

Based on the above assessment, three groups of tests were conducted. First, 15 samples of vulcanized sheets were submitted to the ASTM D-series described above. In addition, a modification of test D 865 was also performed to determine the total volatiles at 150°C and the volatiles condensible at 23°C. In addition, liquid immersion tests were conducted on rubber used in direct contact with typical heat transport and storage liquids. The second group of samples was tested according to modified methods of the ASTM C-series listed above.

The third testing procedure dealt with the problem of outgassing -- that is the degradation of materials within a solar collector and the subsequent deposition of products on the underside of the collector cover. Although the measurement of volatile condensibles gives an indication of the amount of material that might be deposited, it does not provide a means of determining the effect of the condensibles on the cover plate transmittance. Since no standard test method existed, a new method needed to be developed.

The new method calls for heating the specimen for 3 to 6 hours at 150°C in an enclosed chamber under a glass plate which is cooled by an air stream, and measuring the mass of the glass plate and test specimen, as well as the transmittance of the glass specimen, both before and after heating.

The results of the first series of tests (ASTM designations D) showed that several samples were not properly formulated to give optimum performance in solar collectors. On the other hand, several kinds of rubbers, when properly vulcanized, were shown to be suitable for use as seals in flat-plate solar collectors. Ethylene-vinyl acetate copolymer (EAM), terpolymer of ethylene, propylene and a diene (EPDM) (when properly formulated and vulcanized), and silicone copolymer (VMQ) were found to be suitable for use in all climates. Acrylate polymer (ACM) and fluoro-rubber (FKM), were found to be suitable for use in warm climates only. Chloro-sulfonyl-polyethelyne (CSM), copolymer of ethylene oxide and chloromethyl oxirane (ECO), and polychloromethyl oxirane (CO) have higher compression sets than desirable for performed gaskets. The polysulfide rubber (EOT) tested was found unsuitable since it melted at 150°C and in subsequent tests at 121°C. (It may be possible to develop improved satisfactorily performing formulations for the above unsuitable rubbers.)

In the immersion tests, only fluoro-rubber (FKM) performed satisfactorily in all liquids. In addition, chloro-sulfonyl-polyethylene (CSM), terpolymer of ethylene propylene and a diene (EPDM) (properly vulcanized), and silicone copolymer (VMQ) performed satisfactorily in polyalkylene glycol ether; silicone copolymer in polyaromatic and modified terphenyl; acrylate copolymer (ACM), ethylene-vinyl acetate copolymer (EAM), and terpolymer of ethylene propylene and a diene (EPDM) (properly formulated) in silicone liquids.

The results of the second group of tests (ASTM designations C) showed lower mass losses for silicone sealants than for polysulfide sealants (3.2 to 8.1 percent versus 4.0 to 13.6 and 11.8 to 21.0 percent, respectively).

The hardness values for silicone sealants were relatively independent from test temperatures and ranged from 27 to 44 after exposure. The hardness of polyurethane ranged from 45 to 69, and that of polysulfides from 0 to 65, with with two samples becoming harder and two softer.

Bond loss was rated as greater than or less than 25 percent. This value represents bond to an aluminum substrate and cohesive bond within the sealant. Four of six silicone samples had less than 25 percent bond loss, and two of five tested with glass had less than 25 percent loss. About one-half of the polysulfides showed less than 25 percent bond loss after exposure to 82°, 100°, and 121°C (179.6°, 212°, and 249.8°F). Of two polyurethane samples, one had greater and one less than 25 percent bond loss.

In accelerated weathering tests, none of the silicone sealants developed cracks after 1,000 hours UV exposure, nor did any cracks develop after the 180-degree bend tests at a temperature of -26°C. Only one of eight polysulfide sealants developed cracks after UV treatment, but five of the eight polysulfide samples developed cracks after the bond tests followed temperature treatments.

The tests indicated that silicone sealants might be the best choice for sealing joints around solar collectors where temperatures may reach 125°C (257°F). However, the tests also suggest that bonding properties of some silicone sealants to certain substrates are unsatisfactory. In applications where temperatures do not exceed 80°C, polysulfide and polyurethane sealants may be suitable.

The results of the tests on outgassing were insofar unexplainable, as percents of volatiles and condensibles measured after 3 and 6 hours did not in any way correlate with the values measured after 70 and 166 hours run according to the modified ASTM D 865 procedure. Table 19 provides a comparison of the test results. The results did indicate that the change in transmittance is not directly related to the gross weight of condensibles collected on the glass and that the change in transmittance is more related to the chemical composition of the condensibles.

5.4.3 ASTM Standards

The NBS research [74] determined that the performance of the various rubber materials varied widely, depending on the laboratory test used. Based on these results, five proposed standards on rubber seals in solar systems were submitted to ASTM Committee D11 on Rubber. Three of the standards have subsequently been accepted. Each standard will be discussed in turn.

5.4.3.1 ASTM D 3667-78

Standard Specification for Rubber Seals in Flat-Plate Solar Collectors [77] defines two types of seals: one to be used in all climates (Type C) and the other to be used only where minimum temperatures are above -10°C (Type W). It also specifies six hardness grades for preformed rubber seals and three hardness grades for sealing compounds.

Requirements for preformed seals include assessment of: minimum elongation for each grade; compression set after heating at 150°C for 70 hours to determine

Table 19. Results of Outgassing Tests for Materials Used to Seal Flat-Plate Solar Collectors (from Ref. 74)

Sample Number	Type	Results of Modified ASTM D865				Results of Tests on Effects of Outgassing					
		Volatiles (%)		Condensibles (%)		Volatiles (%)		Condensibles (%)		Change in Transmittance1/	
		70 hrs	166 hrs	70 hrs	166 hrs	3 hrs	6 hrs	3 hrs	6 hrs	3 hrs	6 hrs
4	FKM	2.53	2.66	0.04	0.02	0.16	0.18	0.0	0.0	0.0	0.0
5	EPDM	0.39	0.45	0.03	0.08	0.25	0.40	0.04	0.10	1.4	2.3
7	EPDM	0.84	0.98	0.04	0.05	0.95	1.21	0.15	0.25	0.8	0.8
8	EPDM	0.69	0.71	0.61	0.56	0.73	1.02	0.07	0.16	0.9	0.8
12	VMQ	0.10	0.04	0.03	0.04	0.13	0.69	0.01	0.02	1.0	1.5

1/ Integrated transmittance from 300 to 2100 nm.

that the seal will be effective for extended service periods; compression set after cooling at -10°C for 166 hours to determine that rubber crystallization does not result in air leaks; resistance to heating and ozone to determine that seal deterioration will be slow; resistance to low temperatures (-40°C) for Type C seals; and measurement of total volatile and condensible matter (to determine the amount of material that could cause fogging of the cover plates and reduce transmittance of solar energy).

While the performance requirements for sealing compounds are similar to those for preformed seals, there are some differences. First, requirements for compression set are not applicable. A lower temperature (125°C, 257°F) is also used to test for resistance to heating of sealing compounds. An adhesion requirement, however, is included to assure maintenance of the seal during repeated thermal expansion and contraction within the solar collector. ASTM Standard D 3667-78 provides general requirements for materials used in rubber seals for flat-plate, non-vertically mounted solar collectors. Its requirements pertain only to permissible deflections of rubber during thermal expansion and contraction, and to tolerances for dimensions. It does not contain requirements for the fabrication or installation of rubber seals. The standard classifies materials by: types for a given climate (C for cold climates and W for warm climates); grades of hardness (7); and classes, whether preformed (PS) or a sealing compound (SC). It specifies that the permissible deflection of the seal during thermal expansion and contraction be no more than 25 percent in any direction. It references the RMA Handbook [78] for dimensional tolerances. The standard also addresses workmanship, sampling and inspection, marking, and packaging requirements.

The standard specifies that class SC materials should be prepared in 150 by 150 by 2 mm sheets, and adhesions specimens in accordance with Method C 719. Each sheet and specimen should be conditioned for 14 days at a temperature of 23°C (73.4°F) and relative humidity of 50 percent.

Both PS and SC materials should be heated for 166 hours at the appropriate temperature to determine volatiles lost (by comparing differences in mass both before and after.) Volatiles condensible at 23°C (73.4°F) following heating for 166 hours should also be determined. The standard specifies a series of test methods for both preformed seals and sealing compounds. Test methods for preformed seals (PS) include: ultimate elongation, compression set as a function of elapsed time and temperature, and resistance to heating, ozone, and low temperature. Test methods for sealing compounds (SC) address: ultimate elongation, adhesion loss, and resistance to heating, ozone, and low temperatures. Performance criteria for each test as a function of the grade of the material are given in table 20 for preformed gaskets and table 21 for sealing compounds. In addition to the test methods, the standard contains requirements for number and sizes of specimens and their conditioning.

5.4.3.2 ASTM D 3771-79

Standard Specification for Rubber Seals Used in Concentrating Solar Collectors [79], which was drafted by NBS, is also very similar to the specification for rubber seals used in flat-plate collectors. The only major difference is that use of a maximum service temperature is specified instead of a specific

Table 20. Requirements for Class PS Materials Used to Seal Flat-Plate Solar Collectors (from Ref. 77)

Property	Grade						Method
	3	4	5	6	7	8	
Ultimate Elongation-% min	350	300	250	200	150	100	D412
Compression Set-% max							
after 70 h at 150°C	30	30	30	30	30	30	D395[a]
after 166 h at -10°C	60	60	60	60	60	60	D1229[b]
Resistance to Heating (166 h at 150°C)[c]							D865
Hardness change, max	10	10	10	10	10	10	D1415 or D2240
Ultimate Elongation Change-% max	30	30	30	30	30	30	D412
Tensile Strength Change-% max	20	20	20	20	20	20	D412
Volatiles lost-% max	1	1	1	1	1	1	See TEXT
Volatiles condensible -% max	0.1	0.1	0.1	0.1	0.1	0.1	See TEXT
Resistance to Ozone							D1149
100 mPa, 166 h at 40°C	No Cracking						
Resistance to Low Temperature							D2137
Type C only, °C max	-40	-40	-40	-40	-40	-40	

[a] Method B

[b] Set to be measured at 10 seconds after release. Lubricated plates or polytetrafluoroethylene film is recommended if the rubber adheres to the metal compression plates during test.

[c] The test temperature of 150°C is used to test seals for cover plates. A seal in contact with an absorber plate should be tested at a standard test temperature listed in ASTM D1349 next above the maximum temperature of the absorber plate in service (which generally occurs under stagnation conditions and maximum radiation flux) but not less than 150°C. The higher test temperatures are: 175, 200, 225 and 250°C.

Table 21. Requirements for Class SC Material Used to Seal Flat-Plate Solar Collectors (from Ref. 77)

Property	Grade 2	Grade 3	Grade 4	Method
Ultimate Elongation, % min	200	150	100	D412
Resistance to Heating (166 h at 125°C)				D865
Hardness Change, max	10	10	10	C661
Ultimate Elongation Change, % max	30	30	30	D412
Tensile Strength Change, % max	20	20	20	D412
Volatiles Lost, % max	1	1	1	See TEXT[a]
Volatiles Condensible, % max	0.1	0.1	0.1	See TEXT[a]
Resistance to Ozone				D1149
100 mPa, 166 h at 40°C	No Cracking			
Resistance to Low Temperature				D2137
Type C only, °C max	-40	-40	-40	
Adhesion loss (-cm^2 max)[b]	9	9	9	C719[c]

[a] The test is not required if the design precludes condensing of the volatiles on the cover plates(s) of the solar collector.

[b] The combined loss in bond and cohesion areas for the three specimens tested shall not exceed 9 cm^2.

[c] The temperature in 6.3 of ASTM C719 shall be modified to 125°C.

temperature level for heat aging in compression set tests, and in resistance to heating tests for both PS and SC materials. The maximum service temperature normally occurs when the collector is under stagnation conditions, and is receiving the maximum radiation flux to which it will be exposed.

5.4.3.3 ASTM D 3832-79

ASTM Specification for Rubber Seals Contacting Liquids in Solar Energy Systems [80] contains general requirements for materials to be used in preformed rubber seals which contact circulating liquid in solar energy systems. It establishes six grades of hardness for preformed rubber seals, and two temperature types (C and W). It provides for three classes: Class A, seals for use with aqueous liquids at a maximum service temperature of 100°C (212°F); Class AT, seals for use with aqueous liquids at a maximum service temperature above 100°C (212°F); and Class N, seals for use with nonaqueous liquids.

The standard specifies that test specimens be vulcanized, conform to dimensional tolerances given in the RMA Handbook, and be free of blisters, checks, cracks, and similar imperfections. These specimens must be tested for: minimum (ultimate) elongation as a function of grade; compression set after exposure to elevated temperature for 70 hours and low temperature for 166 hours; resistance to heating and ozone; resistance to low temperatures for type C materials; and resistance to immersion in the liquid used for the particular heat transport system. Performance requirements for these various tests are given in tables 22 and 23.

The standard suggests slightly different temperatures as a function of class. Thus, Class A seals are to be tested for heat resistance and compression set at a temperature of 125°C (257°F) and for resistance to liquids at 100°C (212°F). Class AT and Class N seals are to be tested for heat resistance and compression set at the standard test temperature (specified by ASTM D 1349 to be 25-49°C above the maximum service temperature). These seals are to be tested for liquid resistance at a temperature between 1° to 25°C above the maximum service temperature. Test temperatures for Class AT and N materials are always to be higher than those for Class A seals. The standard specifies procedures for preparing materials for testing, and provides test methods and criteria. These test methods include tests for ultimate elongation as a function of grade, compression set for both high and low temperatures, and resistance to heating, ozone, low temperature, and liquid. The standard provides temperatures to be used in determining heat resistance, resistance to liquids, and compression set tests. The liquid used for the test is specified to be the same as that used in service for the particular system.

5.4.3.4 Proposed Test Method for Outgassing

In the course of the research on the performance characteristics of rubber seals [74], NBS also developed a method for determining effect of outgassing on the transmittance of solar collector covers. This test method was submitted to the ASTM Committee D11 for consideration as a voluntary consensus standard. This committee is currently working with Committee E21 to draw on the methods presently being used in the aerospace industry in developing an outgassing test.

Table 22. Elongation Requirements for Rubber Seals in Liquid Heat - Transport Systems (from Ref. 80)

Grade	Ultimate Elongation percent, minimum
3	350
4	300
5	250
6	200
7	150
8	100

Table 23. Other Requirements for Rubber Seals in Liquid Heat - Transport Systems (from Ref. 80)

Property	Unit	Requirement	ASTM Method
Compression Set			
High temperature[a]	%	30 maximum	D 395, Method B
Low temperature[b]	%	60 maximum	D 1229
Resistance to Heating			
Hardness change[a]	IRHD	10 maximum	D 1415
Ultimate elongation[a] change	% of original	30 maximum	D 412
Resistance to Ozone[c]	-	no cracking	D 1149
Resistance to Low Temperature[d]	°C	-40 maximum	D 2137
Resistance to Liquid[a]			
Volume change	%	+40 to -10	D 471
Hardness change	IRHD	±10	D 1415

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[a] Exposure time and temperature specified in proposed specification.

[b] After compression for 166 hrs. at -10°C. Set shall be measured at 10 sec. after force is released. Lubrication plates or polytetrafluoroethylene film is recommended if the rubber adheres to the metal plates during test.

[c] This requirement does not apply to seals that are not exposed to outside atmospheres.

[d] This requirement applies to Type C seals only.

The procedure outlined in the method proposed by NBS includes heating the specimen in a closed container and collecting the condensible decomposition products on a glass plate. The transmittance of the glass plate is measured (according to ASTM E 424-71) from 300 to 2100 nm (in increments of 50 nm) before and after heating. The mass loss of the specimen and the heating gain of the glass plate must also be determined. Although the test was developed primarily for evaluating rubber seal materials, it can also be used in the evaluation of absorber materials (see section 5.2).

5.4.3.5 Proposed Recommendations for Sealing Joints with Rubber Seals

While the various specifications for rubber seals specifically excluded requirements for the installation and fabrication of sealing materials, NBS also recognized that correct application methods are essential for proper performance of installed seals, and that improper installation can lead to poor seal performance, even for excellent materials.

Because seals used for various solar energy applications are required to perform under more rigorous conditions than seals generally used in building construction, NBS developed a draft recommended practice [74]. These recommendations apply only to the joints used in solar collectors and require that the sealants meet Federal Specifications TT-S-00230C (COM-NBS), TS-S-00227E (COM-NBS), and TS-S-001543A (COM-NBS).

The NBS recommendations [74] provide suggested installation practices for liquid applied seals. The practice stresses the need to ensure that the joint to be sealed be dry and free of dust, dirt, oil or grease. It states that only primers recommended by the sealant manufacturer should be used. Along with recommending installation methods dependent on whether the sealant is in cartridge or bulk form, the recommendation specifies that the sealant should not be applied at temperatures below 4.4°C (40°F), and that the joint should be tooled as soon as possible after application. The practice also requires that sealants should not be placed in a joint if the sealant material has begun to cure.

5.5 RUBBER HOSE

5.5.1 Introduction

The primary function of rubber hose for solar energy systems is to transport heat transfer fluid between various components of the collector. Rubber hose is used because it is flexible, and will easily accommodate some misalignment. Furthermore, it absorbs vibration, dampens sound transmission, is economical, and does not place high stresses on the connected components. However, rubber hose is also susceptible to leakage at connections, has an uncertain life expectancy in the severe environment of solar energy systems, and may require maintenance and replacement, which are often difficult. It may also not be compatible with heat transfer fluids or with connector materials, and is not suitable for use above certain temperatures.

Although there are standards for rubber hose for specific industries such as the automotive or petroleum industries, these standards do not address the particular needs of solar installations. Therefore, NBS conducted a study [81] to assess the performance requirements needed for developing standards and test methods for rubber hose in solar systems.

5.5.2 NBS Research

As a first step, NBS identified the properties that significantly affect the performance of rubber hose in solar applications. The study also identified applicable ASTM standards. The most relevant properties and test methods included [81]:

- Tensile strength and ultimate elongation, both of the inner lining and the outer rubber cover - D 142,
- Flexibility at low temperatures - no standard test,
- Fluid compatibility - no standard test,
- Resistance to air aging - D 573,
- Resistance to ozone - D 380 and D 1149,
- Water vapor transmission - no standard test,
- Compression set - D 395 modified,
- Bursting pressure - D 38,
- Resistance of reinforcement fiber to degradation from the heat transfer fluid at service temperature - no applicable standard test.

The laboratory work consisted of conducting tests on 11 rubber hoses, and 1 polytetra-fluorethylene (PTFE) hose. None of these hoses were specifically designed for use in solar energy systems. The specimens, produced by seven manufacturers, were made of Chloroprene rubber (CR)[2] (Neoprene), Terpolymer of Ethylene, Propylene, and a Diene (EPDM), and silicone rubber having both methyl and vinyl groups on the polymer chain (VMQ).

Since applicable test methods were not currently available for all relevant properties, NBS developed an apparatus for assessing the performance of rubber hose. The apparatus consisted of two circulating systems mounted in an enclosure. One system was constructed of steel and stainless steel, the other of brass and copper. The major components of each system are shown in figure 38. The concept of the tests was to circulate alternatively, hot (100°C, 212°F), fluid (Ethylene Glycol - water mixture) under 125 to 150 kPa pressure and cold (7°C to -40°C) fluid at ambient pressures. The tests were run for slightly over 7 months. Specimens that failed were replaced by fresh specimens, cut from the same hose. The results of the tests are given in table 24. As can be seen, specimens 3, 4, and 5 deteriorated substantially under the conditions of this test. Of the seven hoses that did not fail during the entire period, all but three showed leaks at the hose lamps. (Four different clamps were used - one of which, a plain clamp, showed markedly more failures.) The CR hose produced more leaks at the clamp than any other (and for all clamps), although the specimen did not fail otherwise.

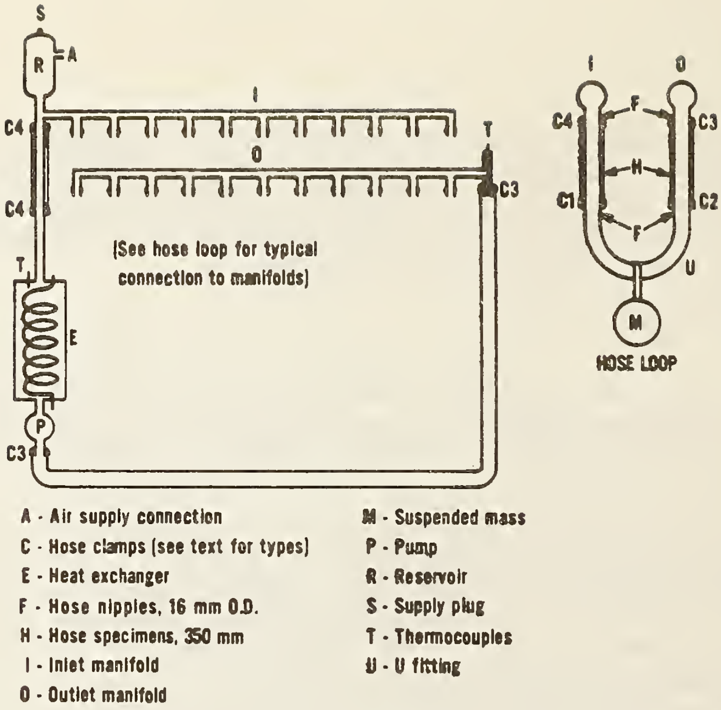

Figure 38. Schematic of circulatory system for performance test apparatus (from Ref. 81)

Table 24. Hose Dimensions, Specimen Failures, and Leaks at Clamps (from Ref. 81)

Hose	Type	Bore	Wall	Specimens	Leaks at Clamps[a]			
		mm	mm	No. failed	C1[b]	C2	C3	C4
1[c]	EPDM	15.8	3.9	0	1	14	3	1
2	EPDM	16.2	4.3	2	1	20	5	4
3	EPDM	15.0	4.2	4	0	3	0	1
4	EPDM	15.4	3.8	6	0	4	1	1
5	EPDM	15.4	4.0	4	3	21	1	7
6	EPDM	15.5	5.1	0	0	0	0	0
7[c]	CR[d]	15.1	5.0	0	2	32	1	2
8	VMQ	16.0	4.3	0	0	0	0	4
9	VMQ	15.7	4.8	0	0	0	0	0
10	VMQ	16.9	5.2	1	2	-	4	2
11	PTFE	16.2	1.7	0	e	e	e	e
12	EPDM	19.9	4.6	0	-	-	-	5

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[a] C1 - Banded clamp; C2-Plain clamp; C3-Screw clamp; C4-Screw clamp with internal band.

[b] When a leak occurred at a banded connection, a screw clamp was applied adjacent to the band.

[c] Hose was purchased locally. Other hoses were supplied by the manufactures.

[d] CR cover; type of rubber in lining is not known.

[e] Special fittings are required with the stainless steel braided hose. None of these connections leaked.

Additional tests were conducted on the seven hoses for ozone resistance, compression set, water vapor transmission, and bursting pressure.

ASTM D 380 and D 1149 were used for ozone resistance. Numerous cracks were observed on the edge of the CR (Neoprene) hose in tension. No cracking was visible on the other hoses.

A modification of ASTM D 395 was used for compression set. The results were shown in table 25. As can be seen from the table, the EPDM and CR hoses 1 through 7 had 100 percent compression set. The VMQ hoses 8 and 9 had high set, but there was still some compression stress after the 94 and 166 hour test. Only the VMQ hose 10 had low compression set even after the 190 hour test. (A high resilience EPDM hose was received too late and was submitted only to the 166 hour test; it had a set comparable to the VMQ hose.)

A non-standard method was used for water vapor transmission. The test consisted of comparing the weight loss of filled and unfilled, sealed hose segments before and after subjecting them to temperatures of 100 ± 1°C. Readings were taken daily for 7 days. In two tests, the hoses were filled with distilled water, and in a third test, an ethylene glycol/water mixture was used. The lowest transmission losses were observed for PTFE, and the highest for VMQ, approximately 25 times that for PTFE. EPDM showed losses about five times of those for PTFE. In test 3 (hoses filled with the glycol-water mixture), the water vapor transmission was similar to the water-filled hoses. For CR, however, the loss was less than one-half.

Since the hoses in the water vapor transmission test were closed off with plugs of different metals, the test on hoses filled with distilled water served to evaluate the compatibility of the metals with the hoses. The results are shown in table 26.

ASTM D 380 was followed for bursting pressure. Results from the tests which were conducted on hoses used in the water vapor transmission tests are summarized in table 27. From the table, it can be seen that all rubber hoses lost strength in the performance test. For example, the values for hose 12 (EPDM) decreased from 7500 to 550 kPa, a loss of over 90 percent. The values for VMQ hoses tended to decrease less in the performance test than those for other hoses. This difference may be attributable to the reinforcement material in those hoses. Some (but not all) of the EPDM hoses showed a loss of approximately 30 percent for hoses that previously were subjected to the water vapor transmission tests.

The laboratory work indicated that tests were available, or could be devised, to assess all performance requirements for rubber hose used in solar energy systems, except deterioration of reinforcing materials. (The behavior of fibers under various conditions is known, however, or can be established. Fibers which deteriorate excessively under service conditions should not be used as reinforcing materials.)

Table 25. Compression Set (from Ref. 81)

Hose	Type	Compression Set at 100°C - Percent		
		94 h	166 h	190 h
1	EPDM	100+	100+	100+
2	EPDM	100+	100+	100+
3	EPDM	100+	100+	100+
4	EPDM	100+	100+	100+
5	EPDM	100+	100+	100+
6	EPDM	100+	96	100+
7	CR	93	100+	100+
8	VMQ	99	84	100+
9	VMQ	39	72	100+
10	VMQ	5	32	33
11	PTFE	Test is not applicable		
12	EPDM	100+	100+	100+
13[a]	EPDM	-	87	-

[+] Compression set is over 100 percent.

[a] Hose received after performance test on other hoses were completed.

Table 26. Effect of Hose on Metal Plugs in Water Vapor Transmission Tests (166 Hours at 100°C) (from Ref. 81)

Hose	Aluminum	Brass	Steel
	Test 2	Test 1	Test 1
1	c	-	-
2	c	d	e
3	b	c	c
4	b	c	c
5	c	c	d
6	b	d	e
7	d	c	a
8	a	b	f
9	c	c	f
10	f	b	f
11	-	-	-
12	b	d	a
13	-	d	c

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[a] clean or nearly clean
[b] very slight discoloration
[c] slight discoloration
[d] dark discoloration
[e] slight corrosion
[f] corrosion

Table 27. Bursting Pressures (from Ref. 81)

Hose	Type	Bursting Pressures in kPa					
		a	b	c	d	e	f
1	EPDM		2210	1240	1100	1240	970
2	EPDM	7000+	5930	1100*	6620*	970	970
3	EPDM	2340	1240	1380*	830*	2000*	2340*
4	EPDM	3310	2620	1240*	830*	--	1100*
5	EPDM	3030	2620	2260*	1380	2380*	830
6	EPDM	7000+	7000+	3100	6760	2140	2620
7	CR	6070	6270	2340	2070	1720	970
8	VMQ	2480	1930	1380	2480	1650	1310
9	VMQ	4830	4270	4410	3450	3720	3720
10	VMQ	7500	7500+	4900	5790	5790	6760*
11	PTFE			not tested			
12	EPDM	7500+	7500+	550	--	690	--
13	EPDM	3450	3450	--	--	--	--

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[a] Specimens used as blanks and heated at 100°C for 166 h.

[b] Specimen used for water vapor transmission and heating at 100°C for 166 h.

[c] Specimens connected to inlet manifold of brass and copper system.

[d] Specimens connected to outlet manifold of brass and copper system.

[e] Specimens connected to inlet manifold of steel system.

[f] Specimens connected to outlet manifold of steel system.

[*] Replacement specimens.

[+] Specimen did not fail at this pressure.

5.5.3 ASTM Standards

5.5.3.1 ASTM D 3952-80

Based on the laboratory results, NBS drafted a Specification for Rubber Hose Used in Solar Energy Systems. This draft was adopted as ASTM Standard D 3952-80 [82].

The standard provides performance requirements for evaluating rubber hose used to transport liquids in solar energy systems. It specifically excludes plastic hoses, as well as general fabrication and installation requirements from its scope. It establishes classes for different fluids (aqueous and nonaqueous), fluid temperatures (above or below 100°C, 212°F), and types based on climate (C, below -10°C in winter; and W, above -10°C in winter). It also specifies eight standard sizes, and establishes tolerances for both internal diameter and length. It further specifies that the hose shall consist of an inner tube, reinforcement, and an outer cover, and provides requirements for each of the three components.

The test methods for the tube/cover assembly given in table 28 require assessment of ultimate elongation, tensile strength, and resistance to heating, heat transfer fluid, ozone, and low temperature. Test methods for the composite hose, given in table 29, require determination of compression set, bursting pressure, vapor transmission rate, corrosion of metals, effect on fluid, and stability of reinforcement. These two tables also specify the level of performance to be met by the test specimens.

In table 28, general reference is made to ASTM D 380 for testing. In table 29, D 395 (modified) is to be used for compression set, and D 380 is specified for bursting pressure. The procedures used in the NBS laboratory work are outlined and required for determining vapor transmission rate and its effect on metals and fluids. These procedures require heating Class A or AT specimens in an oven to 100° ± 1°C and Class N at a standard temperature for 1 day, determining the mass, heating for 6 more days, and determining the mass again. A new procedure is given for determining stability of reinforcement. This consists basically of heating (for 6 months) filled-hose segments at 100° ± 2°C (for Class A and AT), or at the temperature specified in ASTM D 1349 (for Class N), and then conducting bursting pressure tests on the heated and on non-heated specimens. An annex to the standard provides general provisions and guidelines for the connection of rubber hose to solar energy systems.

5.5.3.2 Proposed Revision to ASTM Standard D 3952-80

In response to a negative committee ballot in the vote to approve D 3952-80 [82], NBS studied the need to test hose linings immersed in aqueous liquids above their boiling point. This research [83] included the design of the testing apparatus, the conduct of interlaboratory tests on typical hose linings immersed at liquids at 150°C, comparative tests at 100°C, in accordance with ASTM D 471, and preparation of a proposed revision to the existing standard. Although ASTM D 454 and D 572 require pressure vessels that can be used for

Table 28. Requirements for Tube/Cover Assembly [from Ref. 82]

Property	Requirement
Ultimate elongation, min. %	250
Tensile strength, min. MPa	6.2
psi	900
Resistance to heating[a]	
Change in ultimate elongation, max. %	-40
Change in tensile strength, max. %	-20
Resistance to heat transfer fluid[b]	
Change in ultimate elongation, max. %	±25
Change in tensile strength, max. %	±25
Change in hardness, max.	±10
Change in volume, max. %	±15
Resistance to ozone of outer cover, 100 mPa[c], for 166 h at 40°C	no cracking
Resistance to low temperature, Type C hose only, -40°C	no cracking

[a] Class A shall be heated at 125 ± 2°C (for 166 ± 2 h. Class AT and N hose shall be heated for 166 ± 2 h at a standard temperature in accordance with Recommended Practice D 1349, that is, between 25 and 49°C above the maximum service temperature, but not less than 125°C. These test temperatures are: 125, 150, 175, 200, 225, and 250°C.

[b] The inner tube of Class A and AT hose shall be immersed in a mixture containing equal volumes of ethylene glycol and water for 166 ± 2 h at 100 ± 2°C. The inner tube of Class N hose shall be immersed in heat transfer fluid used in the solar energy system for 166 ± 2 h at a standard test temperature in accordance with Recommended Practice D 1349 next above the maximum service temperature, but not less than 100°C. If the vapor pressure of the fluid is above atmospheric pressure at the test temperature, the next lower standard test temperature shall be used. (A method is being considered in Subcommittee D11.31 that would subject the inner tube of the hose to volatile fluids above their boiling point in pressure vessels so that the inner tube can be tested above the maximum service temperature regardless of fluids used.)

[c] 100 MPa ozone partial pressure is equivalent to 100 pphm at standard atmospheric pressure of 100 kPa.

Table 29. Requirements for Composite Hose [from Ref. 82]

Property	Requirement
Compression set, max. %	85[a]
Bursting pressure, min.	5 times working pressure
Vapor transmission, rate, max. μg/(m·s)	3.5[b,c]
Effect on aluminum, brass, copper, and steel	no corrosion[d]
Effect on fluid	no sediment or dark discoloration[e]
Stability of reinforcement, maximum decrease in bursting pressure, %	50

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[a] Compression set is measured after conditioning under 25 percent compression for 166 ± 2 h at 100 ± 2°C for Class A hose and at the standard test temperature in accordance with Recommended Practice D1349, that is, between 25 and 49°C above the maximum service temperature but not less than 125°C. These test temperatures are: 125, 150, 175, 200, 225, and 250°C.

[b] Equivalent to 0.9 g/day for a specimen having an internal length of 300 mm between plugs.

[c] The requirement for Class N hose with specified fluids should be agreed upon between the manufacturer and the purchaser of the hose.

[d] Condition of the plugs at the end of the test for vapor transmission rate. Discoloration of the plugs without corrosion is permitted.

[e] Condition of the fluid at the end of the test for vapor transmission rate. Slight cloudiness or slight discoloration is permitted.

testing rubber hose, these vessels are expensive, and not generally available. As a result, NBS designed the pressure vessel shown in figure 39. This vessel, which holds seven test tubes, each 38 mm in outside diameter and about 300 mm long, also contains a pressure relief valve that opens at about 1000 kPa.

In the NBS research, 15 specimens were cut from each of six commercially available hose linings, and allocated to participating laboratories. These specimens were randomly selected for each treatment.

The mass of each specimen was determined before and after immersion and heating. The tensile strength and ultimate elongation of the untreated and treated specimens were also determined. In all tests, the change in mass was between 1.1 and 7.2 percent. This change was not considered sufficient to affect the use of hose in solar energy systems. Change in tensile strength was within the 20 percent range (considered acceptable), except for one vulcanizate, in which the change after immersion at 150°C (302°F) was in the 50 to 70 percent range. The change in ultimate elongation was generally within a 20 percent range, except for one vulcanizate, for which the change at 150°C was in the 20 to 60 percent range. The large changes in tensile strength and elongation were observed for the same vulcanizate.

The results of the test series indicated that the temperature and time of immersion was not critical for good vulcanizates, but that for some vulcanizates, the test results obtained at 100°C (212°F) could be misleading if those specimens are to be used at 150°C (302°F). As a result, NBS recommended a revision to ASTM D 3952-80. This revision would be in the form of a footnote to table 28. Footnote B requires that the inner tube be immersed in the liquid contained in a pressure vessel at least 20°C above the maximum service temperature. ASTM D 3952-80 currently allows a lower test temperature if the vapor pressure is above atmospheric pressure. As of this writing, the proposed revision is still being considered by ASTM Subcommittee D11.31.

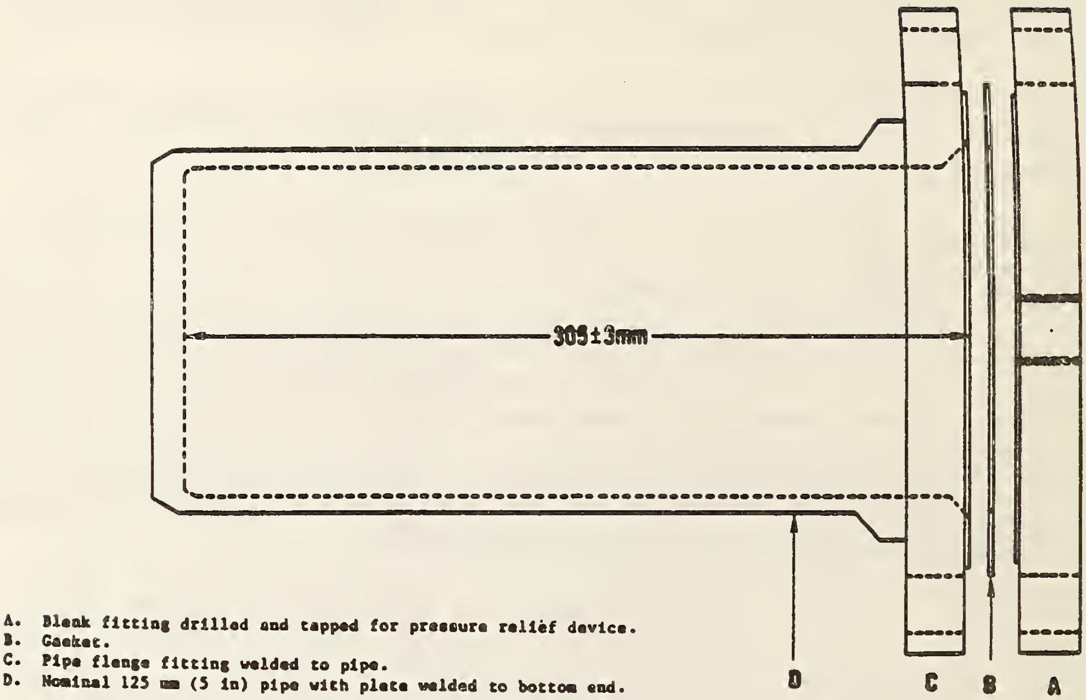
5.6 CONTAINMENT MATERIALS AND HEAT TRANSFER FLUIDS

5.6.1 Introduction

Because containment materials and heat transfer fluids interact in pairs, neither of the two materials can be assessed separately. Accordingly, the evaluation of test methods and the development of screening methods for these materials were carried out together. Since interactions between the heat transfer fluid and surrounding materials may increase the possibility of corrosion of the containment materials, there is a need for laboratory procedures for screening material compatibility, as well as fluid chemical and thermal stability.

5.6.2 NBS Research

Consequently, NBS conducted research to support the development of testing methodologies in several areas. In the first study [84] laboratory methods for assessing the compatibility of metallic containment materials with heat transfer liquids were evaluated. In the second study [85], test methods were



A. Blank fitting drilled and tapped for pressure relief device.
B. Gasket.
C. Pipe flange fitting welded to pipe.
D. Nominal 125 mm (5 in) pipe with plate welded to bottom end.

Figure 39. Pressure vessel for immersion tests at 150°C (from Ref. 83)

developed for assessing the corrosion of various metallic containment materials as a function of different heat transfer fluids under a variety of simulated service conditions, both operational and stagnation. In the third study [86], laboratory procedures were developed for screening plastic containment materials for thermal stability under heat aging and for chemical compatibility with heat transfer fluids.

The liquid heat transfer fluids most commonly used in thermal solar energy systems are ethylene glycol, propylene glycol, or aqueous solutions therof, and silicone oil. Containment materials include various alloys of metals such as aluminum, copper, and stainless steel, as well as plastics such as thermoplastic, thermoset, and elastomers.

In the course of the evaluation of containment materials and heat transfer fluids [84], NBS participated in a round-robin evaluation of a proposed ASTM practice for screening of metallic materials. The tests were conducted solely to evaluate the procedural aspects of the proposed practice, and were not intended to be an assessment of the metals evaluated [84].

- Test A -- Basic Immersion Test at Atmospheric Pressure
- Test B -- Heat-Rejecting Surface Test at Atmospheric Pressure
- Test C -- High-Pressure Test
- Test D -- Repeated Drip-Dry at Atmospheric Pressure
- Test E -- Crevice Test at Atmospheric Pressure
- Test F -- Tube-Loop Test at Atmospheric Pressure

These various test were evaluated during the round-robin testing. The results of the laboratory work indicated that the tests, described in the proposed standard (now ASTM E 712-80), could be carried out within reasonable time, at moderate expense, and, with the exception of Test D, with minimal equipment fabrication. It was found that the tests allow for the screening of fluid/metal pairs. Specifically, Test A allowed the separation of corrosion rates of aluminum and copper-based alloys, and Tests B, D, and E indicated that variation in corrosion rate as a function of alloy composition may be observed. However, Test E indicated a variability in crevice imposition. Results for this test series are shown in table 30, while the different types of apparatus used are shown in figures 40, 41, and 42.

NBS also conducted two series of simulated service tests to evaluate the corrosion of metallic materials with heat-transfer fluids [85]. The two series of tests were designed to simulate field conditions. One set of tests was designed to determine the heat transfer liquid stability, (see figure 43), while the other set assessed the use of a simulated solar loop system (see figure 44). Table 31 summarizes the simulated service conditions.

The loop systems were designed to operate in three modes -- continuous flow; flow stagnation cycles below the boiling temperature of the liquid; and flow-stagnation cycles at a flow-temperature below the boiling temperature of the liquid and at a stagnation temperature above the boiling temperature of the liquid. Because a series of initial tests had revealed ethylene glycol to be less stable than propylene glycol under the desired operating conditions, it

Table 30. Summary of Test Results (from Ref. 84)

Metal Alloy	Test A		Test B		Test D	Test E	
	Average Corrosion Rate	Maximum Pit Depth	Corrosion Rate	Maximum Pit Depth	Average Corrosion Rate	Average Corrosion Rate	Maximum Pit Depth
1100 Al	0.14	0.18	1.42	0.04	0.46	0.22	0.03 to 0.29
3003 Al	0.23	0.12	2.02	0.04	0.31	0.37	0.03 to 0.67
122 Cu	1.52	0.09	8.32	0.05	0.97	1.47	0.03 to 0.06
706 Cu/Ni	1.15	0.04	4.03	*	0.51	1.20	0.02 to 0.05
409 S/S	*	*	-	-	-	-	-
439 S/S	*	*	*	**	*	*	*
444 S/S	*	*	*	**	*	*	*
1105 Steel	46.2	Perforation	-	-	-	-	-

* Negligible rate or too shallow pits to measure.

** No pits observed.

Corrosion rate in mdd (mg/dm^2/day)
Pit depth in mm.

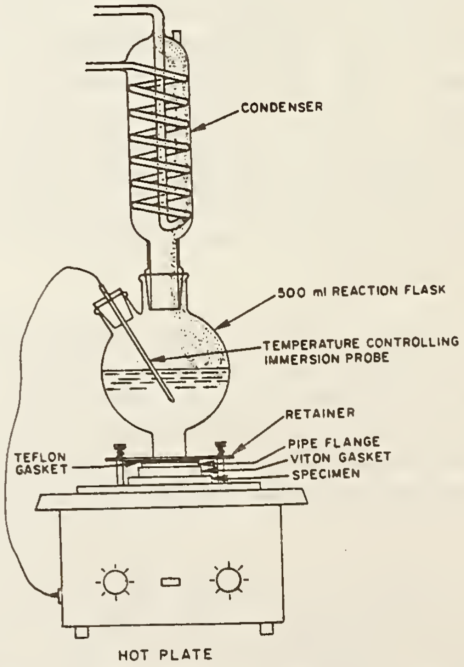


Figure 40. Schematic of apparatus used in test B (from Ref. 84)

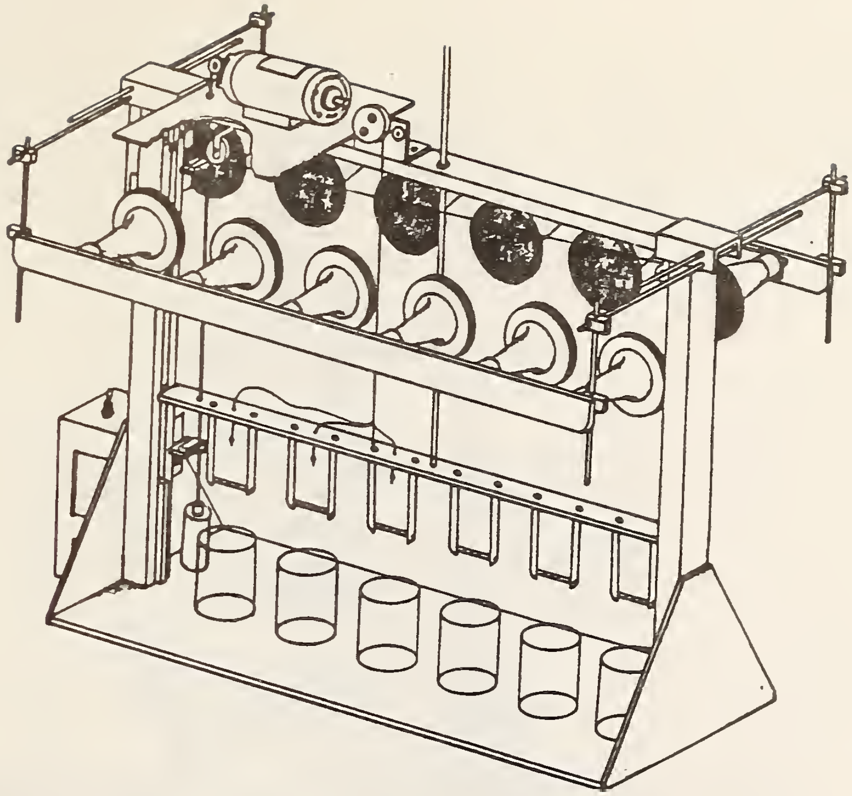


Figure 41. Isometric drawing of apparatus used in test D (from Ref. 84)

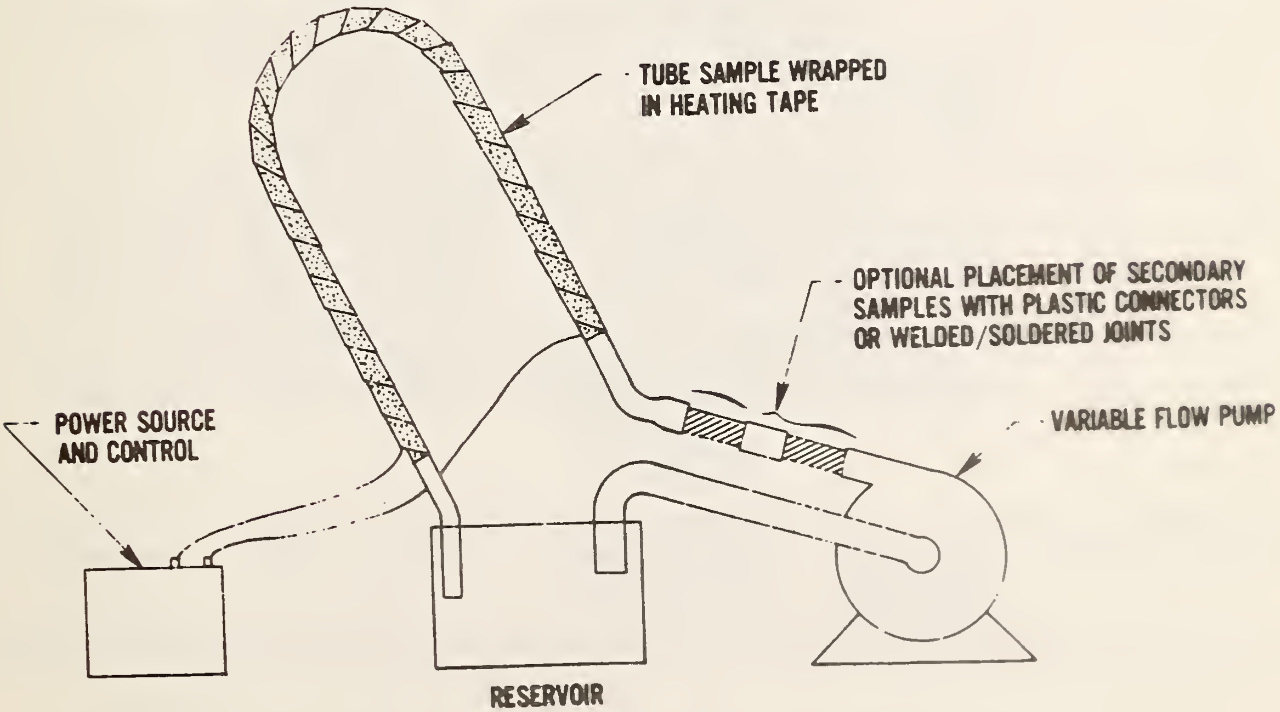


Figure 42. Schematic drawing of apparatus for test F (from Ref. 84)

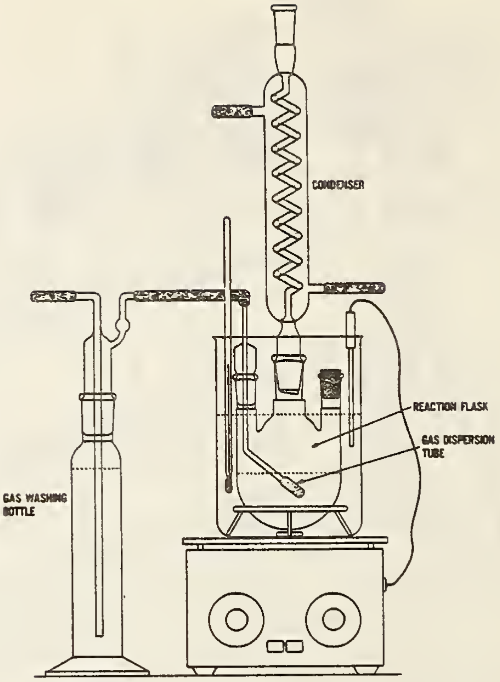
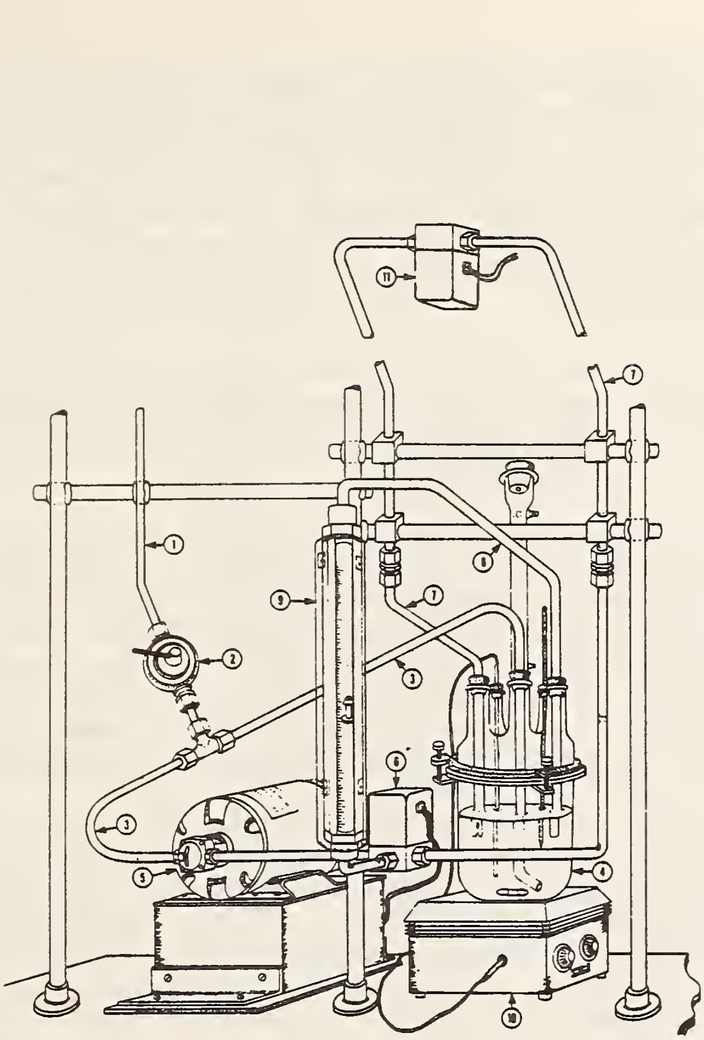


Figure 43. Schematic of the apparatus used to study the degradation of ethylene and proplyene glycol (from Ref. 85)

Table 31. Summary of Simulated Service Test Conditions (from Ref. 85)

Alloy	System	Other Materials Exposed to the Heat Transfer Liquids	Heat Transfer Liquids	Temperature		Flow Rate	Test Duration
				Flow	Stagnation		
3003 Al	Al #1	Teflon, epoxy, polyethylene, glass, 316 stainless steel	Ethylene glycol 50%, ASTM D1384 Water 50%	90°C	—	0.64 m/sec	16 weeks
	Al #2			90°C	90°C	0.64 m/sec	16 weeks
	Al #3			90°C	120°C	0.64 m/sec	16 weeks
	Al #4			90°C	135°C	0.64 m/sec	16 weeks
122 Cu	Cu #1	Above and 95/5 Sn/Sb solder	Ethylene glycol, 25% GM 6038-M, Type A antifreeze 25% ASTM D1384 water 50%	90°C	--	0.64 m/sec	24 weeks
	Cu #2			90°C	120°C	0.64 m/sec	24 weeks
316 S/S	S/S #1	Teflon, epoxy, polyethylene, pyrex glass	Distilled water +1000 ppm NaCl	90°C	120°C	0.64 m/sec	16 weeks



Schematic showing the various components of the loop systems. The systems are initially charged with liquid through the priming port [1] by opening the manual two-way valve [2]. The common flow path [3] is from the reservoir [4], through the pump [5], to the 3-way solenoid valve [6]. The primary flow path [7] is across the samples. The flow path is changed from primary to secondary by activating the 3-way solenoid valve [6] and the secondary path [8] during loop stagnation is through the flowmeter [9]. The hot plate [10] maintains the liquid temperature during stagnation. In systems which stagnate above the boiling point of the liquid, a 2-way solenoid valve [11] placed at the top of the loop is activated during stagnation. In continuous flow systems, a manual 3-way valve replaces the 3-way solenoid valve [6].

Figure 44. Schematic of simulated service loop system (from Ref. 85)

was used as the heat transfer fluid to allow some liquid degradation for assessing the effects of the test conditions. The results indicated that the responses of both the copper and aluminum specimens varied depending on the test conditions, while those for stainless steel were inconclusive. Operation in the flow stagnation cycle was more conducive to copper corrosion, while corrosion occurred for the aluminum samples in a less consistent fashion. Table 32 describes some of the test results, while figures 45, 46, and 47 present the results graphically.

Since plastic materials are becomming more common in solar energy systems, NBS also conducted laboratory studies to obtain data needed for developing standards for screening plastic containment materials for heat effects and for compatibility with heat transfer fluids [86].

The first task was to identify potential uses, service conditions, and degradation factors for plastic containment materials. It was determined that plastics are used in absorbers, transport plumbing, storage tanks, and containers. Service conditions included elevated temperatures, temperature cycling, solar radiation, moisture, air pollutants, internal pressure, contact with heat transfer fluids, and contact with adjacent materials. For the purposes of screening tests, it was decided that performance under elevated temperatures and contact with heat transfer fluids would be most appropriate.

During the screening tests, the plastic specimen was subjected to aging procedures including heat stability aging and immersion in heat transfer fluid (chemical compatibility). Figure 48 presents a flow chart of the testing sequence. Table 33 presents materials studied by NBS. Key material properties such as linear dimensions, hardness, weight change, appearance, and reflectance (absorbers only) were measured before and after aging. Heat aging was conducted at temperatures of 100°C (212°F) and 125°C (257°F), for 100, 250, 500, and 1000 hours of exposures. Heat transfer fluids included water, 100 percent ethylene glycol, 50 percent ethylene glycol in water, 100 percent propylene glycol, 50 percent propylene glycol in water, and 100 percent silicone oil. Immersion tests were conducted at room temperature and at 70°C (158°F) for 7 days.

Heat aging resulted in weight loss for the PVC storage tank liner, along with uneven changes in length and width. Heat aging generally increased hardness slightly, although a significant increase was found for the PVC tank liner. EPDM, CPVC pipe, and PVC pipes had significant weight losses after exposure to 125°C (257°F) for 1000 hours. The CPVC pipe also developed bubble-like bumps on the interior and exterior surfaces, while the cross-linked polyethylene specimen melted.

The tests for chemical compatibility demonstrated generally small changes in weight for room temperature tests. The polypropylene absorber gained 0.1 percent weight in concentrated propylene glycol, but lost 23 percent in a dilute solution. Silicone oil at 70°C (158°F) caused significant weight gains, dimensional changes, and softening, in all materials.

Table 32. Summary of Simulated Service Test Results (from Ref. 85)

System	T, °C Flow	Stag.	pH Initial	Final	Corrosion Rate, mpy Empty Side	Full Side	Deepest Pit Empty Side	Full Side
Al #1	90	-	8.35	5.56	0.49		1.06 mm	
Al #2	90	90	8.35	5.08	0.38	0.40	negl.	negl.
Al #3	90	120	8.35	5.33	0.54	0.28	0.85	0.55
Al #4	90	135	8.35	5.64	1.34	0.67	0.12	negl.
			Reserve Alk.					
Cu #1	90	-	3.89	3.56	0.03			
Cu #2	90	120	3.89	3.05	0.12	0.08		
			pH					
S/S	90	120	7.72	8.57	negligible			

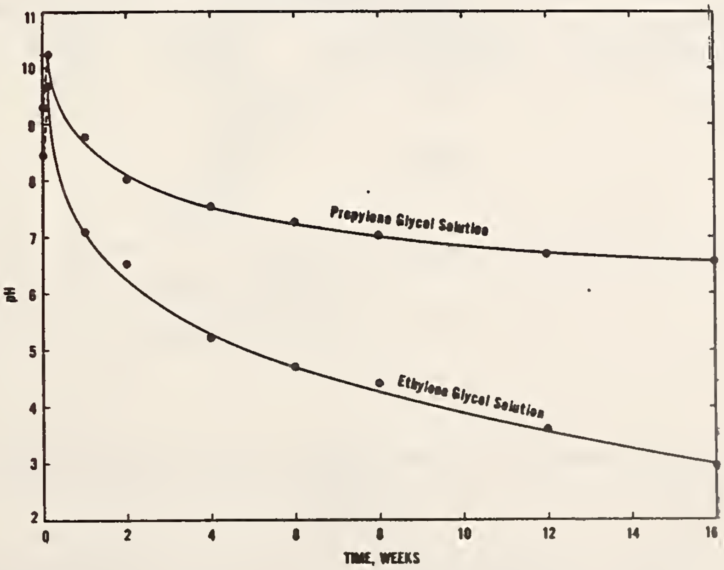


Figure 45. Plots of solution pH vs. time for aerated solutions of ethylene and propylene glycol at 100°C (from Ref. 85)

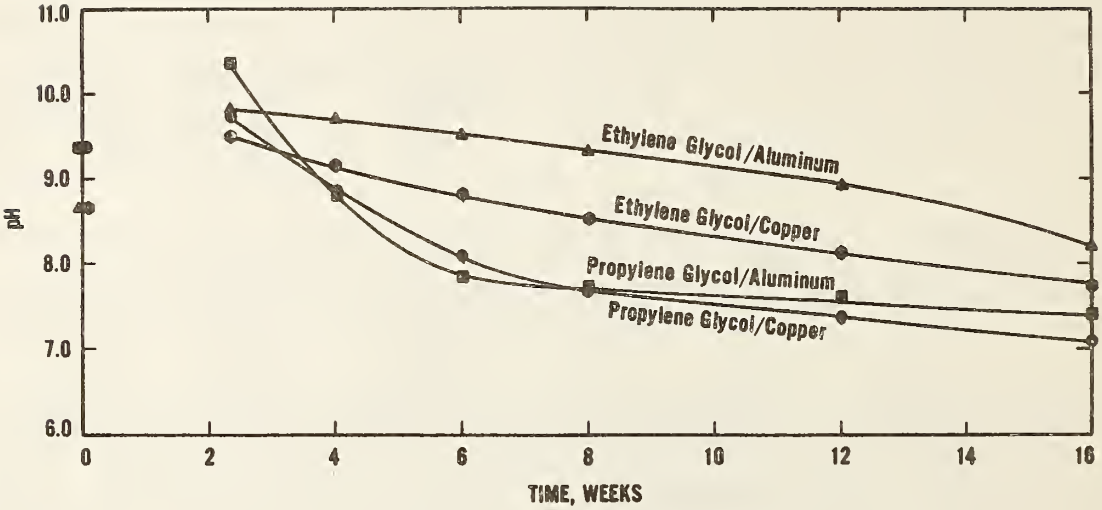


Figure 46. Plots of solution pH vs. time for deaerated solutions of ethylene and propylene glycol in contact with aluminum and copper at 100°C (from Ref. 85)

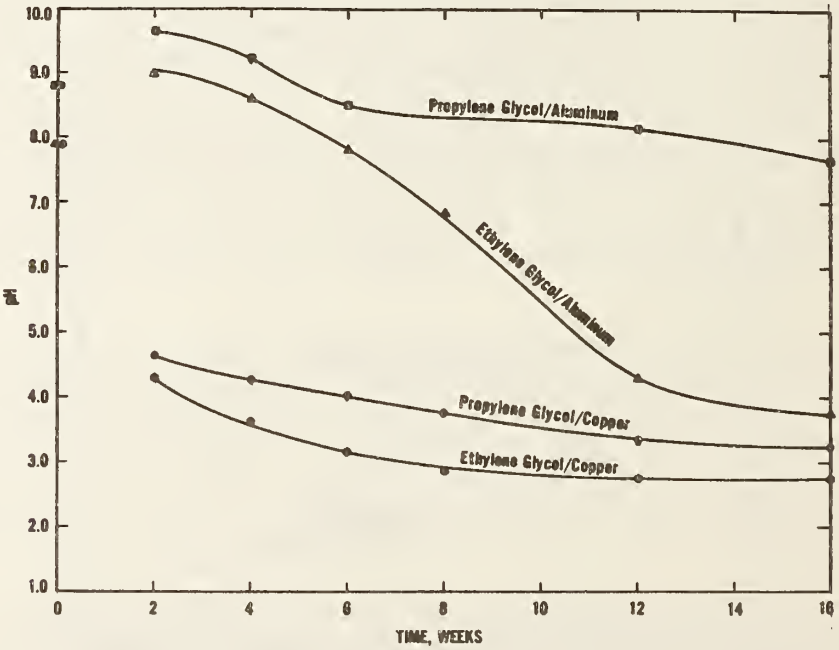


Figure 47. Plots of solutions pH vs. time for aerated solutions of ethylene and propylene glycol in contact with aluminum and copper at 100°C (from Ref. 85)

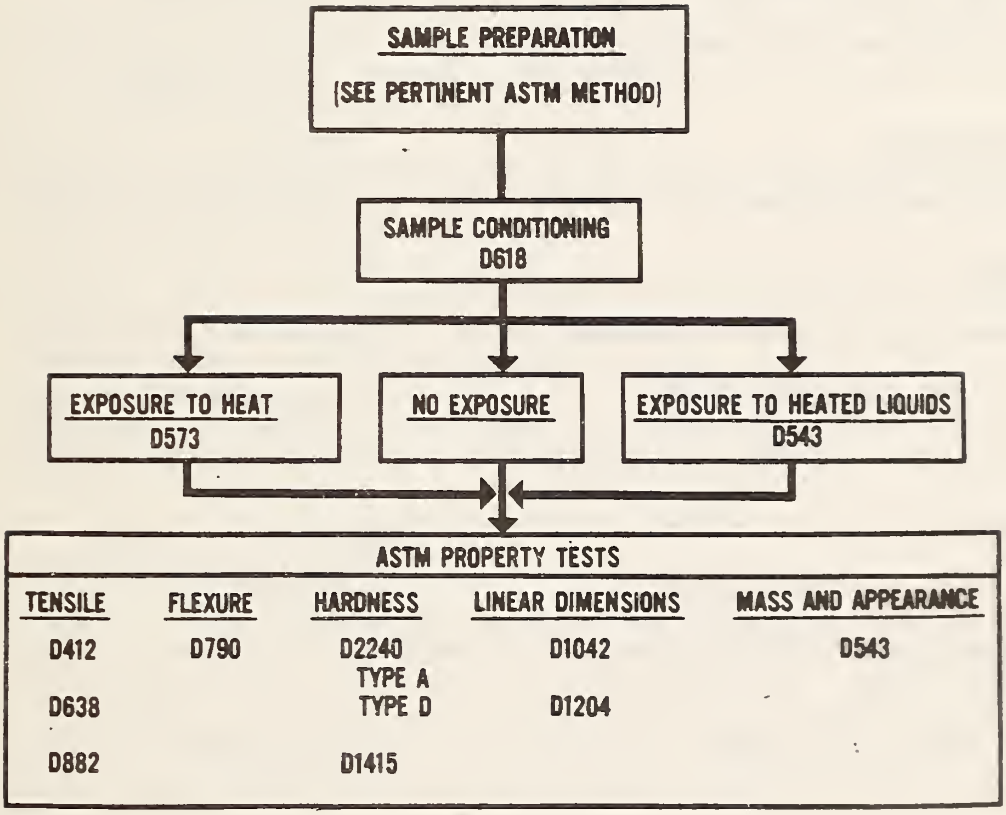


Figure 48. Outline of testing sequence for screening plastic containment materials (from Ref. 85)

Table 33. Plastic Containment Materials Studied by NBS (from Ref. 86)

Materials	Description
Collectors - Absorbers	
Ethylene propylene diene monomer (EPDM)	extrusion with 1.9 mm wall
Silicone coated fiberglass fabric	0.36 mm sheet
Crosslinked polyethylene (XLPE)	17 mm diameter tubing with 1.5 mm wall
Polypropylene	extrusion, with 0.5 mm wall
Polypropylene copolymer	extrusion, with 0.64 mm wall
Piping	
Chlorinated poly(vinyl chloride) (CPVC)	34 mm OD, 4.5 mm wall
Poly(vinyl chloride) (PVC)	34 mm OD, 4.5 mm wall
Acrylonitrile-butadiene-styrene (ABS)	29 mm OD, 2.2 mm wall
Storage	
Poly(vinyl chloride) liner	0.8 mm sheet
Chlorosulfonated polyethylene liner - over woven fabric	0.8 mm sheet
Fiber reinforced plastic tank	1.3 mm sheet

In summary, the data for plastic materials showed that the environment experienced in solar energy systems can degrade some materials. They also indicated that accelerated laboratory screening tests can be effectively used to determine if a plastic material is likely to be affected by specific degrading factors. Additional tests were recommended to evaluate candidate plastic materials for specific applications in solar energy systems.

5.6.3 ASTM Standards

5.6.3.1 ASTM E 712-80

Standard Practice for Laboratory Screening of Metallic Containment Materials for Use with Liquids in Solar Heating and Cooling Systems (ASTM E 712-80) [87], provides laboratory test procedures for evaluating the corrosion performance of metallic containment materials under conditions similar to those that may occur in solar heating and cooling systems. Although the six tests were identified in 5.6.2, they will be briefly summarized here.

- Practice A is concerned with the interaction of metal and fluid at the same temperature. It is useful for plumbing, pumps and tanking, but less useful for collector panels.

- Practices B and F are concerned with the deterioration of the metal when there is heat transfer from the metal to the fluid. These are especially applicable to collector panels.

- Practice C is useful in relation to systems experiencing high temperatures or closed to the atmosphere.

- Practices D and E evaluate specific corrosion problems associated with particular metal/fluid pairs.

Any one or more of the various tests may be used to evaluate the deterioration of the metallic containment material in a metal/fluid pair. These tests require proper consideration of the metal/fluid pairing, and eventual confirmation by component and systems testing under actual or simulated service conditions. The test must be long enough to allow corrosion to occur, as well as to allow exhaustion of any chemical corrosion inhibitor. A minimum of 30 days is recommended.

This standard provides guidance in selecting materials and reagents, sampling, configuration of test specimens including surface finish, and metallurgical condition, and procedures for conventional, electrolytic, or chemical cleaning after testing.

Deterioration of containment material is determined by measurement of the mass loss and microscopic examination (at 10X magnification), for incidence of localized attack. Formulas are given for calculating mass loss per unit area per unit time, as well as the rate of loss in thickness of the specimen. Incidence of localized corrosion, and/or changes in the heat transfer fluid are to be reported.

The six practices for evaluating metal/fluid interaction given in the standard are described below.

Practice A is a basic immersion test at atmospheric pressure. It is a simple, rapid exposure test, open to the atmosphere, and designed to evaluate metal/fluid interaction. In this practice, a reaction vessel such as a 1000 ml (.264 gal) beaker is used. The specimen is placed in this vessel which contains about 500 ml (.132 gal) of heat-transfer fluid. The vessel is then heated to the desired test temperature for the duration of the test (at least 30 days). At the conclusion the specimen is weighed and examined visually.

Practice B is designed to simulate deterioration of containment material as a result of heat transfer through the containment material into the heat-transfer fluid. As typically constructed, it is also open to the atmosphere. The test apparatus was shown in figure 40. In this test a specimen is mounted at the bottom of a reaction flask between a gasket and a heating mechanism. The temperature on the surface of the test specimen is controlled by means of an instrument such as a thermocouple. After the test specimen is cleaned and weighed, it is then secured to the reaction flask, which is filled with 250 ml of the heat transfer fluid. Although any schedule of testing temperatures and durations may be selected, simulation of anticipated field operation through a schedule of heating, holding and cooling is recommended. At the conclusion, the specimen is weighed and examined for corrosion.

Practice C is designed to simulate conditions of high pressure and temperature under full, partially full, and empty stagnant conditions. Unlike Practices A and B, it can provide for test conditions which simulate systems closed to the atmosphere. In this test, an autoclave or comparable device for producing required temperatures and pressures serves as the test chamber. Specimens are mounted independently on a test rack which is filled with test fluid. Fluid levels are selected so that the specimen is totally immersed, partially immersed, or suspended in a vapor phase. Again, the test may be run for any schedule of time, temperature, and pressure, but a minimum of 30 days is recommended. It should be noted that this particular test was not included in the series of tests which formed the round robin in which NBS and other laboratories participated.

Practice D is designed to simulate alternate wetting and drying conditions. Like practices A and B, it is open to the atmosphere. In this test the specimen is repeatedly lowered into the test fluid, then raised from it, dried, and reimmersed. Selection of a drying device should consider the possible degradation effects related to the method of drying such as degradation of fluid by infrared radiation from heat lamps or effects of atmospheric exposure. Again specimens are cleaned and weighed before testing. While any cycle of drip and dry times may be selected, a minimum duration of 30 days is recommended.

Practice E is used to evaluate general corrosion resistance and to detect susceptibility to crevice corrosion attack for metallic containment materials. The procedure differs from ASTM Method G 48 (a test for stainless steel corrosion using ferric chloride) in providing for the use of washers of inert material rather than rubber bands to form the crevice contacts. Again, the test material is placed in a test flask with the heat transfer fluid, and heated to the desired test temperature. Test material is then examined for crevice corrosion attack, at the completion of testing.

Practice F is designed to simulate the deterioration of containment materials when heat is transferred through the containment material tubing to heat transfer fluid located inside the tube. In this test, a U-shaped tube of the containment material is wrapped with heating tape. The tape is attached to a power source. One leg of the U-shaped tube enters a reservoir containing the heat transfer fluid, while the other is attached to a variable flow pump (see figure 42). Provision is made for introducing secondary samples of similar or dissimilar metal tubing as well. A cycling mechanism controls both temperature and fluid flow in any desired cycle for the selected duration.

After the test is concluded, the specimens are weighed and examined for deterioration. Appropriate test conditions include: specimen preparation, time and temperature schedule, degree of atmospheric exposure of heat transfer fluid, stirring, and flow rate. The method of temperature measurement and control must be specified, along with any boiling of the heat transfer fluid.

At the conclusion of all testing, the specimens are cleaned, measured and weighed. They are also examined for evidence of localized deterioration using 10 X magnification. Any changes in the heat transfer fluid such as odor or appearance must be reported, as well as the build up of any film.

5.6.3.2 ASTM E 745-80

Standard Practice for Simulated Service Testing for Corrosion of Metallic Containment Materials for Use with Heat-Transfer Fluids in Solar Heating and Cooling Systems (ASTM E 745-80) [88], contains three practices, A, B, and C, which simulate field service conditions for evaluating the performance of metallic containment materials under corrosive conditions. The material is treated as an integral part of a metal/fluid pair. The practices provide procedures for evaluating deterioration under several conditions, including: operating full flow; stagnant empty vented; stagnant, closed to atmosphere, non-draindown; and stagnant, closed to atmosphere, draindown.

Practice A is a laboratory simulation for evaluating coupon test specimens under different operating conditions of solar heating and cooling systems. Practice B is also a laboratory simulation which utilizes a component or simulated subcomponent. Unlike Practice A, it provides for heating of the heat transfer fluid by the containment material. Practice C is a field simulation of components under various operating conditions of solar heating and cooling systems, using controlled schedules.

Because the various procedures do not restrict the selection of either the containment materials or the fluid, the standard specifies that attention must be paid to pairing material and fluid appropriately, knowing the probable corrosion mechanisms, and avoiding hazardous fluids, materials or material/fluid pairs. The duration of testing must be adequate for measuring the rate of corrosion of the containment material. Because corrosion is both time-dependent and non-linear, a minimum test period of not less than 6 months is recommended. The ratio of metal surface area of fluid volume must be considered for fluids with additives designed to minimize corrosivity (due to depletion kinetics.)

Following completion of the test procedures, the deterioration of the containment material is determined by measurement of weight loss when possible, measurement of metal thinning, and by examination at 10 X magnification for localized corrosion. Formulas are given for calculating corrosion rates based on weight loss or reduced density. Other factors to be identified include: instances of localized corrosion, changes in the heat transfer fluid, and any film formation or build up.

The report should include chemical identification of the containment material and heat transfer fluid, as well as the dimensions and configuration of the material specimen. It should also identify all procedures used, as well as average weight loss and penetration rate.

Practice A is designed to evaluate the resistance to deterioration of (unheated) metallic containment materials in contact with the heat transfer fluid. It provides guidelines for surface finish, metallurgical condition, and cleaning (before and after testing), including general, electrolytic, and chemical. The procedure calls for preparation and cleaning of test specimens and cycling of temperature conditions on a daily schedule. Once every two weeks, the daily cycling is to be replaced with an autoclave cycle. The test should last for at least 6 months, although specimens may be withdrawn at interim periods for checking.

Practice B is designed to evaluate the performance under corrosive conditions of containment materials as components (or simulated subcomponents) under laboratory procedures which simulate field conditions. Test specimens should represent materials and components used in solar applications. The apparatus consists of storage tank, pump, plumbing as needed, process controller, monitoring equipment, refrigeration unit, and means of heating the metallic containment loop (See figures 40 and 41). It is designed to simulate a variety of service conditions. Thus, the standard recommends that consideration be given to selecting a schedule of full operation and stagnation cycles which simulate anticipated field operations. The test should be conducted on a specified cycle for at least 90 days.

Practice C calls for a field test of the performance of containment materials in components or simulated subcomponents in controlled operations which simulate various field conditions. It specifies that the test specimen be a metallic absorber panel, either full-size or a simulation of full-size. Both panel and collector are to be of materials representative of functional systems. The test apparatus includes: the collector, storage tank, pump, suitable plumbing, process controller, and temperature monitoring device.

Practice C permits any schedule of operation, although it recommends use of a schedule similar to intended field operations. If it is desired to test stagnation condtions, procedures are given for determining the effects of accelerated stagnation over 1 year. The practice notes that leaky panels may be patched with compatible sealers. Also, temperature of the fluid and panel should be measured on a regular schedule during the operational and test cycles.

5.6.3.3 ASTM E 862-82

Standard Practice for Screening Polymeric Containment Materials for the Effects of Heat and and Heat Transfer Fluids in Solar Heating and Cooling Systems (ASTM E 862-82) [89] provides procedures for evaluating selected mechanical and dimensional properties of polymeric materials when exposed to heat and heat transfer fluids. This practice is intended to provide short-term exposure data for screening out unsuitable materials and a basis for a relative ranking of the resistance of candidate materials to heat and heat transfer fluids.

The practice provides procedures for assessing the effects of elevated temperatures in terms of physical, mechnical, and chemical changes in the polymeric materials studied. It also provides procedures for determining the chemical compatibility of polymeric materials with either aqueous or organic-based heat transfer fluids. It recommends minimum number of specimens as well as geometry and edge characteristics for each property test. Conditioning procedures are also specified.

The following property measurement tests are to be performed: dimensional stability; mass and appearance; tensile properties; flexural properties and hardness. These tests establish initial properties and dimensions for unexposed specimens.

The second set of procedures is the determination of the specimen response to continuous in-service temperature for 1000 hours, and response to stagnation temperatues for 300 hours for polymeric materials used in components such as absorbers, filters, valves, etc. Following temperature exposure, physical characteristics are again measured.

The third set of procedures involves assessment of chemical compatibility using Method D 543 (Test for Resistance of Plastics to Chemical Reagents) with a 7 day exposure to the appropriate heat transfer fluid, both concentrated and diluted to in-service conditions. Again, physical properties and dimensional stability are to be measured following chemical exposure.

The standard proposes no acceptance or failure criteria, as this practice is intended to standardize the testing and screening procedures. It does note, however, that failure criteria for materials are given in other ASTM standards, and suggest some general definitions that are likely to be appropriate. The standard also indicates that determination of the rate of change with time or temperature in a property may be far more important to determining likely performance in a solar component or system than measurement of a single value under one arbitrary condition.

6. Conclusions

6.1 SUMMARY

The preceding sections have briefly reviewed research and test method development activities for active solar heating and cooling systems during the period 1974 to 1982. The majority of related voluntary national consensus standards which were developed and approved as a result of the various research projects and recommendations were also discussed. Table 34 summarizes the research activities and the test methods and other standards which have been developed to aid in evaluating the thermal and durability/reliability performance of solar domestic hot water systems, thermal storage devices, collectors, and materials. Additional summary information on research and standards development activities pertaining to materials is contained in reference 52.

6.2 RESEARCH NEEDS

The preceding sections indicate that DOE/NBS research played a key role in determining thermal and material properties and subsequent performance requirements for various systems, components, and materials of active solar energy systems. Despite the progress made toward the development of test methods and other standards, additional research is needed to develop new standards, as well as to revise existing standards.

A high priority need is the development of test methods and standards for assessing the long-term performance of collector components and materials in a functioning active solar energy system, and for determining the thermal efficiency, durability, and reliability of the total system.

Thus, high priority should be given to the development of improved test methods for measuring the thermal performance of integrated collector storage domestic hot water systems. There is also a need to expand rating and test procedures to innovative systems and operating conditions which may differ from those for which the procedures were originally developed.

Several area for further research have been proposed for components of solar systems. Previous research studies [36, 37, 48] have identified a number of areas to be considered in revising test methods for thermal performance of solar collectors. Additional durability/reliability test methods (e.g. rain penetration) for solar collectors should also be developed. Section 3.3 discussed the need for improvements in the thermal performance testing of storage devices [22]. Finally, a number of recent studies [90, 91] have recommended the development of test methods for solar controllers and sensors.

For collector materials, a number of research needs have been identified. Recent research data and information [92] contain recommendations for revising existing standards for evaluating cover plate and absorber materials durability. There is also a need to develop test methods and mathematical models for predicting service life for cover plate and absorber materials, phase change storage materials, heat transfer fluids, and reflective surfaces.

Table 34. Summary of Active Solar System, Component, and Materials Standards and Related Research

System/Component/Materials	Standard	Research*
1. Solar Domestic Hot Water Systems		
a. Thermal Performance	ASHRAE 95-81	9-11, 14
2. Thermal Storage Devices		
a. Thermal Performance	ASHRAE 94-77	15-17, 20-22
3. Collectors		
a. Thermal Performance	ASHRAE 93-77 ASHRAE 96-80	16,25,29,30, 33,36,37
b. Durability/Reliability	ASTM E 823-81	40, 47-49
4. Functional Materials		
a. Cover Plates	ASTM E 765-80 ASTM E 782-81 ASTM E 822-81 ASTM E 881-82	53, 62-65
b. Absorptive Materials	ASTM E 744-80 ASTM E 781-81	53,64,69,71
c. Insulation (Collector)	ASTM E 861-82	75
d. Gaskets and Sealants	ASTM D 3667-78 ASTM D 3771-79 ASTM D 3832-79 ASTM D 3930-80	74
e. Rubber Hose	ASTM D 3952-80	82,83
f. Containment Materials/Heat Transfer Fluids	ASTM E 712-80 ASTM E 745-80 ASTM E 862-82	84-86

* The numbers pertain to the references listed in Section 7.

Another need is in the development of test methods, both optical and mechanical, to increase the detectability of materials degradation. Current test methods are not sensitive enough to measure degradation, even though this degradation can be serious enough to impair collector performance. These methods are particularly needed for glazing and absorbers.

Finally, there is need to identify degradation mechanisms of various materials. Before test methods and mathematical models can be developed, the processes occuring in and between materials in a total solar system environment must be identified and understood. In particular, the effects of multiple degrading environments, such as heat and ultraviolet exposure, must be studied as a complete unit. At the same time the compatibility of joined materials in dynamic operation is needed to develop test methods which can predict operational effects observed during field use.

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11. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here*)

Since test methods and standards for active solar heating and cooling systems did not exist in 1976, the Department of Energy sponsored research at the National Bureau of Standards (NBS) and other laboratories to aid in the development of research-based standards. This research was intended to facilitate a sound data base for the development of national consensus standards and test methods. In the present report, research by NBS and other laboratories is described for solar domestic hot water systems, solar collectors, thermal storage devices and collector materials. For collectors, the report describes research and test methods for determining the performance of cover plates, absorber materials, collector insulation, gaskets and sealants, rubber hose, containment materials, and heat transfer fluids.

12. KEY WORDS (*Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons*)

absorbers; collectors; materials; consensus standards; domestic hot water; durability; heat transfer fluids; reliability; solar energy; test methods; thermal performance; thermal storage devices.

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