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Solar Energy Systems: Test Methods for Collector Insulations

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Final Report

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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, ***Secretary***
Luther H. Hodges, Jr., ***Under Secretary***
Jordan J. Baruch, ***Assistant Secretary for Science and Technology***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

ABSTRACT

A preliminary study was performed to evaluate potential procedures for screening the insulation used in solar collectors. Both ASTM standard test methods and newly developed non-standard procedures were used to evaluate twenty-one insulation materials. The insulation parameters measured in this study were selected on the basis of how and to what extent they were affected by the unique environmental conditions within solar collectors. Results of the laboratory tests are discussed and those procedures which offer a potential for screening insulations used in solar collectors are presented. It is intended that these procedures fulfill the first step in the development of a standard set of test methods for evaluating insulations for solar collectors.

Key words: Accelerated aging; collector insulation; insulation; solar collector; insulation test methods.

ACKNOWLEDGEMENT

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CONVERSION UNITS

In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the International System of Units in 1960, SI units of measurement have been used throughout this publication. To assist in conversion to common U. S. Units of measurement, conversion factors have been provided in the table below. The reader interested in making further use of the coherent system of SI units is referred to:

> "The International System of Units," National Bureau of Standards, NBS SP-330, 1977; or "Metric Practice Guide," American Society for Testing and Materials, ASTM E 380-76 American National Standards Institute.

Table of Conversion Factors to Common U.S. Units

Physical Quantity	To	To Convert From	Multiply by
Length	m	ft	3.28
Area	m^2	ft^2	10.76
Volume	m^3	ft^3	35.34
Temperature	Celsius	Fahrenheit	$t_f = 1.8\ t_c + 32$
Density	kg/m^3	lb/ft^3	6.25×10^{-2}
Thermal Conductivity	W/m•K	$Btu \cdot in/h \cdot ft^2 \cdot {}^\circ F$	6.94
Thermal Resistance	$m^2 \cdot K/W$	$h \cdot ft^2 \cdot {}^\circ F/Btu$	5.68

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1. INTRODUCTION

1.1 BACKGROUND

The typical flat plate solar collector has five major components: the cover plate, the absorber plate, the heat transfer fluid, the thermal insulation, and the container or enclosure. Of these, the insulation serves the important function of minimizing the loss of heat from the back and sides of the collector enclosure (Figure 1). Thus, the effectiveness of the insulation in reducing heat losses is a primary factor in determining the overall thermal efficiency of the collector. For maximum efficiency, the insulation should have the properties of low thermal conductivity, dimensional stability, and chemical compatibility (i.e., not react with other collector component materials). Moreover, of particular importance in solar collector applications, the insulation must be able to maintain its thermal and dimensional properties over the lifetime of the collector, and do so under the degrading effects of high and cyclic temperature and possibly high humidity.

The environmental conditions under which solar collectors must operate are defined by the diurnal and seasonal variations in temperature, humidity (or moisture), and solar radiation; in addition, the presence of atmospheric dust and pollutants in combination with the other environmental factors may have a synergistic effect on the degradation of the collector materials[1].[1/] The maxima and minima in the collector operating conditions depend on the local climate, the design of the collector, and the materials used in its construction. For example, the maximum absorber plate temperature will occur on a sunny day when no heat is being removed from the collector, i.e., stagnant operation. Because the insulation may be located directly next to the absorber plate, it is also subjected to temperature extremes.

The effects of extreme environmental conditions on solar collector components have been well documented in a recent report by Skoda and Masters [2]. They reviewed the performance of solar collector materials by conducting on-site inspections of operational solar energy systems, and surveying both the manufacturers and installation contractors of these systems. For insulation, they found that the performance problems included swelling as a result of exposure to elevated temperatures, degradation due to exposure to ultraviolet radiation, and outgassing of

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[1/] Numbers in brackets refer to the references listed in Section 7.

degradation products. Depending on the chemical nature of these products, they may either react with or condense on other collector materials. If condensation occurs on the underside of the cover plate, transmittance may be reduced, leading to a lower thermal efficiency for the collector.

Despite the existence of these problems there are few performace standards or test methods which deal specifically with the use of materials in solar collectors. For example, in the case of insulation, there are numerous standard test methods which may be used to determine its performance in normal building applications but these test methods may not be fully applicable to the evaluation of insulation for use in solar collectors. This is particularly true of durability-related tests (aging tests) where the exposure conditions seldom simulate those experienced in collectors. Consequently, an urgent need exists for standards which ensure the satisfactory performance of the insulation used in solar collectors.

1.2 OBJECTIVES

The purpose of this study was to develop test methods by which the insulation used in solar collectors may be evaluated. To meet this goal, four specific objectives were established:

- To identify the performance requirements for insulations used in solar collectors.
- To identify or develop test methods to measure insulation performance according to these requirements.
- To evaluate and then recommend those test methods which are suitable for the insulation materials that are used in solar collectors.
- To draft a set of standard test methods for solar collector insulations; these methods will be considered for adoption by the American Society for Testing and Materials (ASTM).

2. PROBLEM ASSESSMENT

In the evaluation of insulations for use in solar collectors, one must determine the ability of the insulation to perform its function under the environmental conditions within the solar collector. The first step, then, is to identify the critical in-service operating conditions and insulation performance requirements. Using this information one can identify the properties and corresponding tests which must be used in the evaluation. The following paragraphs are devoted to a discussion of these topics.

2.1 IN-SERVICE CONDITIONS

The in-service operating conditions of a solar collector include the following factors, which must be taken into consideration in any analysis of insulation test methods:

- Sustained high or low temperatures. During stagnation, temperatures may be as high as 260° C within the collector on a sunny day and as low as -40° C outside the collector at night.[1].
- Diurnal temperature-humidity cycling.
- Condensation or accumulation of water within the collector.
- Continuous contact between the insulation and the components of the collector system.

2.2 PRIMARY FUNCTION AND REQUIREMENTS

The primary function of the collector insulation is to minimize the thermal losses that result from the transfer of heat from the back and sides of the absorber plate through the collector enclosure. In order to attain and maintain maximum thermal efficiency, these losses must be reduced through the use of an insulation which not only has good initial insulating properties, but also maintains these properties over the lifetime of the collector. This requires that the insulation withstand the chemical and/or physical changes which can be brought about by both the normal diurnal temperature-humidity cycles and sustained high or low temperatures which occur during stagnation. In addition, unless the insulation is unreactive toward other collector materials (particularly metals), and does not absorb water; both the material and performance degradation of the insulation as well as other collector materials can take place.

2.3 KEY PROPERTIES AND TEST METHODS

The key properties of insulations which were identified for inclusion in the laboratory studies were: mass, size, density, water adsorption, moisture absorption, thermal conductivity, and friability. The degradation factors that could affect these properties and thereby reduce the ability of insulations to perform as intended are: high and low temperature, water, high relative humidity, mold and vibration. In addition, the contact compatibility between insulations and other collector materials is an important factor affecting performance. Table 1 lists the ASTM test methods that were used to determine the effect of these degradation factors on the key properties. Due to the severe environmental conditions under which the solar collector must operate, some tests had to be slightly modified. For example, to simulate in service collector conditions, higher and/or lower temperatures were used in some tests. Finally, the uniqueness of the solar collector system required that four new non-standard tests be designed to determine the effects of such factors as thermal cycling and corrosion. These test methods are listed in Table 1 and described in the next section.

3. LABORATORY STUDIES

3.1 MATERIALS

The twenty-one insulations tested in this study are listed in Table 2. Insulations were classified according to the four generic types and four physical forms given in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 1977 handbook [3]. The four generic types include:

- Mineral fibrous materials such as glass, rock or slag wool.
- Mineral cellular materials such as calcium silicate, foamed glass, perlite and vermiculite.
- Organic fibrous materials such as wood, paper or synthetic fibers.
- Organic cellular materials such as urea-formaldehyde, polystyrene or polyurethane foams.

The above types are available in four basic shapes or forms:

- Loose-fill - This form consists of fibers, granules or nodules which are usually poured or blown into place.
- Flexible - This includes blanket, batt and felt insulation materials. They have varying degrees of compressibility and flexibility, and are available in sheets or rolls of many types and varieties. The thickness and shape of the insulation may be of any dimension conveniently handled, although standard sizes are generally used.
- Rigid - These materials are available in rectangular dimensions called block, board or sheet, and are preformed during manufacture to standard lengths, widths and thicknesses.
- Foamed-in-Place - These materials are available as liquid components which may be poured, frothed or sprayed in place to form rigid or semirigid foam insulation.

3.2 TEST METHODS

Both ASTM and non-standard test methods were necessary to characterize the aging process in solar collector insulations and to determine the effect of the degradation factors and the magnitude of any change in the several insulation properties given in Table 1. These properties and the factors which affect them had been identified as potentially contributing to the overall material and performance degradation of a solar collector. The following gives a brief statement concerning the reasons for selecting each of the ASTM tests listed in Table 1 and what, if any, modifications were made in the existing test method. For the non-standard tests the importance of each and a description of the test is given.

3.2.1 ASTM Tests Performed

C 167 "Thickness and Density of Blanket or Batt Type Thermal Insulating Materials." This is the standard test for determining the density and thickness of insulations; these two important properties identify the gross physical characteristics of an insulating material.

C 209: Section 13 "Testing Insulation Board (Cellulosic Fiber), Structural and Decorative: Water Absorption." This test was used in conjunction with D 1037: "Evaluating the Properties of Wood-Base Fiber and Particle Panel Materials", Sections 100-106: "Water Absorption and Thickness Swelling," to determine the percent water absorption by weight of all form types of insulation tested. Although these tests are only strictly applicable to cellulosic fibrous materials, the test procedures closely simulate the conditions whereby the collector insulation may be partially or completely submerged in water if it becomes present in the collector enclosure.

C 553: Section 15 "Mineral Fiber Blanket and Felt Insulation (Industrial Type): Moisture Adsorption." This test method is one of several under C 553 designed specifically for determining the properties of insulations used on heated or refrigerated surfaces, e.g., the absorber plate or enclosure of a solar collector. The test conditions were modified in the following way: Samples were exposed for 30 days to 50 and 90 percent relative humidity at 23° C, and to 70 percent relative humidity at 94° C. The longer exposure time and higher temperature served to accelerate any possible insulation degradation which might increase the adsorption of moisture.

C 518 "Steady-State Thermal Transmission Properties by means of Heat Flow Meter." This is the standard method for measuring the thermal transmission properties of insulation; it is a comparative method which utilizes C 177 to calibrate a standard comparison sample. For the purpose of this study results are reported as thermal conductivities (W/m·K).

C 411 "Hot Surface Performance of High-Temperature Thermal Insulation." This method is specifically designed to determine the performance of insulation that is used in contact with surfaces hotter than 93° C (viz. the solar collector absorber). For the purposes of this study, samples were exposed for 96 hours to the following temperatures: 94, 150, 209, and 260° C. These temperatures are representative of the high temperatures experienced by insulation in a solar collector [1].

C 356 "Linear Shrinkage of Preformed High-Temperature Thermal Insulation Subjected to Soaking Heat" - This test is used to determine the change in the linear dimension and the loss in mass of preformed insulation when exposed to temperatures greater than 93° C. In the current study temperatures of 150 and 260° C were used -- the same temperatures used in the Hot Surface Performance test. Although the standard 24-hour exposure was used for the linear shrinkage tests, only one-hour exposures were used for the mass loss tests.

D 3273 "Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber" - Although this standard test was designed specifically to determine the resistance of a paint film to the growth of mold that might occur on its surface in a severe interior mold environment (e.g., high humidity), the procedure is sufficiently general to be applicable to a variety of materials, including the insulation used in solar collectors. The tests reported here used the following organisms: aspergillus niger, aureobasidium pullulus, and penicillin citrinium.

3.2.2 Non-Standard Tests Performed

Thermal Cycling - The diurnal temperature changes both inside and outside the solar collector may be quite extreme. Thermal cycling may cause insulation to contract, expand or crack which, in turn, could lead to a general degradation in both the physical and chemical properties of the insulation. In order to determine the effect of thermal cycling on the properties of insulation the following test procedure was developed:

1. Insulation samples were conditioned for 48 hours at 23 ± 2° C and 50 ± 5% rh, then placed in the aluminum pan (Figure 1) and covered.

2. The pan (containing the insulation) was then subjected to 30 cycles of:

   ° Heating for 7.5 hours at 94, 150, 209 or 260° C[2/].

   ° Conditioning at 23 ± 2° C and 50% rh for 30 minutes.

   ° Cooling at -40° C for 15-1/2 hours.

   ° Conditioning at 23 ± 2° C and 50% rh for 30 minutes.

3. After exposure, the acidity, water absorption and thermal conductivity of the samples were measured. In addition, the samples were examined for expansion, cracking and fluffing; expansion was measured in terms of the height of the bow

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[2/] The maximum cycle temperature was established in another test: Effect of Thermal Cycling on the Appearance of Insulation Materials (Table 9).

formed. Finally, the inside of the cover was visually examined for the deposition of binder or water.

Outgassing - The high temperatures within the solar collector are known to cause the volatile components of an insulation to vaporize and condense on the cooler cover plate [2]. Volatile components may include water, organic binders, unpolymerized monomer, and low-temperature pyrolysis products. The principal effect that these compounds have on the solar collector is a reduction in the transmittance of the cover plate when the volatiles condense on its inside surface; this can lead to reduced thermal efficiency. In order to quantify the transmittance loss, a newly developed outgassing test method described in [4] was used. In brief, the outgassing test procedure involves placing a sample into a heated test chamber; the volatiles released subsequently condense on the glass collecting plate which is cooled by a measured flow of air over its surface. The magnitude and effect of outgassing were measured by the mass lost by the sample, mass gained by the glass plate, and percent decrease in transmittance of the glass plate after three hours of heating. For the purposes of this study the test procedure given in Appendix B was employed with the following modifications:

1. Insulation test samples were cut to a size of about 16 cm^3. These samples along with the glass plates were weighed to the nearest 0.01 mg. In addition, the transmittance spectrum of each plate was recorded between 300 and 2100 nm using a recording spectrophotometer.

2. After the sample chamber was heated to a constant temperature of 300° C, a sample was placed in the chamber, covered with a weighed glass collecting plate, and tested for a period of three hours. To maintain the temperature of the plate below that of the chamber, the cooling air flow rate was maintained at 0.55 ℓ/sec throughout the duration of the test.

3. Data were reported as mass of sample lost, mass deposited on the collector plate, and percent decrease in transmittance.

Corrosion - Contact between the insulation and the metal components of the solar collector (e.g., the absorber plate or enclosure) under the conditions of high temperature and relative humidity, can result in a significant amount of corrosion to the metal components. This could result in early failure of these metal components, and, therefore, a reduction in the lifetime of the collector.

Corrosion was studied in terms of the amount of pitting which took place when the metal was put in contact with the insulation under controlled test conditions. Four types of metals commonly used in solar collector enclosures and absorbers were tested: 1) stainless steel-type 304;

2) aluminum - 6061 T6; 3) brass - composition #24; and 4) copper - cold rolled, oxygen free.

Procedure:

1. Metal samples (50 x 75 x 3.1 mm) were scrubbed and then ultrasonically cleaned for 30 minutes in 1,1,1-trichloroethane to remove any surface grease. The samples were then rinsed in distilled water, drained and rewashed if water breaks appeared on the surface.

2. Samples were dried for one hour in a desiccator at room temperature and then examined under a microscope at 10 to 100 times magnification to determine the amount of pitting (see 5 below).

3. Each metal sample was placed on a piece of insulation (180 x 180 mm) and then placed on a ceramic plate in a crystallyzing dish (Figure 2) containing 500 ml of distilled water. Samples were kept 25 mm above the water level.

4. The crystallizing dish was covered with a watch glass and then placed in an oven at 100°C for 30 days.

5. At the completion of the test, the metal samples were removed and examined at 10 to 100 times magnification for corrosion as evidenced by pitting. The amount of pitting was classified as none, very mild, mild, severe, and very severe.

Friability - This property is potentially important because roof-mounted solar collectors may sustain vibration-induced damage caused by wind, rain, hail and normal roof maintenance. For the insulation, such damage takes the form of a breaking-up of the insulation caused by abrasion and impact between the insulation and the absorber plate or enclosure. In order to determine the extent of this breaking-up or friability the following test was devised. This test measured the weight of material shaken free from a known weight of insulation enclosed in a wire mesh container.

Procedure:

1. An insulation sample was cut to fit snugly into a retangular 75 x 100 x 75 mm container made of 16 mesh (25 mm) wire screen.

2. The tared container and its contents were weighed to the nearest 0.1 mg placed in the base of a sieve (Figure 3), covered, and shaken for 30 seconds at a rate of 150 cycles per minute.

3. At the termination of the test, the wire mesh container and insulation were reweighed to 0.1 mg. Any weight change was reported as a percentage of the original weight of the insulation.

4. RESULTS AND DISCUSSION

The tests described in the previous chapter are listed in Table 1. Table 2 contains a description of the insulations tested and their assigned codes. These codes were used to identify the samples in Tables 3 through 11, which contain the the results. The remaining portion of this chapter presents a discussion of the test results obtained in this study.

4.1 ASTM TESTS

Density and Thermal Conductivity - Data on these two insulation proper ties are given in Table 3. Note that the range in densities for the mineral fiberous and organic cellular insulations was nearly the same: 10 to 150 kg/m^3. However, ranges for the thermal conductivity showed a considerably greater difference: for the mineral fibrous insulations values fell between 3.80 and 4.75 X 10^{-2} W/m·K -- a range of only 0.95 units, while the values for the organic cellular fell between 2.60 and 5.49 X 10^{-2} W/m·K -- a range of 2.89 units. Thus for this study, the thermal conductivity parameter appears to distinguish between insulation types.

Water Absorption and Moisture Adsorption - The water absorption data (Table 4) show that insulations vary widely in their tendency to absorb water and whether they absorb more or less moisture after thermal cycling. In general, fibrous insulations absorbed more water than their cellular counterparts. On the other hand, the data in Table 5 show that insulations adsorbed very little moisture, although, at 90% RH and 23° C all but one of the fibrous insulations were found to adsorb moisture. Finally, the cellular insulations generally adsorbed less moisture than the fibrous at all three test conditions -- a result anticipated from the water absorption tests.

Hot Surface Performance - Results of the hot surface performance test are reported in Table 6 as visible changes and percent shrinkage. The data show that most insulations exhibited visible changes at various temperatures when heated from 94 to 260° C in increments of 55 ± 3° C. Three distinct levels of performance were noted: 1) those insulations that performed at moderately high temperature (150 and 209° C) with changes in color or evolution of water without change in linear dimension -- this type of performance was limited to the mineral-type insulations; 2) those insulations that performed at the highest temperature (260° C) without any observable changes -- the mineral-type insulation; and, 3) those insulations that reached their exposure limits at a low temperature (94 or 150° C) with melting and the associated shrinkage -- observed only in organic-type insulations.

Linear Shrinkage and Loss in Mass - Table 7 summarizes the linear shrinkage data for the organic cellular insulations exposed to a soaking heat of 150 and 260° C for 24 hours. The table does not show data for the mineral fibrous, mineral cellular, and organic fibrous insulations because these types suffered no change in linear dimensions under the test conditions.

The data from the "Loss in Mass" part of this test are given in Table 8. Although the data indicate a general trend toward increasing loss in mass with increasing temperature, particularly for the organic type insulations, this test was not considered essential. Any loss in mass from the collector insulation is only important when correlated with the materials or performance degradation of the collector, such as the loss in collecter plate transmittance. This correlation was made in the "outgassing" test discussed in the next section.

Resistance to Growth of Mold - The mold resistance test results showed that only three of the insulation test specimens supported the growth of mold: Calcium silicate (11-CS), cellulose (13-CL), and wood fiber (15-WF). The remaining samples showed no growth. These results indicate that the growth of mold is not a principal factor in the degradation of insulation.

4.2 NON-STANDARD TESTS

Thermal Cycling - The effects of thermal cycling on water absorption have already been discussed and the results of this test are given in Table 4. Table 9 summarizes the effects of thermal cycling on the appearance of insulations. Note that the mineral-type insulations had the highest maximum cycle temperature and exhibited relatively minor changes in appearance compared to the organic-type insulations which had low maximum cycle temperatures, accompanied by expansion, bowing, crumbling, or compaction.

Thermal cycling was also used as a degradation factor for the thermal conductivity of insulation materials. However, data for this test are not included here because with the exception of a few materials which showed only a slight decrease in thermal conductivity, little change in this parameter was observed after thermal cycling.

Outgassing - The results of the outgassing test and the effects of outgassing on transmittance through the cover plate are shown in Table 10. The few insulations tested showed only slight decreases in the weight with a corresponding increase in the weight of the glass plate and decrease in its transmittance. The only exception was the single organic cellular insulation tested (polyurethane) which lost nearly one-fourth of its original weight; this resulted in an effective decrease in cover plate transmittance of 8 percent.

Corrosion - The results of this test, which are given in Table 11, are reported in terms of the amount of pitting that took place on the metal surface. Note that only the fibrous insulations caused severe pitting of the metal surfaces, whereas the effect of the cellular insulations was restricted to mild or no pitting.

Friability - Results from this test showed that only two of the twenty-one insulations tested lost mass when subjected to vibration. As a result, the data from this test are not included in this report.

5. DRAFT PROCEDURES

Based upon the laboratory tests and results described in sections 3 and 4, the following tests have been included in the "Draft Procedures for Screening Insulation Materials used in the Solar Collectors" which is given in Appendix A.

The tests included were either identical with existing ASTM tests or newly developed tests, as indicated below:

Water Absorption - ASTM C 209
Thermal Conductivity - ASTM C 518
Linear Shrinkage - ASTM C 356
Corrosion - Newly developed
Hot Surface Performance - ASTM C 411
Outgassing - Newly developed
Thermal Cycling - Newly developed

These tests, in combination, are presented as a methodology for screening insulation materials used in solar collectors with respect to the level of performance and relative stability of solar collector insulation under simulated in-service conditions. The tests are applicable to both flexible, semirigid and rigid, loose-fill, and foamed-in-place insulation materials. Moreover, tests were chosen to allow testing of all types of insulations: mineral fibrous and cellular, and organic fibrous and cellular.

Finally, although correlations between performance under laboratory and actual in-service conditions have not yet been firmly established, the proposed standard should aid significantly in the assessment of the long-term performance of insulation materials by the type of before/after and comparative testing utilized in the above tests.

6. RECOMMENDATIONS FOR FURTHER WORK

The tests and results discussed in this report represent a small portion of the research which must be done to identify the degradation factors affecting not only the properties of solar collector insulation but also the other solar collector components. Thus, this report may be considered as a preliminary investigation. Further work should be directed toward conducting more extensive, quantitative studies of those degradation factors and properties found to be important in this study, i.e., those which are part of the tests included in the Draft Procedures. In addition, particular attention should be paid to conducting studies which will show if correlations exist between two or more insulation properties, e.g., mass lost from outgassing as a function of temperature and its affect on the loss of cover plate transmittance. These and similar in-depth correlation-type studies should lead to a greater understanding of insulation properties and solar collector performance. Finally, these studies will provide a firmer data base for proposing new recommended testing practices for the insulation and other components used in the solar collector system.

7. REFERENCES

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Table 1. Test Methods Used to Evaluate Solar Collector Insulations

ASTM Tests	
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 Absorption"
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	
Thermal Cycling	
Outgassing	
Corrosion	
Friability	

Table 2. Description of Insulations Tested

Generic Type	Sample No. and Description[a]	Form	Thickness (mm)
Mineral Fibrous	1-FG Fiber Glass	Batt	87.5
	2-FG Fiber Glass	Batt	87.5
	3-FG Fiber Glass	Board	48.4
	4-FG Fiber Glass	Board	25.0
	5-FG Fiber Glass	Batt	21.9
	6-FG Fiber Glass	Batt	37.5
	7-FG Fiber Glass	Batt	31.3
	8-SW Slag Wool	Batt	100.0
	9-SW Slag Wool	Batt	31.3
	10-RW Rock Wool	Batt	31.3
Mineral Cellular	11-CS Calcium Silicate	Tubular	25.0
	12-GF Foam Glass	Board	46.9
Organic Fibrous	13-CL Cellulose	Loose-fill	N.A.*
	14-CL Cellulose	Loose-fill	N.A.*
	15-WF Wood Fiber	Board	12.5
Organic Cellular	16-UF Urea Formaldehyde	Foamed-in-place	21.9
	17-PS Polystyrene	Board	50.0
	18-PS Polystyrene	Board	12.5
	19-PS Polystyrene	Board	50.0
	20-PU Polyurethane	Board	23.4
	21-RB Foamed Rubber	Tubular	12.5

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* N.A. - Not Applicable.

[a] These descriptions are based on the classification of insulations given in the "ASHRE Handbook of Fundamentals-1977," and, therefore, are not necessarily the same as those given by the manufacturer.

Table 3. Density and Thermal Conductivity of Insulation Materials[a]

Generic Type	Sample No.	Density (kg/m^3)	Thermal Conductivity (W/m·K x 10^2)
Mineral Fibrous	4-FG	144.0	b
	10-RW	104.0	b
	3-FG	72.0	3.80
	8-SW	52.8	3.99
	9-SW	44.5	3.77
	6-FG	19.2	4.60
	7-FG	16.0	4.49
	5-FG	16.0	b
	1-FG	12.0	4.75
	2-FG	10.0	4.60
Mineral Cellular	11-CS	184.0	b
	12-GF	140.8	5.49
Organic Cellular	21-RB	86.0	b
	19-PS	35.2	3.17
	17-PS	32.0	4.50
	20-PU	32.0	2.60
	16-UF	24.0	b
	18-PS	14.9	3.17

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[a] The organic fibrous insulations were not tested.
[b] Not determined.

Table 4. Water Absorption Before and After Thermal Cycling

Generic Type	Sample No.	Water Absorption, % by Mass		
		Before	After	% Change
Mineral Fibrous	1-FG	3064	1548	-49.5
	2-FG	1853	1893	+ 2.1
	7-FG	1874	1892	+ 1.0
	6-FG	1300	1830	+29.0
	9-SW	1136	474	-58.3
	8-SW	586	473	-19.3
	4-FG	113	35	-69.0
	3-FG	89	105	+15.2
	5-FG	43	40	- 7.0
	10-RW	20	15	-25.0
Mineral Cellular	11-CS	371	379	+ 2.1
	12-GF	14	18	+22.2
Organic Fibrous	13-CL	2273	2279	+ 0.2
	14-CL	1774	1491	-16.0
	15-CL	45	38	-15.2
Organic Cellular	16-UF	308	364	+15.4
	17-PS	92	45	-51.1
	18-PS	56	41	-26.8
	20-PU	38	56	+32.1
	19-PS	34	30	-11.8
	21-RB	26	8	-69.2

Table 5. Moisture Adsorbed by Insulations during 30-day Exposure to Different Temperatures and Levels of Relative Humidity

Generic Type	Sample No.	Moisture Adsorbed, % by Mass[a,b] 23 °C 50% RH	23 °C 90% RH	94 °C 70% RH
Mineral Fibrous	1-FG	0.4	5.3	1.0
	3-FG	1.7	4.0	-
	2-FG	-	4.0	0.4
	8-SW	-	1.7	-
	6-FG	-	1.0	-
	5-FG	0.4	0.8	-
	7-FG	-	0.5	-
	4-FG	0.1	0.4	-
	9-SW	-	0.1	-
	10-RW	-	-	-
Mineral Cellular	11-CS	0.5	13.2	0.2
	12-GF	-	-	0.1
Organic Fibrous	15-WF	1.5	10.3	-
	13-CL	1.7	4.0	-
	14-CL	0.2	1.8	-
Organic Cellular	16-UF	0.5	8.8	-
	21-RB	-	4.0	-
	20-PU	-	0.7	-
	19-PS	-	-	0.1
	17-PS, 18-PS	-	-	-

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[a] Where no value is recorded, there was no measurable gain in mass.

[b] Note that Sample Nos. 10-RW, 17-PS and 18-PS showed no moisture adsorption.

Table 6. Effect of Hot Surface Contact on the Appearance and Linear Shrinkage of Insulations

Generic Type	Sample Nos.	Surface Temperature at which First Observable Change Takes Place[a]	Linear Shrinkage[b] at 150 and/or 260 °C
Mineral Fibrous	1-FG, 2-FG 3-FG, 5-FG	209 °C - Discolors and chars	None
	8-SW, 10-RW	209 °C - Discolors	None
	4-FG	150 °C - Discolors and chars	None
	6-FG, 7-FG, 9-SW	None	
Mineral Cellular	12-GF	None	None
	11-CS	209 °C - Evolves water	None
Organic Fibrous	13-CL	209 °C - Evolves water	c
	14-CL	94 °C - Evolves water	c
	15-WF	94 °C - Discolors	3% at 150 °C >95% at 260 °C [e]
Organic Cellular	20-PU	150 °C - Melts[d] and chars	18% at 260 °C
	17-PS, 18-PS 19-PS	150 °C - Melts[e]	>95% at 150 °C[e]
	21-RB	94 °C - Discolors	18% at 150 °C
	16-UF	94 °C - Bows	14% at 150 °C >95% at 260 °C[e]

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[a] All observations made after 96 hours of exposure to the hot surface; samples were exposed successively to 94, 150, 209 and 260 °C to determine the lowest temperature required to induce an observable change.

[b] Linear shrinkage calculated as the percent reduction in the original length of the sample.

[c] Shrinkage not applicable to cellulosic loose-fill insulations.

[d] Sample melts on side exposed to hot surface.

[e] Sample melts completely.

Table 7. Linear Shrinkage of Cellular Insulation Materials Exposed to High Temperature

Generic Type	Sample No.	150 °C	260 °C
Organic Cellular[a]	20-PU	0.0 %	25.0 %
	16-UF	5.0	25.0
	21-RB	27.0	40.0
	19-PS	82.0	>95.0
	17-PS	86.0	>95.0
	18-PS	93.0	>95.0

[a] All other insulations showed no shrinkage under the same test conditions.

Table 8. Percent Loss in Mass After Heating Insulation Materials for One Hour

Generic Type	Sample No.	94 °C	150 °C	209 °C	260 °C
Mineral Fibrous	3-FG	7.0 %	10.1 %	15.3 %	42.0 %
	5-FG	1.7	1.7	3.8	4.0
	2-FG	0.8	0.8	2.9	3.0
	1-FG	1.1	1.1	2.8	3.0
	7-FG	0.9	2.1	2.1	2.0
	4-FG	0.2	0.6	1.0	2.0
	9-SW	0.3	0.3	1.0	1.3
	6-FG	0.9	0.9	0.9	1.0
	8-SW	0.5	0.5	0.5	0.8
	10-RW	0.2	0.2	0.4	0.8
Mineral Cellular	11-CS	0.7	0.7	2.6	3.5
	12-GF	0.2	0.2	0.2	0.2
Organic Fibrous	15-WF	4.1	5.3	83.1	83.1
	13-CL	31.0	36.8	73.3	74.0
	14-CL	5.6	6.4	5.2	64.0
Organic Cellular	18-PS	1.2	1.2	21.4	82.5
	16-UF	3.0	9.7	60.0	71.4
	17-PS	1.4	1.4	11.3	63.7
	19-PS	1.2	3.1	25.8	62.0
	20-PU	1.7	10.7	32.3	44.7
	21-RB	0.8	1.8	25.0	32.0

Table 9. Effect of Thermal Cycling on the Appearance of Insulation Materials

Generic Type	Sample No.	Max Cycle Temp[a] - Change in Appearance
Mineral Fibrous	3-FG, 4-FG	94 °C - Deposits binder
	8-SW, 9-SW	260 °C - Deposits binder
	1-FG, 2-FG, 5-FG	260 °C - Fluffs, Deposits binder
	6-FG, 7-FG	260 °C - Fluffs
Mineral Cellular	11-CS, 12-GF[b]	94 °C - None
Organic Fibrous	15-WF	94 °C - None
	13-CL, 14-CL	94 °C - Evolves H_2O, compacts
Organic Cellular	16-UF	94 °C - Cracks then crumbles
	20-PU	94 °C - Expands, forming 66 mm bow
	17-PS, 18-PS, 19-PS	150 °C - Expands, forming 50, 40, and 30 mm bows, respectively

[a] Thirty-cycle test; minimum cycling temperature for all samples was -40 °C.

[b] Cracked after extended 45 cycle test.

Table 10. Effect of Insulation Outgassing on Cover Plate Transmittance

Generic Type	Sample No.[a]	Mass of Sample Lost, mg (%)	Mass Deposited on Plate, mg	Decrease in Transmittance of Plate, %
Mineral Fibrous	8-FG	6.39 (0.99)	0.32	0.69
	2-FG	1.64 (1.0)	0.13	0.21
	9-SW	2.27 (0.28)	0.24	0.16
	10-RW	1.61 (0.27)	0.66	0.14
	1-FG	2.24 (0.70)	0.56	0.04
Organic Cellular	20-PU	130.53 (24)	0.48	8

[a] Sample numbers not listed were not tested.

Table 11. Corrosion of Metals by Insulation Materials[a]

Generic Type	Sample No.	Degree of Pitting			
		Stainless Steel	Brass	Copper	Aluminum
Mineral Fibrous	7-FG	Severe	Severe	Severe	V. Mild
	1-FG, 4-FG, 9-SW	--	Mild	Mild	--
	3-FG	Mild	--	--	--
	2-FG, 6-FG, 7-FG 8-FG, 10-RW	--	--	--	--
Mineral Cellular	11-CS	--	--	Mild	--
	12-GF	--	--	--	--
Organic Fibrous	13-CL	Severe	--	Mild	Mild
	14-CL	Severe	Mild	Mild	Mild
	15-WF	--	--	Mild	--
Organic Cellular	20-PU	Mild	Mild	Mild	--
	16-UF	--	Mild	Mild	Mild
	17-PS, 18-PS, 19-PS, 21-RB	--	Mild	Mild	--

[a] Results reported as severe or mild pitting of the metal surface after 30-day contact with insulation; where no pitting occurred, no result is given.

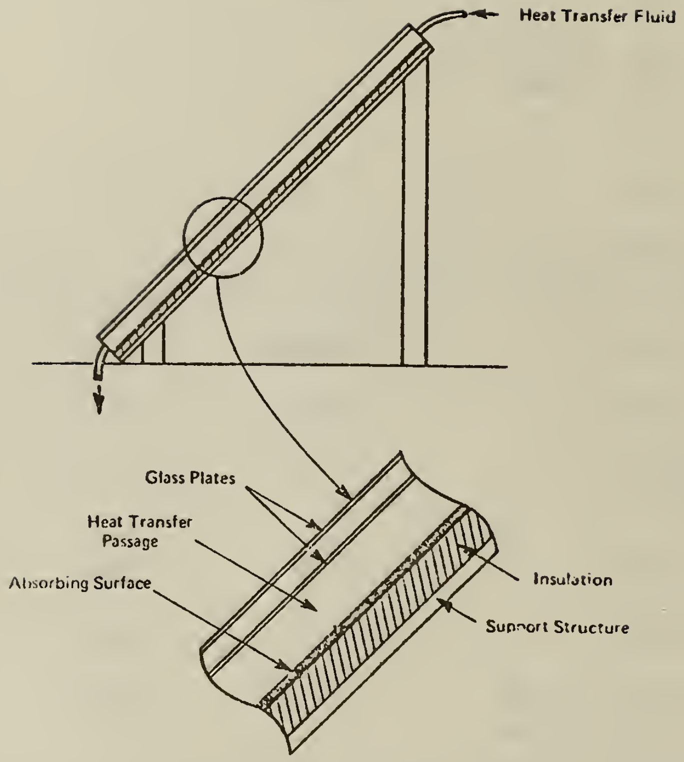

Figure 1. Essential features of a flat plate solar collector.

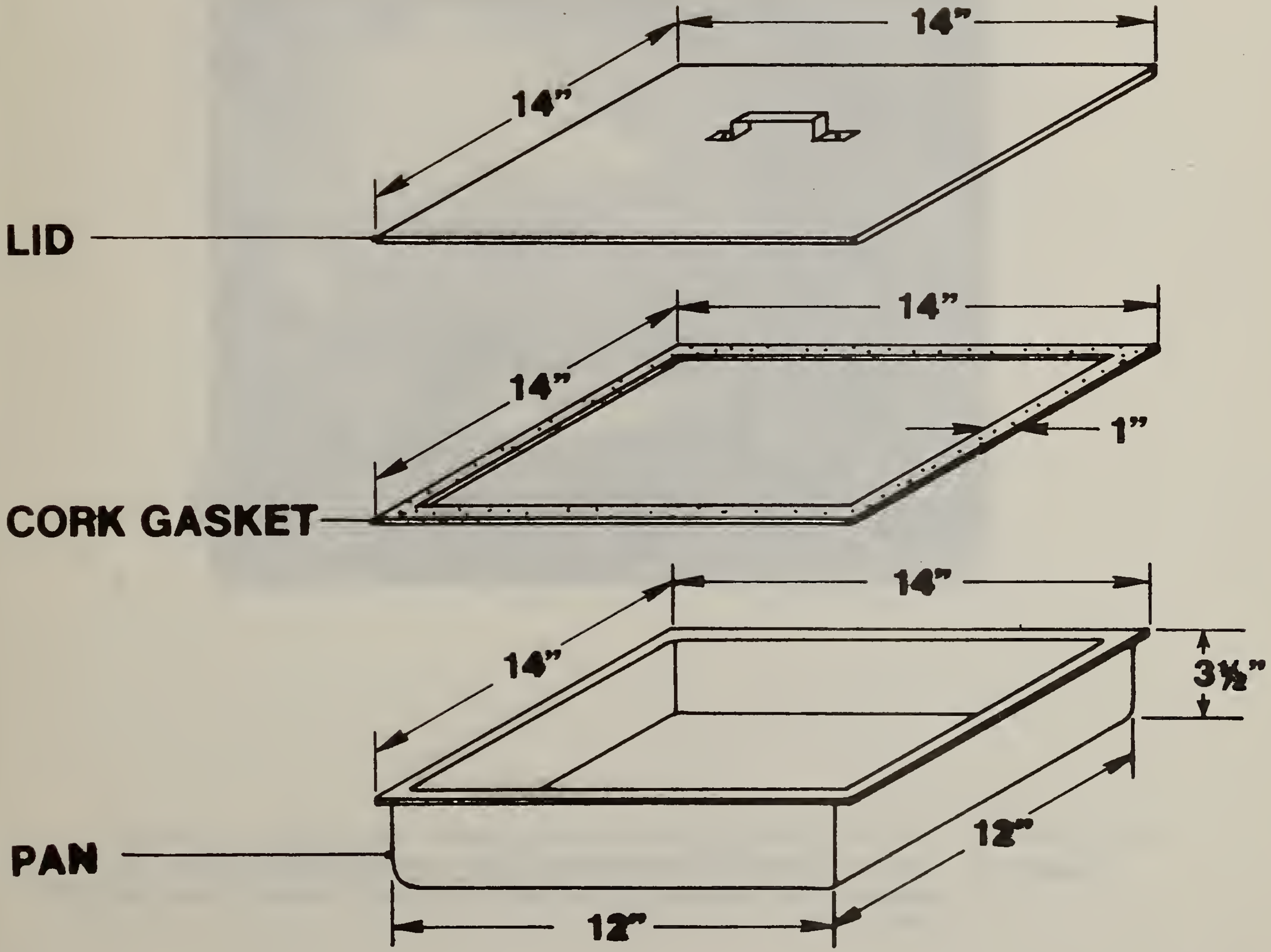

Figure 2. Diagram of the aluminum pan used in the thermal cycling test.

Figure 3. Crystallizing dish containing water and metal specimens in contact with insulation, as used in the chemical compatability test.

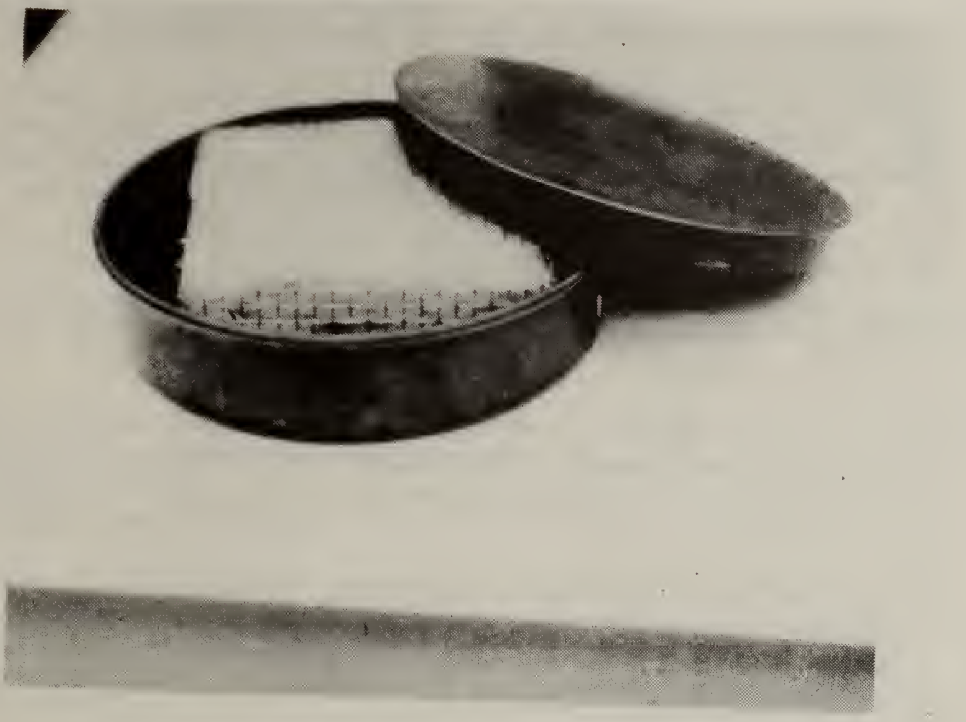

Figure 4. Insulation sample enclosed within the wire mesh container and sieve pan as used in the friability test.

APPENDIX A

Draft Procedures for Screening Insulation Materials Used in Solar Collectors

1. Scope

1.1 This set of draft procedures provides a methodology to screen insulation materials used in solar collectors with respect to their level of performance and relative stability under simulated in-service conditions. Test methods are given to measure water absorption, thermal conductivity, corrosion, hot surface performance, outgassing, and thermal cycling. It is intended that these procedures fulfill one of the steps in the development of a standard set of test methods for evaluating insulations used in solar collectors.

1.2 The methods are applicable to flexible, semirigid, and rigid board, loose-fill, and foamed-in-place insulation materials. Tests were chosen to allow testing of all types of insulation: mineral fibrous and cellular, and organic fibrous and cellular.

1.3 The assumption is made that elevated temperature, temperature cycles, moisture and their resulting stresses are the primary factors that cause degradation of the insulation materials used in solar collectors.

1.4 Test methods included in the document are both property measurement tests and aging tests. Property measurement tests are tests which provide for measurement of various properties of insulation, e.g., thermal conductivity.

Aging tests are tests which provide for exposure of insulation to environments that may induce changes in the properties (degrade) of test specimens. Measuring properties before and after aging test provides a means of determining the possible effect of aging.

2. Significance and Use

2.1 This draft set of procedures is intended to aid the assessment of long-term performance by comparative testing of insulation materials. However, correlations between performance under laboratory and actual in-service conditions have not been established.

3. Applicable Documents

ASTM C 209	Testing Insulating Board (Cellulosic Fiber), Structural and Decorative.

ASTM C 411	Test for Hot-Surface Performance on High-Temperature Thermal Insulation.
ASTM C 518	Steady State Thermal Transmission Properties by Means of the Heat Flow Meter.

3. Test Specimens

3.1 Specimens for each test condition shall be randomly selected from the original sample lot so as to be as representative as possible.

3.2 At least three specimens shall be measured for each property tested.

3.3 The size and shape shall be as specified in the property measurement test.

4. Conditioning

4.1 Unless otherwise specified, test specimens shall be conditioned at 73 ± 5°F (23 ± 2° C) and 50 ± 5% rh for at least 48 hours before testing.

5. Methods of Test

5.1 Property Measurement Tests

5.1.1 Water Absorption

5.1.1.1 Determine water absorption of the insulation material in accordance with ASTM C 209.

5.1.1.2 Determine the quantity of water absorbed (expressed as a percentage by weight and by volume) by the insulation material.

5.1.2 Thermal Conductivity

5.1.2.1 Measure thermal conductivity according to ASTM C 518.

5.2 Aging Tests

5.2.1 Corrosion

5.2.2 Determine the contact corrosion between the insulation and metals (e.g., absorber plate or enclosure) using the following procedure:

a. Cut metal samples to a size 50 X 75 X 3.1 mm and then scrub samples and clean them ultrasonically for 30 minutes in 1,1,1-trichloroethane. Rinse samples with distilled water. Drain. If water breaks appear, rewash.

b. Dry for one hour in a desiccator at room temperature. Examine each sample under a microscope at 10 to 100 times magnification and record the amount of pitting (see "e" below).

c. Place each sample on a 180 X 180 mm piece of insulation, and then place both in a crystallizing dish containing 500 ml of distilled water.

d. Cover the crystallizing dish with a watch glass and place in an oven at 100° C for 30 days. Keep samples 25 mm above the water level by adding make-up water as necessary.

e. At the completion of the test, remove metal samples and examine the contact side for corrosion under a microscope at 10 to 100 times magnification. The corrosion is based on a subjective visual evaluation of the amount of pitting which has occurred on the surface of the sample; five classes of pitting are used to describe the results: none, very mild, mild, severe and very severe.

5.2.2 Hot Surface Performance

5.2.2.1 Hot surface performance shall be determined in accordance with ASTM C 411. Test at 200 ± 10° F (94 ± 5° C) and 500 ± 10° F (260 ± 5° C) if maximum temperature conditions are unknown.

5.2.3 Outgassing

5.2.3.1 Determine the effect of outgassing products in cover plate transmittance using the method described in Appendix B with the following modifications to the procedure: 1) weigh test specimen and the glass plate to the nearest 0.01 mg, and 2) adjust the temperature of the test apparatus to a temperature which is representative of the maximum in-service temperature.

5.2.4 Thermal Cycling

5.2.4.1 Determine the effect of thermal cycling on the properties of insulation using the following test procedure:

a. Condition insulation samples for 48 hours at 73 ± 5° F (23 ± 2° C) and 50 ± 5% rh, then place in a suitable aluminum pan and cover.

b. Subject the pan (containing the insulation) to 30 cycles of:

- Heating for 7.5 hours at the maximum in-service temperature.
- Conditioning 73 ± 5° F (23 ± 2° C) and 50% rh for 30 minutes.
- Cooling at the minimum in-service temperature.
- Conditioning at 73 ± 5° F (23 ± 2° C) and 50% rh for 30 minutes.

6. Procedure

6.1 Select 4 sets of specimens for each insulation material to be evaluated. Each set shall consist of at least three identical test specimens.

6.2 Water absorption (5.1.1) and thermal conductivity (5.1.2) of Set 1 specimens. Measure the dimensions of Set 4 specimens.

6.3 Expose Set 1 specimens to thermal cycling as described in 5.2.4.

6.4 Remeasure the water absorption and thermal conductivity of Set 1 specimens as decribed in 6.2. Also, visually examine specimens for expansion, cracking and fluffing and examine the inside of the cover for deposition of binder or water.

6.5 Expose Set 2 specimens to the corrosion test (5.2.1). After exposure, determine extent of corrosion as described in 5.2.2.e.

6.6 Expose Set 3 specimens to the outgassing test described in 5.2.3.

6.7 Expose Set 4 specimens to the hot surface performance test described in 5.2.2. After the exposure, visually inspect the insulation and remeasure the dimensions of specimens.

7. Report

7.1 The report should include:

7.1.1 Complete identification of the insulation material

7.1.2 Water absorption and thermal conductivity obtained from 6.2 and 6.4.

7.1.3 Results of the corrosion test (6.5).

7.1.4 Results of outgassing of test (6.6)

7.1.5 Results of hot surface performance test (6.7).

7.1.6 Test temperature used, the thermal cycling test (6.3) and the hot surface performance test (6.7).

7.1.7 Documentation of instrument and procedures for measuring transmittance in the outgassing test (6.6).

7.1.8 Deviations from specified procedures or conditions.

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

A preliminary study was performed to evaluate potential procedures for screening the insulation used in solar collectors. Both ASTM standard test methods and newly developed non-standard procedures were used to evaluate twenty-one insulation materials. The insulation parameters measured in this study were selected on the basis of how and to what extent they were affected by the unique environmental conditions within solar collectors. Results of the laboratory tests are discussed and those procedures which offer a potential for screening insulations used in solar collectors are presented. It is intended that these procedures fulfill the first step in the development of a standard set of test methods for evaluating insulations for solar collectors.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Accelerated aging; collector insulation; insulation; solar collector; standard insulation test methods.

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