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Self-Heating to Ignition Measurements and Computation of Critical Size for Solar Energy Collector Materials

Joseph J. Loftus

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Fire Research
Gaithersburg, MD 20899

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Final Report

Prepared for:

**U.S. Department of Energy
Office of Solar Heat Technologies
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Washington, DC 20585**

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

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SELF-HEATING TO IGNITION MEASUREMENTS AND COMPUTATION OF
CRITICAL SIZE FOR SOLAR ENERGY COLLECTOR MATERIALS

Joseph Loftus

Abstract

Kinetic constants of the self-heating reaction were determined for plywood, a retardant treated plywood, and eight samples of polyurethane foam representing possibly two different kinds of foam materials. Under the assumption that self-heating follows a first order reaction, these constants were used to calculate the critical half thickness of slabs of these materials for surface temperatures likely to be experienced during long term use in solar energy collectors. Based on these calculations, estimates are provided on the self-heating or ignition hazards associated with the size and use of these materials in solar energy systems.

Key words: Critical temperature; ignition hazards; polyurethane foams; plywood; reaction rate; self-heating; solar collectors; wood.

1. Introduction

In May of 1980 a solar energy collector fire incident occurred in Boulder, Colorado in an unoccupied single family dwelling. It was reported that the house was part of a Federal residential solar heating and cooling demonstration program and that damage due to the fire was limited to the collector and adjacent roofing and framing materials. Further investigations revealed that the solar collector itself was the only possible source of heat

for ignition and that the most likely point of ignition was the plywood base or backing of the collector. Identical collectors on three other dwellings at the same site were found to have backing material or plywood deck in various stages of thermal degradation. This may have ultimately led to similar fire incidents.

In July 1980, the Department of Energy (DOE) requested that the National Bureau of Standards (NBS) review the factors which may have led to the ignition of the Colorado collector system and to provide recommendations as to how similar events may be prevented in the future. The Solar Technology Group, Building Equipment Division, Center for Building Technology at the Bureau, gave this task to the Center for Fire Research and requested that the ignition characteristics of polyurethane foam insulation materials be determined.

2. Description of a Collector and Solar Energy System

From information supplied by investigators [1]*, the solar energy collector was reported to be a flat plate type with overall dimensions of approximately 91 cm (36 in.) wide by 239 cm (94 in.) long by 8.9 cm (3.5 in.) thick. Glazing consisted of two sheets of tempered glass separated by an air space. The absorber was pressure-bonded copper with a black chrome selective surface. The insulation directly behind the absorber plate consisted of approximately 4.4 cm (1 5/8 in.) of factory-applied spray-in-place urethane foam. The back of the collector was 0.95 cm (3/8 in.) exterior grade plywood; the framing was clear heart redwood.

*Numbers in brackets pertain to references listed in Section 14

The manufacturer of the collector reported that the frame and plywood back were assembled and then urethane foam was sprayed on the plywood prior to the absorber and glazing being set in place. This process was said to cause a natural adhesion between the plywood back and the foam insulation. The collectors were mounted in direct contact with the roof which had a slope of 6 in. rise per linear foot.

The roof consisted of "90-lb." rolled roofing with a granular surface between the collector backing and the 1.3 cm (1/2 in.) CDX plywood roof deck. Insulation for the roof was 15 cm (6 in.) kraft paper faced glass fiber insulation between 2 x 8 in. joists which were 61 cm (24 in.) on center. A layer of gypsum board underneath formed the interior finish of a cathedral type ceiling. A cross section of the collector and roof is illustrated in Figures 1 and 2 respectively.

The solar energy system used with the collector was an active fluid type designed to provide domestic hot water and space heating. The heat transfer fluid was water, and freeze protection was provided by a drain-down design. Since the house was unoccupied, it was likely that the collector experienced non-operating or stagnation conditions during a significant portion of time between its installation and the fire. Flat plate solar collectors under stagnation conditions can have absorber plate temperatures over 204°C (400°F) in the case of double glazed, selective surface collectors. After some period of time at these temperatures, degradation of plastic foam insulation, wood and other combustible materials would likely occur within the collectors.

3. Cause of the Fire

It was reported that the foam in all the collectors investigated had degraded. The plywood backing showed signs of blackening or conversion into charcoal only in areas where the urethane foam layer had partly melted away and become very thin or when large cracks had opened exposing the plywood. As the plywood was heated over long periods at moderate temperatures, it is suspected that charcoal was formed and that it self-heated or smoldered to a glowing combustion. Porous charcoal containing a large surface area is subject to rapid oxidation and self-heating. There are a number of articles in the literature [2-7] which describe the behavior of wood exposed to moderately elevated temperatures. At low temperatures, wood degrades over a long period of time. Experiments on ignition of wood after prolonged heating are difficult to conduct and results vary because of variation in exposure conditions, wood types and material geometries. Experimental work by fire researchers indicate that cyclic periods of heating and cooling, the moisture content of the wood, the oxygen supply, the wood type, and material thickness may all be factors in determining the length and severity of exposure required for ignition.

Polyurethane foams have been known to self-heat especially when freshly made and stocked in large piles [8]. There is very little information available on the temperature at which rigid urethane foams degrade when heated for extended periods of time. This is due in part to the fact that their composition and properties vary widely. Investigators of the Colorado

collector fire proposed that the polyurethane did not supply sufficient heat to start the plywood ignition; however, it may have contributed to the fire when ignited by glowing plywood. This fire incident clearly suggests that a need exists to gain an understanding of the relationships between self-heating and the physical parameters involved.

4. Self-Heating

For the purposes of this report, self-heating will be defined here as that condition which occurs when the rate of heat generation within a material exceeds the rate at which heat is lost by radiation, convection, and conduction to its surroundings.

The problem of self-heating was addressed by Gross and Robertson [9] who used an adiabatic furnace test apparatus to measure self-heating of materials under conditions of negligible heat loss. Under these conditions, the specimen temperature remained uniform throughout its mass and the heat generated within the body increased its temperature according to the relation:

$$\rho c \frac{dT}{dt} = A \exp (-E/RT) \quad (1)$$

where: ρ	= density	g cm^{-3}
c	= specific heat	$\text{cal g}^{-1} \text{K}^{-1}$
T	= temperature within material	K
t	= time	sec
A	= heat generation coefficient	$\text{cal sec}^{-1} \text{cm}^{-3}$
E	= activation energy	kcal mole^{-1}
exp	= Napierian base	
R	= gas constant = 0.0019872	$\text{kcal mole}^{-1} \text{K}^{-1}$

By transposing terms, taking logarithms and plotting $\ln \frac{dT}{dt}$ versus $\frac{1}{T}$, the resultant line has a slope of $-\left(\frac{E}{R}\right)$ and intercepts the $\ln \frac{dT}{dt}$ axis at the $\ln \frac{A}{\rho c}$. For a test material, the determination of the values of A and E can be made if the thermal properties ρ and c are known. General self-heating problems can then be solved, including the case where size and temperature become critical and ignition results.

5. Critical Size

The critical condition of ignition in the theory of thermal explosions was proposed by Frank-Kamenetskii [10]. Chambre [11] presented analytical solutions in terms of known functions for a sphere, a cylinder, and a semi-infinite slab. Analyses by Genensky [12] for a sphere and by Thomas [13] for all three geometries have assumed that temperature differences within the material are small in comparison to the absolute temperature. Enig, Shanks, and Southworth [14] removed this restriction and provided solutions in the form of convenient tables of the center and surface temperatures for sphere,

cylinder, and semi-infinite slab geometries. They proposed that the critical size for materials may be determined by the relation,

$$B_s^2 = \frac{\gamma \lambda R T_c^2}{A E} \exp (-E/RT_c) \quad (2)$$

where: B = radius or half thickness cm
 γ = experimental parameter
 λ = thermal conductivity cal sec⁻¹cm⁻¹ K⁻¹
(assumed uniform and constant)

From their tables, the critical half thickness of a slab B_s can be determined given an assumed surface temperature T_c.

The size of material and its corresponding surface temperature are referred to here as critical size and critical surface temperature because the steady state condition is critical to ignition. Also, the ambient temperature corresponding to given critical steady state conditions with given heat losses is considered the critical ambient or self-ignition temperature. Note that in this analysis a heat transfer coefficient is not included but would be required in order to determine the critical size for a given ambient air temperature. For reasons described in Section 3, critical conditions developed at the location of the solar collector system's plywood roof deck/polyurethane foam interface where heat energy from the sun collected at this

surface faster than it could be dissipated through the well insulated roof deck. Because the plywood ignited in this particular scenario, it is clear that material thickness becomes a critical factor for certain levels of temperature exposure and work needs to be done to determine critical size for solar collector materials.

6. Test Apparatus

Figure 3 shows a schematic diagram of the adiabatic furnace test apparatus used to make the self-heating determinations. Briefly the apparatus consists of a 5 liter capacity Dewar flask which is enclosed within a close fitting cylindrical shell. The shell consists of two concentric stainless steel cylinders containing electric heating elements and insulating fill material. The shell also contains a bottom guard heater; a top heating element is located in the plug that fits into the top of the Dewar flask. Air is circulated around the test specimen by a fan whose motor assembly is mounted at the top of the furnace. A multiple junction thermocouple system consisting of eight No. 28 gauge chromel-alumel thermocouples arranged in series is used as the sensing element for a servo controller designed to maintain null temperature differences between the specimen surface and its center. The controller can sense temperature differences on the order of 0.01°C . Typical surface/center differentials or sample/air differentials were 0.1. The rate of drift of furnace temperatures as observed with an inert specimen was 0.003°C/hr .

7. Test Materials

It is unfortunate that the sprayed-in-place urethane foam insulation from the Colorado solar collector fire incident was not available for this study, however, a total of 8 polyurethane foam samples gathered from a number of different solar collector test sites throughout the country were furnished for test. In the labeling scheme, a letter identifying the collector type (C,F,G and H) is followed by a number identifying the test site (3,4) which in turn is followed by another number identifying the test series (2). For example, C-32 represents collector type C, exposed at test site (3), to a series (2) exposure condition. For this test series the "32" samples were exposed at site (3) Palo Alto, California under (2) stagnation conditions. The "42" samples were exposed at site (4) Gaithersburg, Maryland also under (2) stagnation conditions. Stagnation here means no fluid flow through the collector plate. Table 1 lists the color and thickness of the materials and indicates whether aluminum foil facing was attached to one or both surfaces of the rigid foam materials. Visual inspection showed that none of the sample materials were damaged in any way and, except for color, no differences were noted among the foam materials. Plywood and retardant treated plywood rounded out the test material listing and these were supplied by the Center for Fire Research. The retardant treatment used for the plywood materials is not known.

8. Material Conditioning

Test samples were made up of 7.6 cm (3 in.) diameter disks stacked to form a cylinder 7.6 cm (3 in.) high. Two sample sets were prepared from each of the plywood test materials. One was conditioned in the laboratory at room conditions of 20°C (68°F) and 50 percent relative humidity, while the other was conditioned in an air circulating oven operated at 95°C (203°F). The length of time a sample remained in the room or the oven before testing, was recorded as the total number of days conditioned for test samples listed in Tables 3 and 4. Oven conditioning was used to determine whether long term aging (up to 2 years) at an elevated temperature would have any effect on the self-heating characteristics of the plywood materials. The polyurethane foam samples were not oven conditioned prior to test to avoid the possibility of ignition of the sample in the oven or the release of noxious gases into the laboratory.

9. Test Results

Although it may have been possible to start the self-heating tests at lower ambient air temperatures, a decision was made to initiate testing at approximately 120°C (248°F). This temperature selection was based in part on (a) past self-ignition experience with wood materials, (b) a report by the American Plywood Association [7] that the critical temperature for wood materials range from 110 to 150°C (230 to 302°F), (c) an attempt to reproduce those temperatures reported by Boeing Co. in simulated solar collector tests

on a built up roof deck, and (d) on a desire to complete the self-heating tests in a reasonable length of time.

The plywood test samples, randomly selected and tested over a two year period, self-heated to destruction in times ranging from 40 to 45 hours, while the eight polyurethane foams required 5 to 10 hours to destruct.

Table 2 lists the physical and kinetic properties for the test materials. The values of ρ and c were obtained from handbook sources [15,16]. The estimated accuracy for the polyurethane foam values is about 3 to 4 percent. The kinetic constants E and A were determined over the indicated temperature ranges from a least squares fit of the experimental data assuming first order reaction (equation 1). Figures 4 and 5 show typical plots of the rate of temperature change ($^{\circ}\text{C}/\text{min}$) versus the reciprocal of temperature (K) for plywood and retardant treated plywood samples with zero days conditioning. Tables 3 to 5 show computed critical half thickness (cm) for slabs of retardant treated plywood, plywood, and the polyurethane foams respectively, for projected ambient temperatures ranging from 20 to 120°C (68 to 248°F).

Figures 6 to 11 show plots of these data from zero day ambient conditions taken from tables 3 to 5.

10. Observations

1. The retardant treated plywood discolored and charred badly as a result of one week of oven conditioning at 95°C .

2. Activation energy values determined for plywood ranged from 21 to 23 kcal/mole. By comparison, Stamm [17] reported values ranging from 23 to 26 kcal/mole for wood, alpha-cellulose and lignin.
3. Room conditioned plywood and retardant treated plywood samples showed (with one exception) increased critical pile size with the number of days conditioned before test. Reasons for this phenomenon are not clear. It may be due to changes in moisture content, glue curing, or loss of retardant treatment with time.
4. Oven conditioned plywood and retardant treated plywood samples showed generally lower computed critical size values than did room conditioned materials for 20°C (68°F). However, at higher temperature levels, 40 to 120°C (104 to 248°F), pile size differences were negligible.
5. Aging of plywood samples at 95°C (203°C) for extended periods of time (up to 2 years) did not appear to affect the self-heating characteristics of the plywood and retardant treated plywood materials tested here. MacLean [4], however, reports charring of wood samples at temperatures as low as 93°C (203°F). He concludes that wood should not be exposed to temperatures appreciably higher than 66°C (150°F) for long periods. McGuire [5] suggests that the maximum safe temperature on the surface of a combustible material adjacent to a constant heat source should not be more than 100°C (212°F). Numerous documented fires involving the ignition of wood members near low pressure steam pipes [6] suggest an upper limit for

wood exposed to long-term low-level heating should not be appreciably higher than 100°C (212°F).

6. Data for polyurethane foams shows that the "42" labeled samples (with the exception of "G") produced slightly larger half thickness values for slabs than the "32" labeled foams. Since no information was furnished on the properties of the urethane foam samples, the significance of slab size differences between the foam sets could not be established.
7. Considering 20°C (68°F) ambient temperature conditions, slab half thicknesses for all foams ranged from 11 to 57 cm (4.3 to 22 in.). At 120°C (248°F) slab thicknesses for all foams were similar to those determined for the plywood samples.

11. Discussion

The Boeing Company (Report TR-2-5612-8000-039) used a solar simulator to determine the effects of radiant heat transfer on materials used in a full size solar collector mounted on a simulated roof deck. For tests simulating non-operating or stagnant condition, Boeing used a solar irradiance ranging from 0.08 to 0.11 watts/cm (250 to 350 BTU/ft hr), (solar constants 0.566 to 0.792). After seven hours of testing, the peak temperature measured at the plywood/foam interface was 144°C (292°F) and inside the polyurethane foam insulation it was 173°C (344°F). Material inspection after the tests showed degradation of the polyurethane foam and charring on the plywood collector base surface. Additional tests showed that for a collector not mounted

directly on a simulated roof, the plywood/foam interface peak temperature was 89°C (188°F) and the foam temperature was 136°C (278°F).

Based on Boeing's findings one may conclude that the solar collector not mounted directly on the roof was a slightly better assembly because the air space between the bottom of the collector and roof surface allowed for lower temperatures in the solar collector materials. In effect, the insulation contribution of the roof to the assembly was negated. Comparison of this temperature data with the self-heating data reported here, however, indicates that these polyurethane foam materials would be destroyed in either solar collector assembly. Plywood/foam interface temperatures in Boeing's work were 173°C and 89°C (344 and 188°F) for the direct mount and air mount assemblies. Based on the CFR data, the 173°C (344°F) temperature would be unacceptable and the 89°C (188°F) temperature would only allow for a few cm thickness for foam and plywood material to be used in the collector.

12. Conclusions and Recommendations

Analysis of self-heating to ignition tests were made under the assumption that self-heating follows a first order reaction law. Experimental determinations of kinetic constants of this reaction were made for the solar collector materials furnished for test and for plywood and retardant treated plywood. These constants were used to compute critical ambient temperatures as a function of sample size. The critical half thicknesses for slabs predicted from these measurements were only a few centimeters for temperatures in the vicinity of 120°C. This suggests that self-heating ignition may be expected,

and that proper fire-safe designs of collectors should ensure that (1) permissible operational and stagnation temperatures be lowered, or (2) material thicknesses decreased, or (3) less ignition prone materials be employed in regions of expected high temperatures. If plywood and polyurethane materials, similar to those tested, are retained, steps should be taken to ensure that the allowable ambient temperature limit is reduced considerably. From the critical size data developed in this test series it appears that 60°C (140°F) would be about the maximum allowable temperature for plywood layers but thicknesses of approximately 8 cm (3.2 in.) would be the largest acceptable for the polyurethane materials.

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TABLE 1. SOLAR COLLECTOR MATERIALS

Material	Color	Thickness mm	Al. Facing
C-32 urethane foam	pink	76	none
C-42 urethane foam	cream	76	none
F-32 urethane foam	tan	25	2 surfaces
F-42 urethane foam	tan	25	2 surfaces
G-32 urethane foam	tan	25	1 surface
G-42 urethane foam	tan	25	1 surface
H-32 urethane foam	pink	25	2 surfaces*
H-42 urethane foam	pink	25	2 surfaces*
plywood	natural	12	none
retardant treated plywood	natural	12	none

* one surface painted

TABLE 2. PHYSICAL AND KINETIC PROPERTIES

MATERIAL	THERMAL			KINETIC			STARTING FURNACE TEMPERATURE RANGE ° C
	ρ g cm ⁻³	c cal g ⁻¹ K ⁻¹	λ cal sec ⁻¹ cm ⁻¹ K ⁻¹	E kcal mole ⁻¹	A cal sec ⁻¹ cm ⁻³		
C-32	.027	0.38	5.51 x 10 ⁻⁵	11.3	7.58 x 10 ⁺²	(119-180)	
C-42	.030	0.38	5.51 x 10 ⁻⁵	12.3	1.97 x 10 ⁺³	(122-186)	
F-32	.034	0.38	5.51 x 10 ⁻⁵	12.3	6.12 x 10 ⁺³	(117-196)	
F-42	.032	0.38	5.51 x 10 ⁻⁵	14.1	3.99 x 10 ⁺⁴	(118-198)	
G-32	.029	0.38	5.51 x 10 ⁻⁵	17.7	2.36 x 10 ⁺⁶	(120-183)	
G-42	.029	0.38	5.51 x 10 ⁻⁵	16.6	4.74 x 10 ⁺⁵	(116-192)	
H-32	.034	0.38	5.51 x 10 ⁻⁵	12.2	6.91 x 10 ⁺³	(120-215)	
H-42	.036	0.38	5.51 x 10 ⁻⁵	14.6	7.97 x 10 ⁺⁴	(116-226)	
PLYWOOD	.47	0.55	2.56 x 10 ⁻⁴	21.0	1.00 x 10 ⁺⁹	(120-154)	
RETARDANT TREATED							
PLYWOOD	.59	0.55	2.56 x 10 ⁻⁴	23.0	1.16 x 10 ⁺¹⁰	(120-170)	

TABLE 3. RETARDANT TREATED PLYWOOD

Slabs - Computed Critical Half Thicknesses (cm) at Various Temperatures

Conditioning		Temperature (C)					
@ Ambient 20°C	@ 95°C	20	40	60	80	100	120
<u>Days</u>	<u>Days</u>	<u>Half Thickness (cm)</u>					
0		180	53	18	7	3	1.5
420		214	60	20	7	3	1.4
540		180	52	18	7	3	1.4
730		263	72	23	9	4	1.5
	14	51	20	9	4	2	1.3
	69	202	59	20	8	3	1.3
	100	103	36	15	7	3	1.3
	171	114	37	14	6	3	1.4
	266	131	42	15	6	3	1.4
	630	257	70	23	8	4	1.5
	730	78	28	11	5	3	1.5

TABLE 4. PLYWOOD

Slabs - Computed Critical Half Thickness (cm) at Various Temperatures

Conditioning		Temperature (C)					
Ambient 20°C	@ 95°C	20	40	60	80	100	120
<u>Days</u>	<u>Days</u>	<u>Half Thickness (cm)</u>					
0		96	33	13	5	3	1.3
420		198	56	19	7	3	1.4
540		302	79	25	9	4	1.3
690		401	103	31	11	4	1.8
	21	55	20	8	4	2	1.4
	85	103	35	14	5	3	1.5
	177	62	23	10	5	3	1.3
	248	206	60	20	8	3	1.6
	540	74	26	11	5	3	1.3
	600	112	37	14	6	3	1.4
	680	122	40	15	7	3	1.5

TABLE 5. POLYURETHANE FOAMS

Slabs - Computed Critical Half Thickness (cm) at Various Temperatures

Foam Material	Temperature (C)					
	20	40	60	80	100	120
	Half Thickness (cm)					
C-32	16	10	6	4	3	1.9
C-42	23	13	8	5	3	2.2
F-32	13	7	5	3	2	1.2
F-42	22	11	6	4	2	1.4
G-32	57	23	10	5	3	1.6
G-42	52	22	11	6	3	1.9
H-32	11	6	4	3	2	1.1
H-42	24	11	6	4	2	1.3

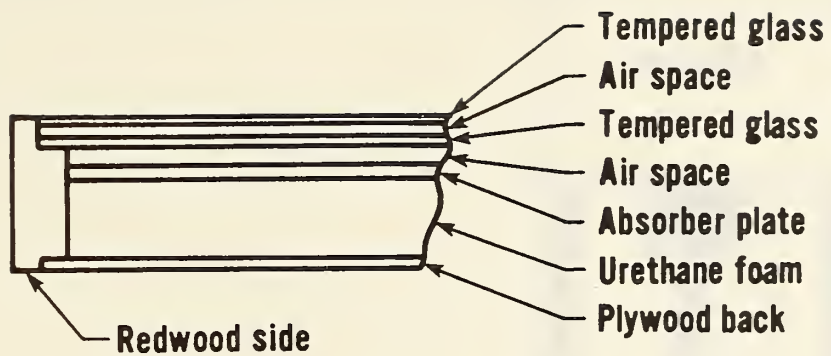
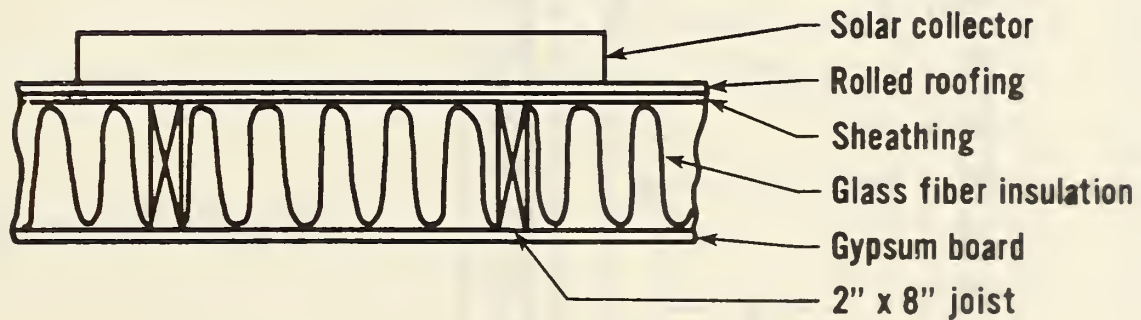


Figure 1. Collector Section



Not to scale

Figure 2. Roof Section

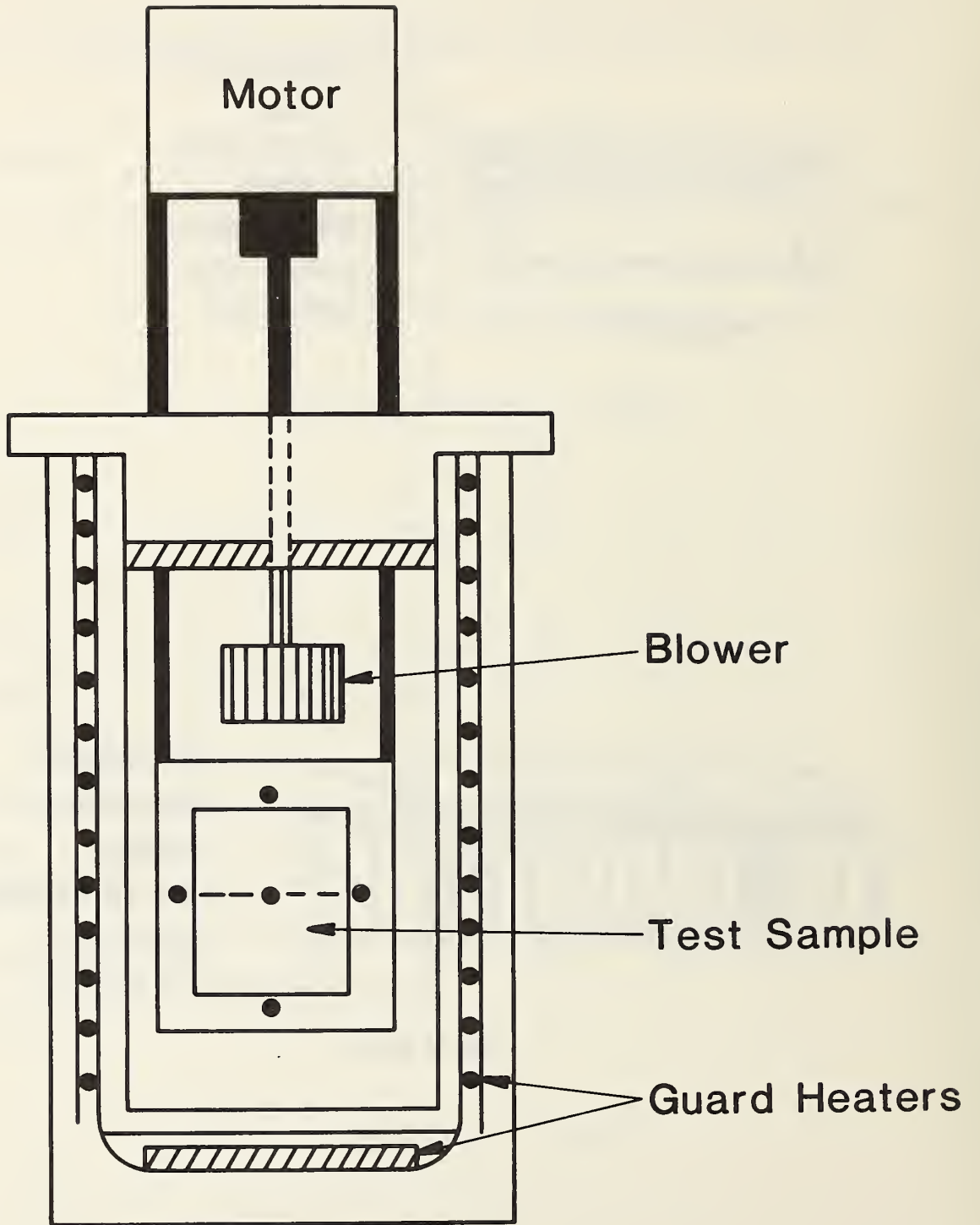


Figure 3. Adiabatic Furnace Test Apparatus

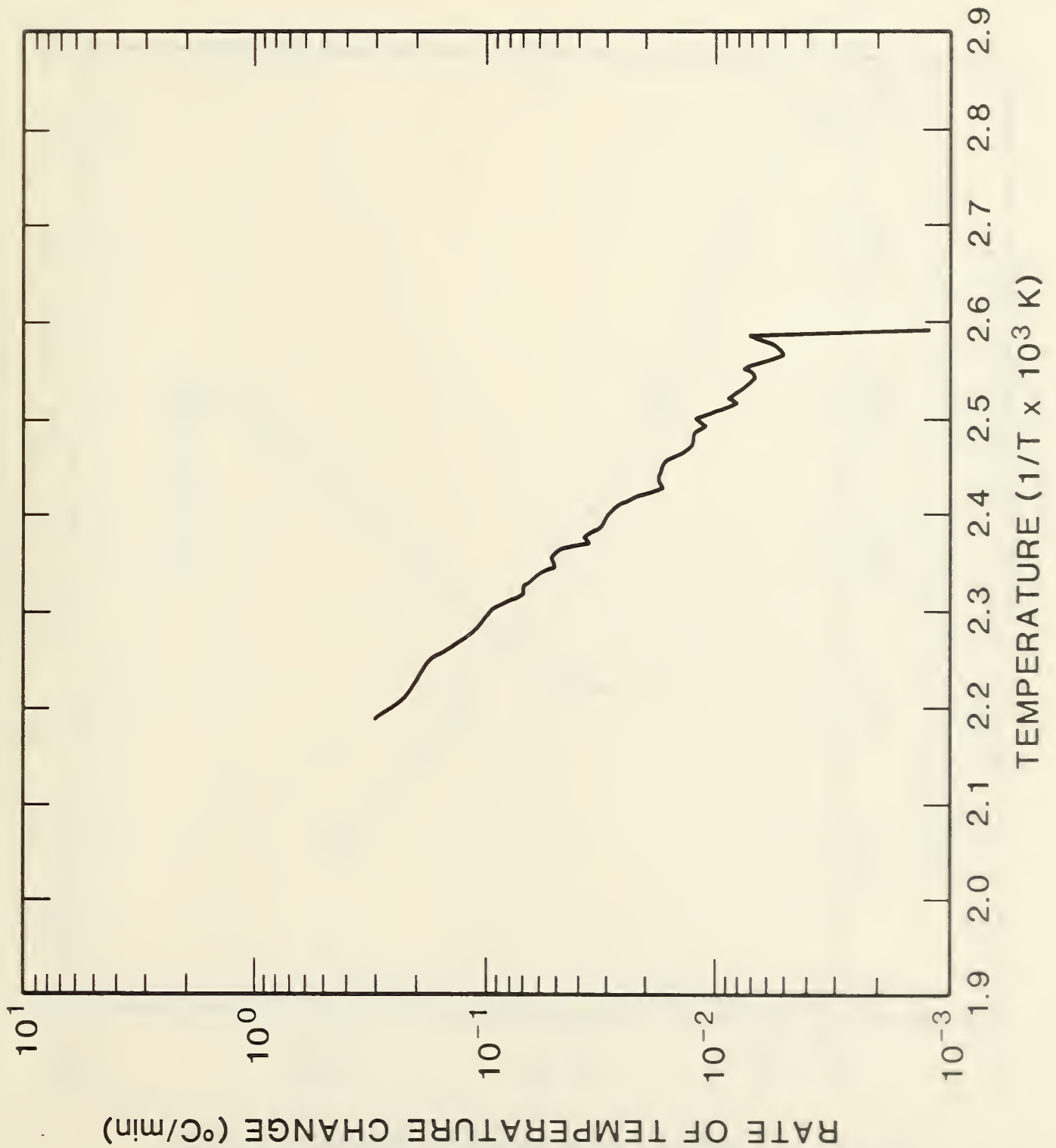


Figure 4. Plywood: Zero days Conditioning at Room Conditions. Rate of Temperature Change Versus Reciprocal Temperature K

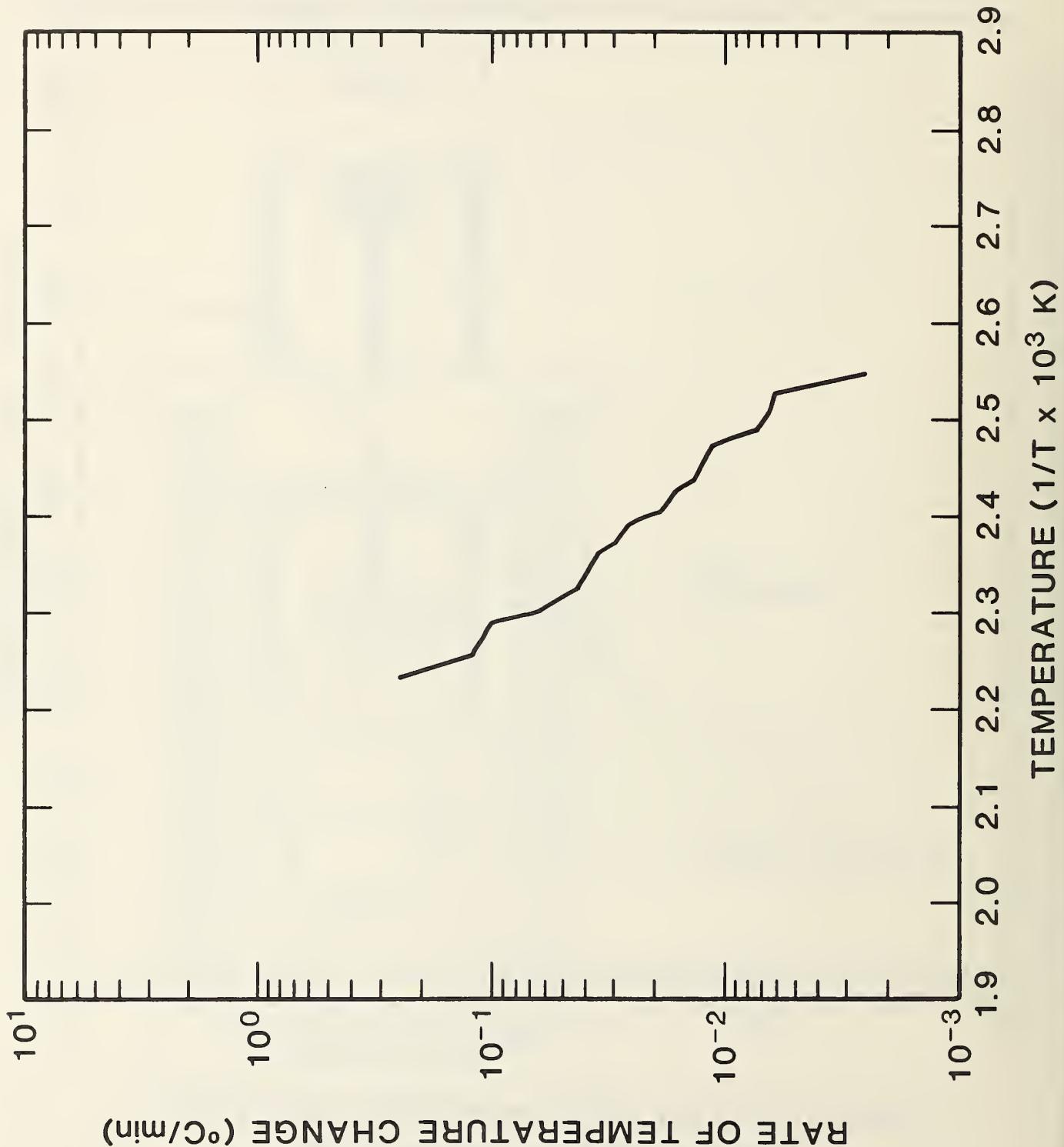


Figure 5. Retardant Treated Plywood: Zero Days Conditioning at Room Conditions. Rate of Temperature Change Versus Reciprocal Temperature K

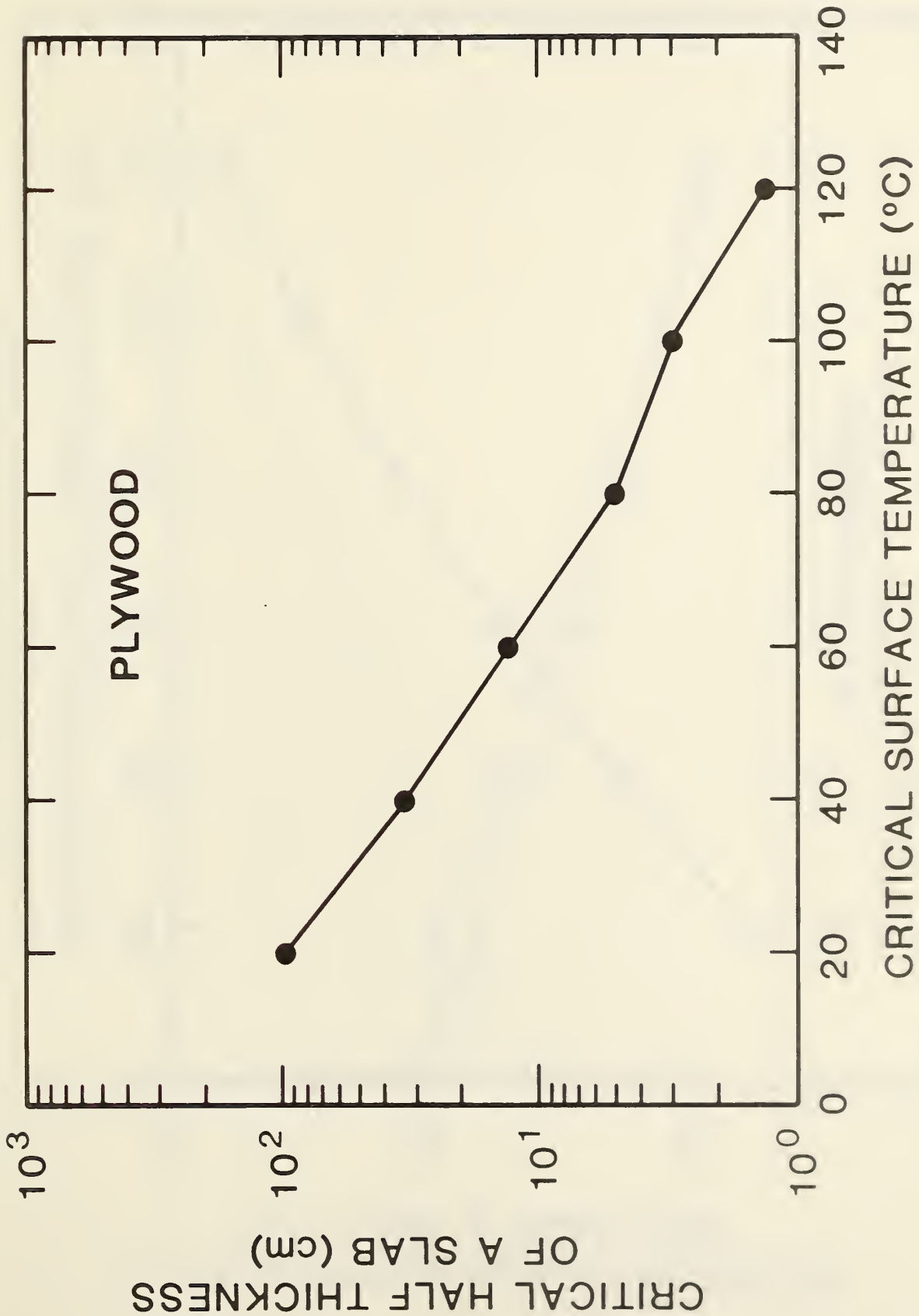


Figure 6. Plywood - Computed Critical Half Thickness (cm) of a Slab Versus Critical Surface Temperature °C

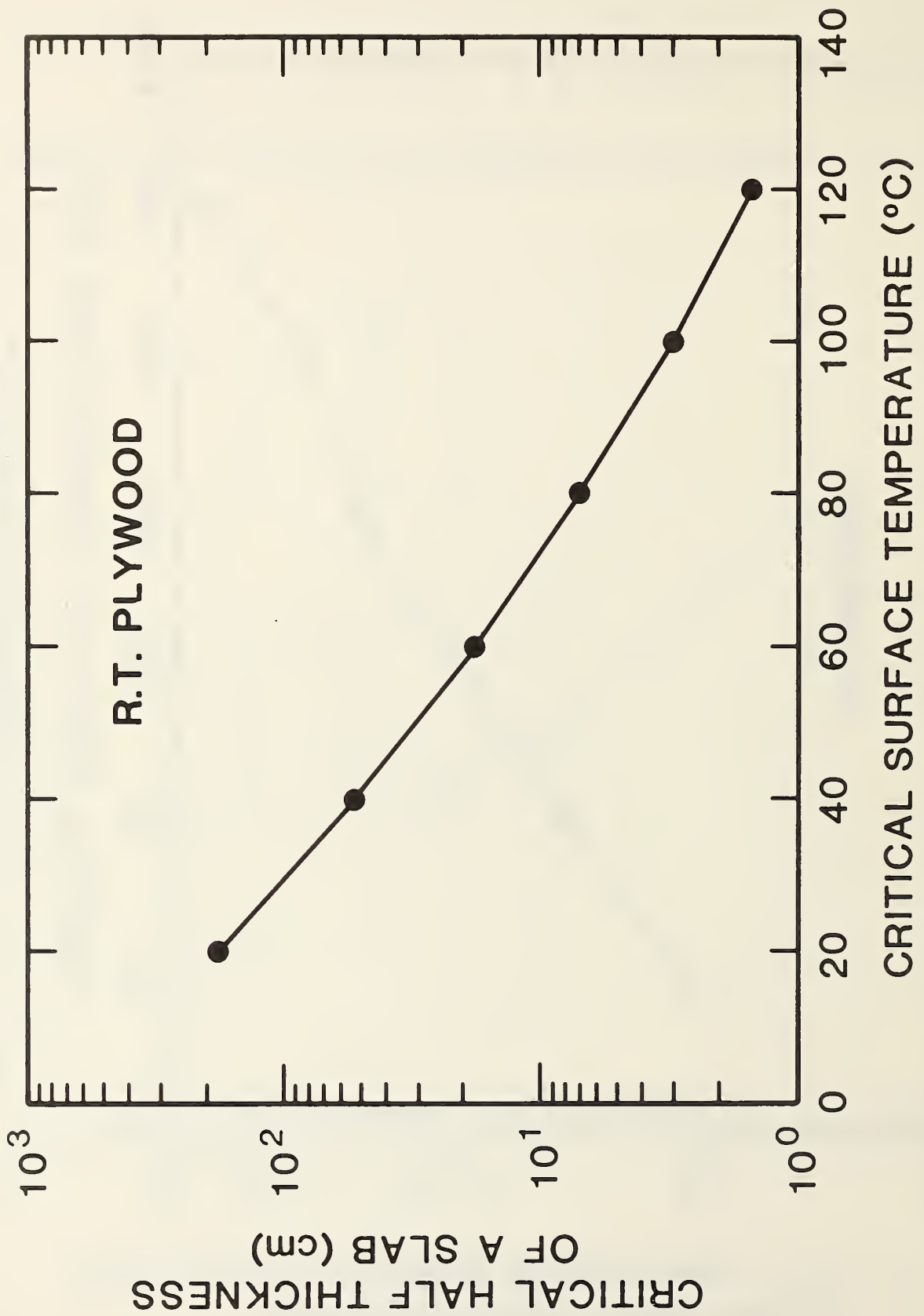


Figure 7. Retardant Treated Plywood - Computed Critical Half Thickness (cm) of a Slab Versus Critical Surface Temperature °C

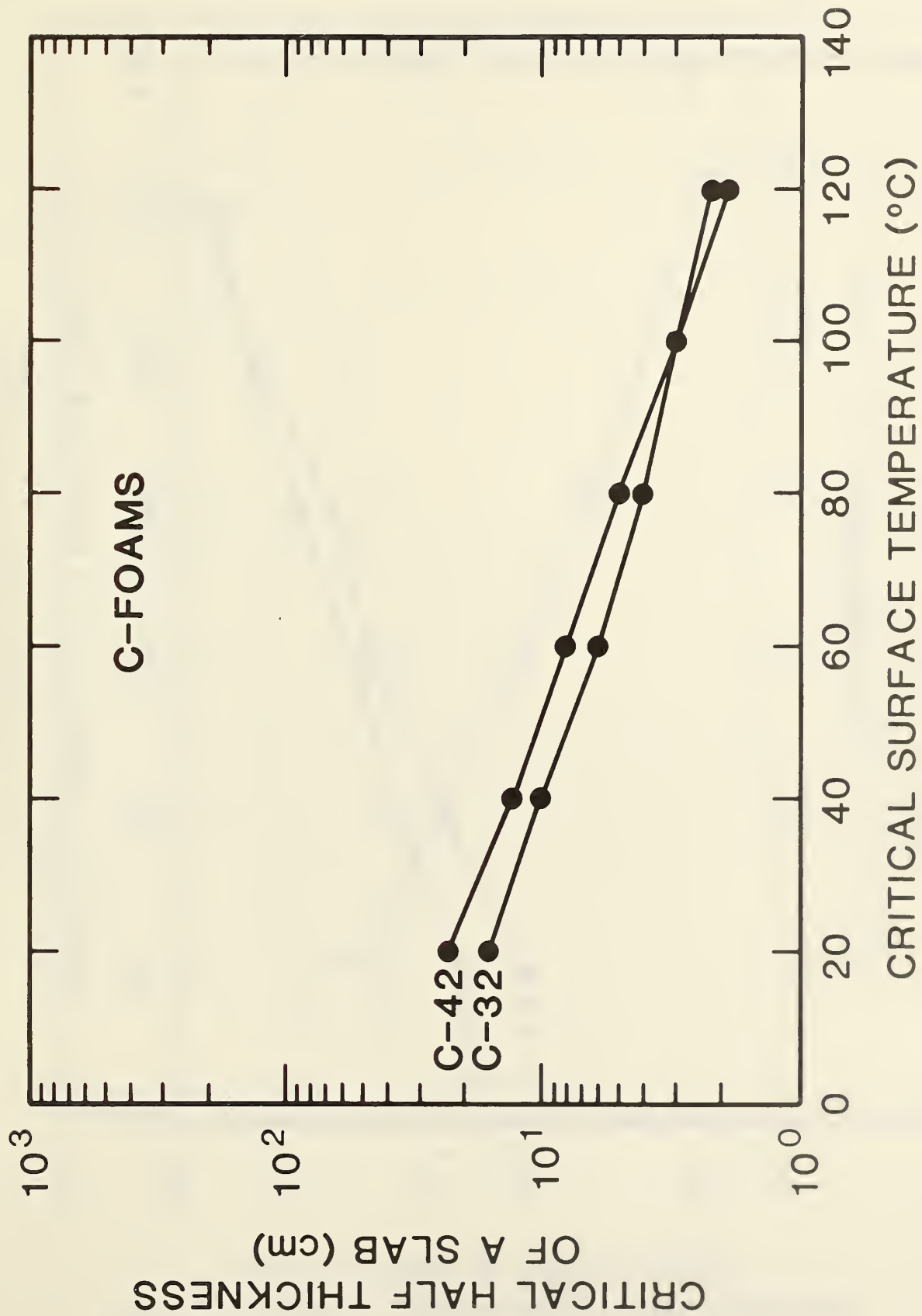


Figure 8. Computed Critical Half Thickness (cm) of a Slab for Urethane Foam C-32 and C-42 Versus Critical Surface Temperature °C

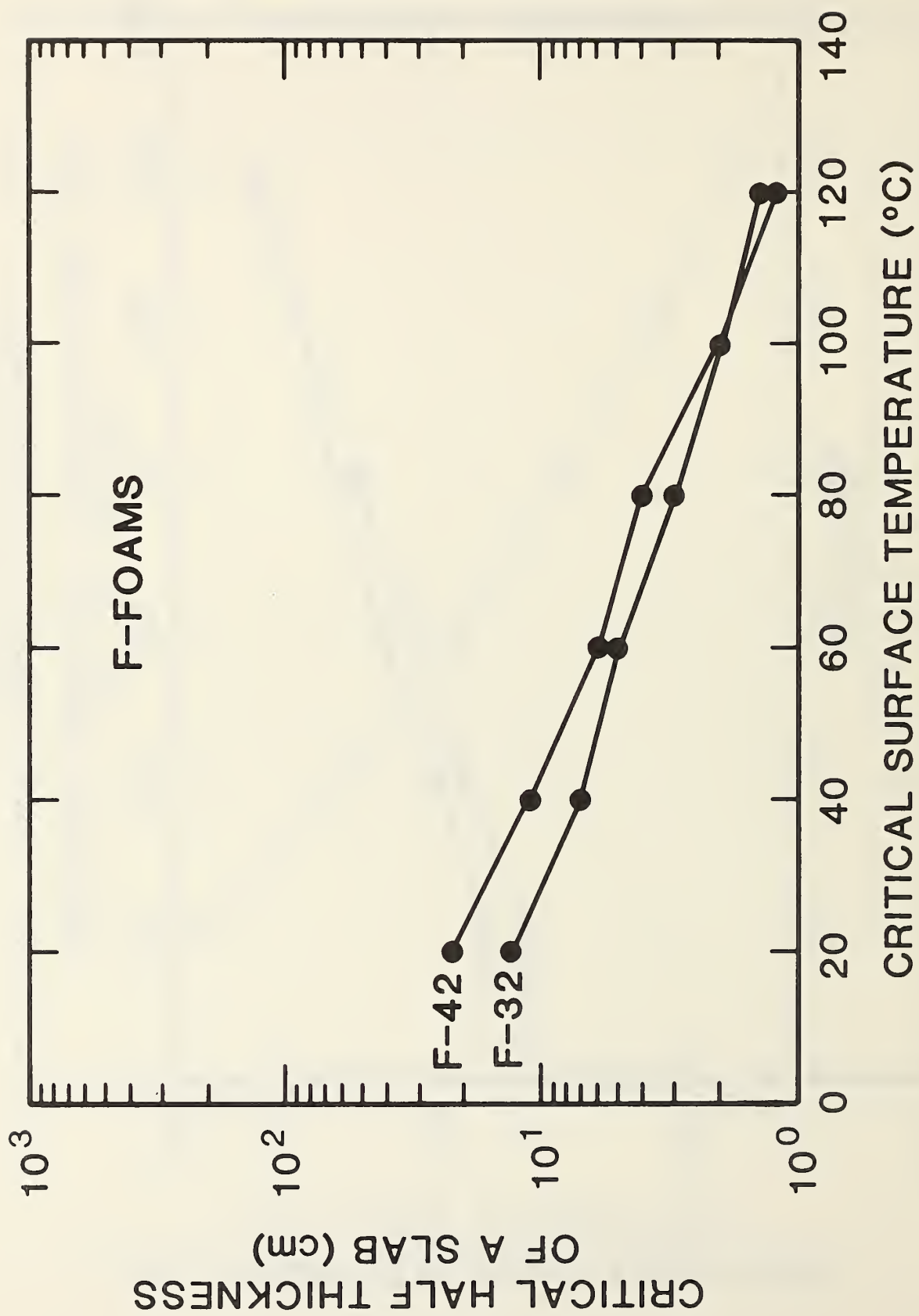


Figure 9. Computed Critical Half Thickness (cm) of a Slab for Urethane Foam F-32 and F-42 Versus Critical Surface Temperature °C

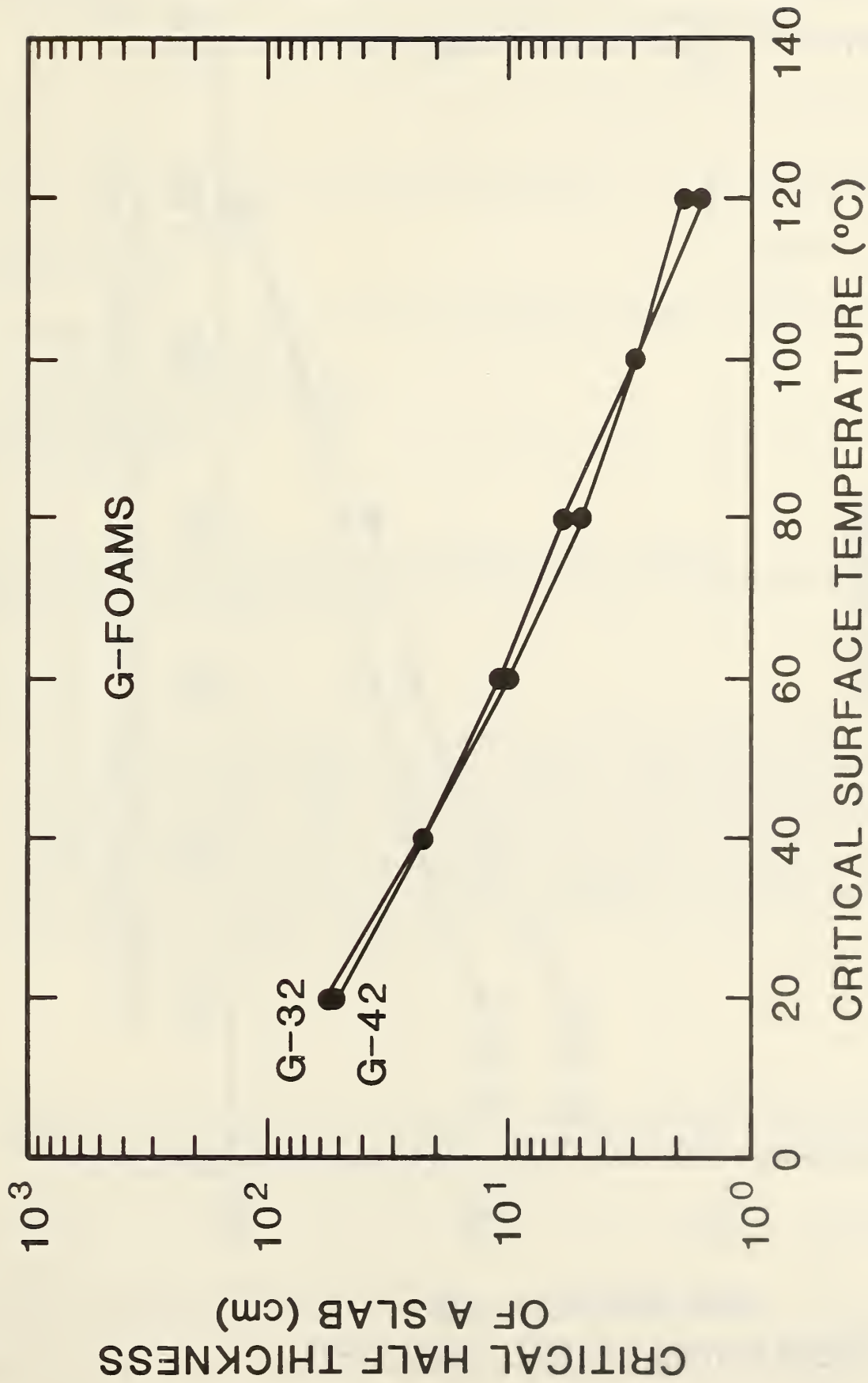


Figure 10. Computed Critical Half Thickness (cm) of a Slab for Urethane Foam G-32 and G-42 Versus Critical Surface Temperature °C

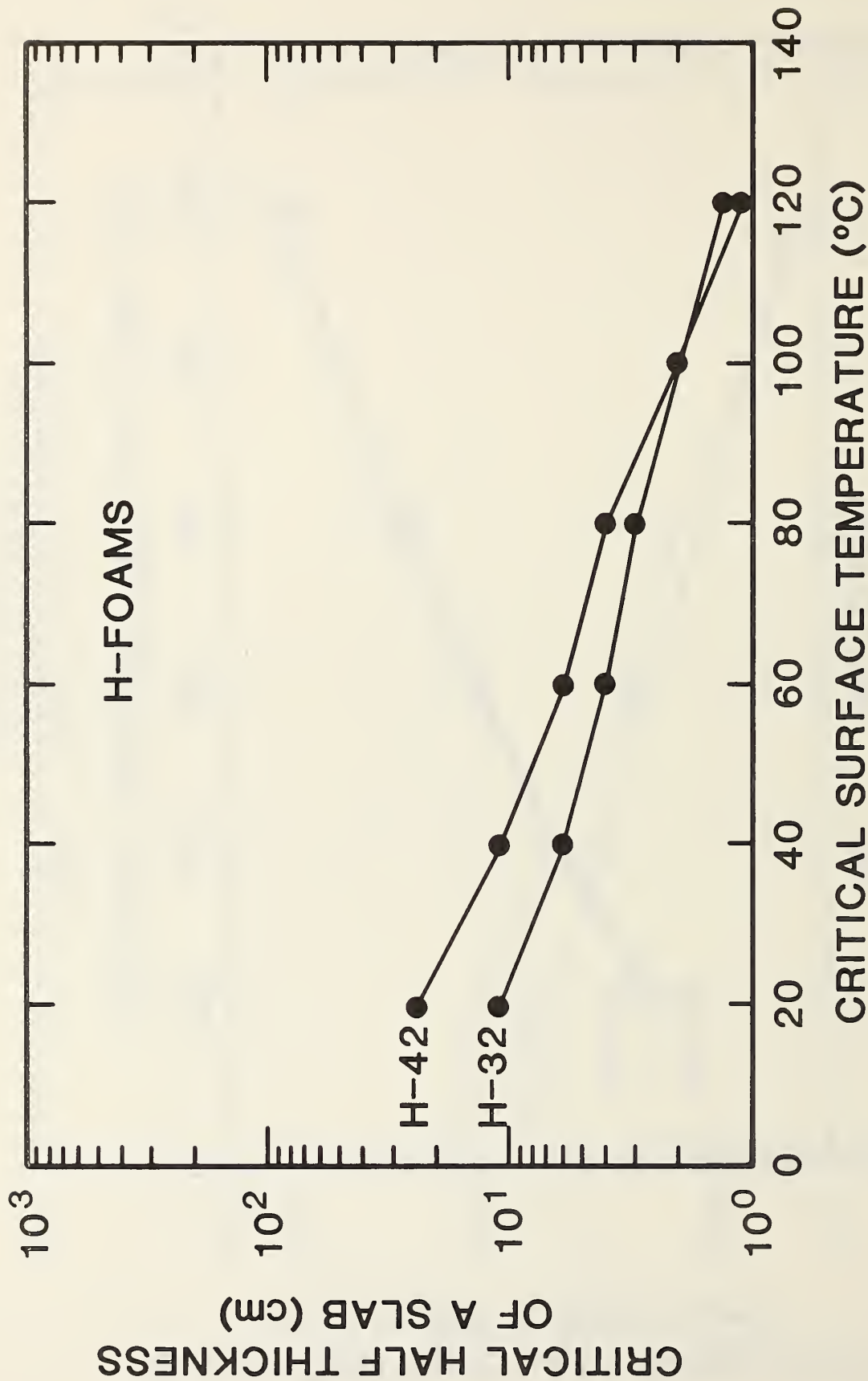


Figure 11. Computed Critical Half Thickness (cm) of a Slab for Urethane Foam H-32 and H-42 Versus Critical Surface Temperature °C

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11. ABSTRACT <i>(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)</i> Kinetic constants of the self-heating reaction were determined for plywood, a retardant treated plywood, and eight samples of polyurethane foam representing possibly two different kinds of foam materials. Under the assumption that self-heating follows a first order reaction, these constants were used to calculate the critical half thickness of slabs of these materials for surface temperatures likely to be experienced during long term use in solar energy collectors. Based on these calculations, estimates are provided on the self-heating or ignition hazards associated with the size and use of these materials in solar energy systems.			
12. KEY WORDS <i>(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)</i> Critical temperature; ignition hazards; polyurethane foams; plywood; reaction rate; self-heating; solar collectors; wood.			
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