NATIONAL BUREAU OF STANDARDS REPORT

10 495

THE DEVELOPMENT OF A TEST FOR EASE OF IGNITION BY FLAME IMPINGEMENT

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Progress Report
by
William J. Parker
Fire Research Section
Building Research Division
Institute for Applied Technology
National Bureau of Standards

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1.0 INTRODUCTION

The buildup of fire in a room starts with the ignition of an item of furnishing or a part of the room structure followed by flame spread which increases the burning area. The heat released in the burning of this enlarged area may ignite nearby items or simply cause a rise in temperature of the gases near the ceiling. If the upper wall and ceiling surfaces are combustible, pyrolysis gases are eventually produced, if sufficient heat is released from the burning area to cause the combustible surfaces in the upper part of the room to exceed their pyrolysis temperature. These gases can either be ignited spontaneously by further increases in temperature or be ignited by contact with flames extending upward into this zone. The sudden spread of flame across the ceiling is referred to as flashover.

When the walls and ceiling are not combustible the hot gases can still raise their temperatures to a point at which the thermal radiation levels exceed the critical irradiance of the combustible materials everywhere in the room. Since nearly all of these items can catch fire within a very brief interval of time, this phenomenon is also sometimes referred to as flashover. Both types of flashover mark the onset of a fully involved room fire.

Ignition, flame spread, and heat release all play a role in the buildup of fire in a room. Each of these fire phenomena must be quantified and examined in order to make the best assessment of the fire vulnerability of a room. Ultimately the buildup must be described mathematically in terms of these quantified fire variables. This requires a meaningful measurement of these variables for the materials comprising the structure and furnishings of the room.

Fire test methods are designed to measure these fire variables for a given set of test conditions, which attempt to simulate a realistic fire environment. Since this environment changes from one room fire to another, from one time to another in a given fire, and from one place to another at a given time, it is important that the test be able to specify how the materials respond over a range of environmental conditions. Since a given test method cannot be expected to permit the full range of environmental variation encountered in room fires it is necessary to develop techniques for extrapolating the results to situations which cannot be tested. This is best accomplished by the development of a physical and mathematical model, which itself can be tested by predicting the results of the test method over its limited range of environmental variation. Therefore, it is imperative that the test method be amenable to as simple a mathematical description as possible. As the results of the test become successfully predictable by the model, in terms of the thermochemical and thermophysical properties of the material, an attempt to rationalize the results of full scale fire from these properties can be made.

This report deals with the development of an ignition test method along with some discussion of the considerations leading to an accompanying mathematical model.

2.0 BACKGROUND

There are several alternate types of ignition: piloted or spontaneous, transient or sustained, radiation induced or flame contact. Both ignition time and ignition temperature have been used to characterize the ease of ignition of a material. The multiple efforts to evaluate these parameters were reported (1).

Even when the ignition type and characterization parameter are specified, the ease of ignition of a particular material may depend on its dimensions, incident heat flux, and the environmental conditions, such as air composition, air velocity, and air temperature. Variations among the conditions, characterization parameters, and ignition types can lead to a different fire hazard ranking of the materials being tested. Until a comprehensive ignition model can be established, the most desirable procedure for setting up an ignition test is to expose the specimens to the most severe conditions likely to be encountered, in the type of fire environment to which the material might be subjected. The ignition type and characterization parameter should be chosen for the particular application being considered.

The test method described here was designed to evaluate the ease of ignition of building materials in contact with flames from incidental or low energy fires. A typical example is a wastebasket fire adjacent to a wall. In the case of fires in the corners of a room or in narrow spaces between walls and furniture there can be an appreciable exchange of heat between the exposed surfaces. In the case of an isolated surface this heat would be lost to the surroundings. Since the trapping of this heat represents the most severe case in practice, the present test was designed to take this situation into account. The large reduction in heat losses from the surface of the specimen also serves to simplify the mathematical description and thus facilitate the development of the model. An attempt was made to make the surface heat flux as uniform as possible for the same reason.

3.0 TEST APPARATUS

A schematic of the test apparatus is shown in Figure 1 and a photograph of the apparatus can be seen in Figure 2. Two specimens 5½ inches wide and 6 inches high face each other 7/8 of an inch apart. The exposing flame passes between their surfaces and extends about 10 inches above them. The burner consists of two water cooled brass blocks, 4½ inches high, 6 inches wide, and 1 inch thick, facing each other with a gap of 3/4 inch between them. City gas passes into the gap by means of a horizontal row of 1/16 inch holes, ½ inch apart, located 3/8 of an inch up from the bottom of each block and extending the full width. These holes are drilled into a cylindrical plenum, 3/8 of an inch in diameter, running the full width of the block. The gas inlet connection passes into the center of the plenum from the back of the block. A 20 mil coiled michrome heater wire, 3 inches long, with a current of 7 amperes, located between the blocks, 1/4 of an inch above the row of holes, serves to ignite the gas as soon as it is turned on. The current is immediately cut off after ignition of the gas in order to avoid burning out the wire due to the combined heating by the current and the flame. The water cooled blocks are given a coating of black velvet paint to provide

a constant, high, and known value of absorptance for calculation purposes.

A network of intersecting holes, 3/8 of an inch in diameter, provide a path through each block for water cooling. The blocks are mounted on a table 16 inches long by 10 inches wide. The area of the table between the two blocks is cut away so that the air for combustion of the gas can be drawn in from underneath by free convection. The table is located in a cabinet 24 inches long, 30 inches high, and 12 inches deep with a pyrex viewing window in the door. The location of the table is adjustable with respect to the cabinet in order to balance the effect of the walls on the exposing flame. Openings 9 inches wide and 3 inches high, 3 inches from the bottom of each end of the cabinet admit the required fresh air. There is also an opening 5 inches wide and 5 inches deep at the top of the cabinet to permit the escape of the combustion products. The cabinet is located inside of a chemical hood.

The frame extending above the two water cooled blocks holds the specimens exactly 7/8 inches apart and shields their edges from the exposing flame. Each specimen is held against the frame by two 3/8 inch wide spring loaded clamps which contact its back surface adjacent to the vertical edges. The back surfaces of the specimens are open to the atmosphere except where they are contacted by the clamps.

The heat flux into the specimens from the exposing flame is measured with the copper disk calorimeter seen in Figure 3. It consists of two blackened copper disks each flush mounted with 3 pins in an asbestos cement board of the same dimensions as one of the specimens. The disks are 1/8 inch thick and 3/4 inches in diameter, located 1½ inches from the top and bottom of the asbestos cement board. The heat flux at the two elevations is measured from the rate of temperature rise of the two copper disks. The average heat flux and its variation with height are obtained from this measurement. At a total gas flow rate of 23 CFM of city gas the average flux is 3.3 watts/cm^2 with a variation of 40% over the height of the specimen. The flame which is stabilized along the surface of the block is well established along the length of the specimen and extends about 10 inches above it. The effective flame temperature measured with an uncorrected 10 mil thermocouple in the center of the space between the specimens was 910°C. The highest heat transfer rates and effective flame temperatures measured above trash barrel fires in tests at NBS were 5.26 watts/cm^2 and 1050°C (2). Usually, however, they were smaller than the values used in the test.

4.0 TEST PROCEDURE

The test begins by igniting the gas with the nichrome wire and simultaneously starting a stop watch. The object of the test is to determine the flame exposure time required to produce sustained flaming of at least one of the two specimens. Sustained flaming is defined as having occurred if a flame persists anyplace on the specimen one minute after the gas has been cut off. The ignition time is determined from a series of exposures on pairs of previously unexposed specimens. For each exposure the gas is turned off at some predetermined time, the presence or absence of sustained flaming is noted, and the next exposure time is chosen.

The ignition time is taken to be the median time between the shortest exposure resulting in sustained ignition and the next lower exposure level used in the test. The time between these determining exposures must not be over 10% of the largest one. Although the present data does not reflect this practice, it is suggested that there be at least three unsuccessful exposures at times within 5% of the quoted ignition time; or at the next lower second for times less than 20 seconds.

5.0 INITIAL TESTS

An earlier model of the ease of ignition test was used to compare the ignition times for three fiber glass reinforced polyester panels with and without flame retardant treatment with that of wood fiber insulating board; oak, pine and redwood boards; and fir and marine mahogany plywood. These data are included here to illustrate the ability of this test procedure to distinguish between the ignitability of different materials and different treatments.

These tests showed that the fire retardant treatment was sufficient to reduce the ignitability of the fiber glass reinforced panel to a value comparable to that of the marine mahogany plywood, which was the most difficult to ignite of the woods tested. The exposure times used to estimate the time of ignition for each of the materials are listed in Table I. Numbers B1, DR682T, and H26641 refer to untreated plastics, while numbers A1, FR6692T, and H24370 refer to those with fire retardant treatment. The variation of ignition time with the different materials is illustrated on a linear time line in Figure 4. The larger incident heat flux of 4 watts/cm^2 and the different exposure pattern resulted in shorter times to ignition than those reported for the present apparatus.

6.0 RESULTS WITH PRESENT APPARATUS

Tests were run on red oak, redwood, and wood fiber insulating board using the present apparatus. Each material was tested under two conditions, dried at 65°C for 24 hours and in equilibrium at 50% relative humidity. The times to ignition are based on 5 to 8 specimen pairs for each material at each condition. The exposure times are listed in Table II. The variation in ignition times with the different materials and conditions is illustrated on a linear time line in Figure 5. The dried samples are taken from different lots than the conditioned ones. Therefore the differences in ignition times are not entirely due to moisture content.

TABLE I

EXPOSURE TIMES USED TO ESTIMATE IGNITION TIMES (ti) IN THE INITIAL TESTS

Wood fiber Insulating Board	Pine	Redwood	Fir Plywood	Red Oak	Marine Mahogany Plywood
17 (0)	34 (0)	45 (2)	60 (2)	50 (0)	90 (0)
19 (1)	40 (2)	40 (1)	50 (2)	90 (2)	93 (0)
20 (2)	37 (1)	38 (0)	45 (2)	80 (2)	95 (0)
19 (2)	34 (0)	39 (1)	38 (0)	70 (2)	95 (0)
18 (2)	35 (0)	38 (2)	41 (0)	60 (0)	96 (2)
18 (1)	35 (0)	37 (2)	43 (1)	66 (0)	97 (2)
17 (0)	35 (0)	37 (2)	42 (0)	68 (0)	100 (2)
20 (2)		32 (0)	43 (1)	70 (0)	105 (2)
		36 (0)			120 (0)
ti=18	ti=36	35 (0)	42 (0)	ti=70	120 (2)
		ti=37	ti=43		ti=96

UNTREATED PLASTICS			TREATED PLASTICS		
DR 682T	B1	H 26641	A1	H 24370	FR 6692T
80 (2)	60 (2)	45 (0)	100 (2)	60 (0)	100 (0)
60 (2)	54 (2)	90 (2)	60 (0)	120 (2)	120 (2)
50 (2)	48 (0)	60 (2)	80 (0)	75 (0)	104 (0)
48 (0)	51 (2)	52 (1)	85 (0)	100 (2)	106 (0)
54 (0)	50 (0)	50 (0)	87 (2)	90 (0)	115 (0)
57 (1)	52 (0)	54 (1)	87 (0)	95 (0)	125 (0)
	53 (0)	55 (1)	87 (0)	97 (0)	115 (0)
ti=50	ti=51	ti=52	ti=87	98 (0)	125 (2)
				ti =100	ti=120

Times are in seconds. Number in parentheses indicates whether both (2), one (1), or neither (0) specimen sustained ignition.

TABLE II

EXPOSURE TIMES USED TO ESTIMATE THE IGNITION TIMES (t_i) IN THE PRESENT TESTS

Conditioned at 50% R.H.			Dried at 65°C for 24 hours		
Red Oak	Redwood	Wood Fiber Insulating Board	Red Oak	Redwood	Wood Fiber Insulating Board
150(0)	55(0)	26(0)	90(0)	24(0)	20(0)
175(0)	55(0)	27(0)	100(0)	25(0)	22(0)
178(0)	56(0)	28(0)	104(0)	26(1)	22(0)
180(0)	56(1)	29(1)	106(0)	30(2)	23(0)
184(2)	57(2)	30(2)	108(2)	35(1)	23(2)
188(2)	58(2)	t_i = 29 sec	110(2)	t_i=26 sec	24(2)
195(2)	60(0)		t_i=107 sec		24(2)
210(2)	t_i=56 sec				25(2)
t_i=182 sec					t_i=23 sec

Times are in seconds. Number in parentheses indicates whether both (2), one (1), or neither (0) specimen sustained ignition.

TABLE III

DATA ON TEST SPECIMENS

Conditioned at 50 percent Relative Humidity

Material	Ignition Temperature (Deg C)	Density (g/cm^2)	Thermal Conductivity x 10^4 (cal/(sec.cm.degC))	Ignition Time (sec)	$\frac{t_i}{KDC}$ x 10^{-6} (cm^2.sec.deg/cal)^2
Red Oak	445	0.767	3.02	182	2.63
Redwood	468	0.356	1.84	56	2.85
Wood Fiber Insulating Board	390	0.264	1.02	29	3.59

Dried at 65°C for 24 hours

Red Oak	423	0.650	3.4	107	1.62
Redwood	400	0.269	1.92	26	1.68
Wood Fiber Insulating Board	418	0.292	1.25	23	2.10

7.0 AUXILIARY MEASUREMENTS

7.1 Temperature

For the samples in Table II, front surface temperature histories were obtained for each material and condition with a 10 mil chromel alumel thermocouple, with a welded junction. The bare leads were pulled through very small holes 1 inch apart on the surface and were secured to the back of the specimen. The junction which was located midway between the holes laid flat against the surface without any penetration or separation of the thermocouple from the surface throughout the exposure. The required shape of the lead wires was produced by putting a metal plate under the thermocouple temporarily and tapping it lightly with a hammer. The temperature history for a dried redwood specimen is shown in Figure 6 and the temperatures at the time of ignition for all the materials and conditions are listed in Table III. These temperatures are estimated to the nearest one half millivolt in the output of the thermocouple or about $\pm$ 12 degrees C.

7.2 Thermal Conductivity

The thermal conductivity was measured for all the materials and conditions tested, using a hot plate and a heat flux meter. The configuration is shown in Figure 7. Each specimen was cut along a line 1 inch from its center to permit the drilling of two 1 inch long thermocouple holes into the center of the specimen parallel to the surface near the top and the bottom. The thermocouple junctions were located at the ends of the holes, and the insulated lead wires were led to the top surface through a groove between the two parts of the specimen. The two parts of the specimen were then stappled together again so that one dimensional heat flow at the center could be closely approximated when the specimen was placed on the hot plate. The heat flux meter which has a calibration factor of 3.75 watts/cm^2/volt was centered on the top surface of the specimen. The temperature of the hot plate was turned down to keep the lower thermocouple below 150^{o}C, to prevent scorching of the specimen. Thermal equilibrium was established after 2 hours. The thermal conductivity was calculated from the formula, $K=qL/(T_b-T_t)$ where q is the heat flux indicated by the meter, L is the distance between the holes, T is the temperature, and the subscripts b and t refer to the bottom and top thermocouples. The values of the thermal conductivities and densities are listed in Table III.

8.0 ANALYSIS OF RESULTS

The test has been designed to approach as nearly as possible the conditions of a particularly simple classical conductive heat transfer problem. The following assumptions are made in this treatment:

(1) the plane front surface of the specimen is exposed to a constant temperature environment.

(2) the net heat flux into the front surface is proportional to the difference in temperature between the surface and the environment. (This implies that there are not uncompensated radiation losses from the specimen.)

(3) the specimen is infinitely thick.

(4) there are no sources or sinks of energy due to chemical reactions, vaporization, etc.

(5) the thermophysical properties are not a function of temperature.

(6) the chemical and physical changes in the material are not extensive enough to alter the thermophysical properties significantly at the time the calculation is made.

It is realized that these assumptions are violated to some extent. It remains to compare the experimental results with the calculations to determine the severity of the deviations.

The front surface temperature rise, T, for the above case is given by Carslaw and Jaeger (3) as,

$$(T/T_f) = 1 - e^{Z^2}\,\mathrm{erfc}(Z) \qquad (1)$$

where T_f is the effective flame temperature, erfc=1-erf, erf is the error function, $Z^2 = h^2 t/(KDC)$, h is the surface heat transfer coefficient, t is the time, K is the thermal conductivity, D is the density, and C is the heat capacity. Figure 8 shows a plot of equation 1. If the ignition temperature T_i is constant, Z_i is constant. The ignition time is given then by:

$$t_i = \frac{Z_i}{h^2} KDC \qquad (2)$$

The subscript i indicates that the variable is evaluated at the time of ignition. If h and Z_i are constant, the grouping t_i/KDC should be constant, The range of variation of $t_i/(KDC)$ can be seen in Table III for low, intermediate and high density cellulosic materials. Since the thermal conductivity is nearly proportional to density for these materials, the ignition time is nearly proportional to the square of the density.

The effective flame temperature was found to be 890 C above ambient while the initial heat flux into the specimens, q_o, was 3.3 watts/cm^2. The surface heat transfer coefficient, h, is equal to $q_o/T_f = 37.2 \times 10^{-4}$ watts/(cm^2 deg C) or 8.9×10^{-4} cal/(cm^2 sec deg C).

The heat capacity, C, is 0.3 cal/(g.deg C). Hence Z_i=1.13 and from Figure 8, the ignition temperature should be 865°C above ambient which is very close to the effective temperature of the exposing flame. Actually the measured temperatures are around one half of this value. This indicates the need for a substantial revision of the assumptions at the beginning of this section.

Some preliminary measurements on the front surface temperature history of an inert specimen and some calculations on the amount of radiant energy which might escape through the opening between the specimens indicate that a large part of the difference between the calculated and measured ignition temperature could have been eliminated if the theoretical curve in Figure 8 were modified to take this escaping radiation into account. Undoubtedly, the increase in thermal conductivity of the charred material at the surface further reduced the measured ignition temperature below the calculated one. Both of these effects will be incorporated into the model.

9.0 DEVELOPMENT OF THE MODEL

9.1 Ignition Temperature

The ignition temperature, T_i, as far as this test is concerned, is defined as the temperature of the surface of the specimen at the instant that the specimen is just able to sustain a flame. This temperature will depend on the exposure conditions and the nature of the specimen. Thus it is one of the variables to be measured rather than a constant of the system. However, for a particular class of materials and a limited range of exposures, it is nearly constant. Although this fact has been often exploited for the correlation of ignition data for a limited variety of materials, the constant ignition temperature criterion is not a useful concept for a general ignition test. For example, flame retardant materials can exhibit large differences in ignition behavior with relatively small changes in the thermophysical properties.

Nevertheless, in the development of an ignition test model we can capitalize on the ignition temperature in two ways, even though it does vary. First, it is a convenient check point, The surface temperature would be one of the easiest variables to calculate from any workable mathematical model of the test. It is also a variable which is easy to measure experimentally. Second, the small variation of ignition temperature within a class of materials provides a quick way to get the approximate ignition time for a new material in that class by simply monitoring the front surface temperature of the specimen. This can cut down appreciably on the number of specimens required for the test.

9.2 Critical Mass Flow

Critical mass flow, $\dot{M}$, is defined as the minimum mass flow rate of volatiles per unit area of the surface required to sustain a flame. This depends on the characteristics of the pyrolysis gases and thus varies with the material. However, the value should be relatively independent of the exposure conditions and the thermal properties of the specimen. It is more fundamental than the ignition temperature but more difficult to measure. The calculation would be in the field of combustion science, and the principal variation from one material to another would be through the heat of combustion of the pyrolysis gases. It is not the purpose of this project to calculate $\dot{M}$, which would be impossible except in those special cases where the pyrolysis products are known. The value will be measured experimentally along with the heat of combustion of the pyrolysis products. An empirical relationship will be sought between $\dot{M}$ and the heat of combustion of the pyrolysis products.

Basing ignition behavior on the critical mass flow rate of a material has the advantage of tying ignition in with the flame spread and heat release rate, both of which also depend on this quantity.

9.3 Application of the Critical Mass Flow Rate

In the simpliest case of a zero order decomposition reaction, where the reaction rate depends on the temperature but not on the amount of remaining material the actual mass flow rate is given by

$$\dot{m} = \int_{o}^{\infty} (D-D_c)\ A\ \exp(E/RT)dx$$

where D is the density of the virgin material, D_c is the density of the completely charred material if any, A is the reaction frequency factor, E is the activation energy, R is the gas constant, and T is the absolute temperature. The temperature is expressed as a function of the time and distance from the surface and is found by solving the heat conduction problem. In the case of a first order reaction where the rate of decomposition is proportional to the amount of remaining unreacted material the above equation should be written

$$\dot{m} = \int_{o}^{\infty} (D-D_c)(1-\int_{o}^{t} A\exp(E/RT)dt)A\exp(E/RT)dx$$

The solution of the above equations for the time at which the actual mass flow rate equals the critical mass flow rate ($\dot{m} = \dot{M}$) yields the ignition time, t_i . In any practical case this has to be done numerically be means of a computer program. If the program is successful in predicting the results of the ignition test in terms of the known critical mass flow rate, the thermochemical properties, and the thermophysical properties of the material, it can be altered to take into account the environmental conditions of the real fire; and thereby determine whether the material would have ignited in the actual fire. The environmental conditions of the fire at present have to come from measurements in typical fires since there is no workable model as yet for fire buildup in a room.

9.4 Supporting Measurements

In order to test the model it is necessary to know several properties of the material. The range of materials to be investigated include the whole spectrum of materials which might be subjected to the ignition test. The emphasis is not on testing a lot of materials but a few widely different materials. In general the required property values will not be available in the literature. It is necessary then to be able to measure them on the project.

The technique for determining thermal conductivity was described in the Auxiliary Measurements section. The heat capacity can be determined with the differential scanning calorimeter. Since the change in the properties due to decomposition cannot be neglected, measurements of these properties will be made on specimens having

undergone various degrees of pyrolysis. The frequency factor and activation energy are normally derived from thermal gravitational analysis. However, it is important that the measurement be done in air since the rates can be considerably greater in an oxydizing atmosphere. This may require setting up a special arrangement whereby a thin specimen instrumented with a thermocouple is supported by a load cell and exposed to the radiant panel.

In order to obtain the critical mass flow rate, the specimen will be thoroughly dried and then exposed to a uniform irradiation from the radiant panel. During the exposure the specimen will be supported on a load cell to follow the rate of mass flow through the surface. At the time in which a piloted flame will sustain itself at the surface the mass flow rate per unit area will be recorded as the critical mass flow rate.

In order to obtain the heat of combustion of the pyrolysis gases, a specimen will be pyrolyzed in the absence of air. The heat of combustion of its char will be determined with the oxygen bomb calorimeter. This will be compared with the heat of combustion of an unpyrolyzed specimen in order to determine the heat of combustion of the pyrolysis gases.

10. CONCLUSIONS

The ease of ignition test has performed well in its early stage of development. It not only distinguishes between the ignitability of different materials, but also between woods of the same type with different densities and moisture contents. Based on a limited amount of data, the results appear to be reproducable and independent of the operator. The exposure conditions are typical of a real fire. The test satisfies the preliminary goal of ranking materials in the order of increasing ease of ignitability. Thus materials exceeding an arbitrary ease of ignition level might be excluded for a particular application, thereby screening out the most hazardous materials.

Some consideration has been given to the development of a computerized model which could rationalize the ignition data in terms of the thermophysical and thermochemical properties of the materials and predict the ignition behavior of the material in a typical fire for which environmental data are available.

11. FUTURE PLANS

The ignition test apparatus appears to work well in its present state so that only minor modifications of a convenience nature are anticipated. Several adjustments are provided in order to equalize the exposure on both sides and to make it as uniform as possible. In order to facilitate this adjustment, it is planned to build a bank of radiometers for each specimen location. Since these have instantaneous response any required adjustments can be quickly made whenever the exposure level is changed. Each bank will consist of five circular iron plates about 20 mils thick

and one inch in diameter embeded in a water cooled brass block the same size as the specimen. The temperature rise at the center of each disk would be proportional to the heat flux at that point. The radiometer banks would be placed in the specimen holder whenever the adjustments were to be made.

After completion of the radiometer banks an investigation of the attainable range of heat flux levels will be determined. Also a radiation compensated thermocouple will be used to determine the variation in the effective temperature of the exposing flame. The variation in ignition time and ignition temperature with different exposure conditions will be investigated for some typical materials.

A more careful examination of the effect of moisture content on the ignition characteristics of the wood will be accomplished by selecting specimens with different moisture contents but with the same dry density.

Some measurements will be made to demonstrate the effect of paint and varnish on the surface of the wood.

The measurements techniques and the computer program mentioned in the Model Development section will be developed.

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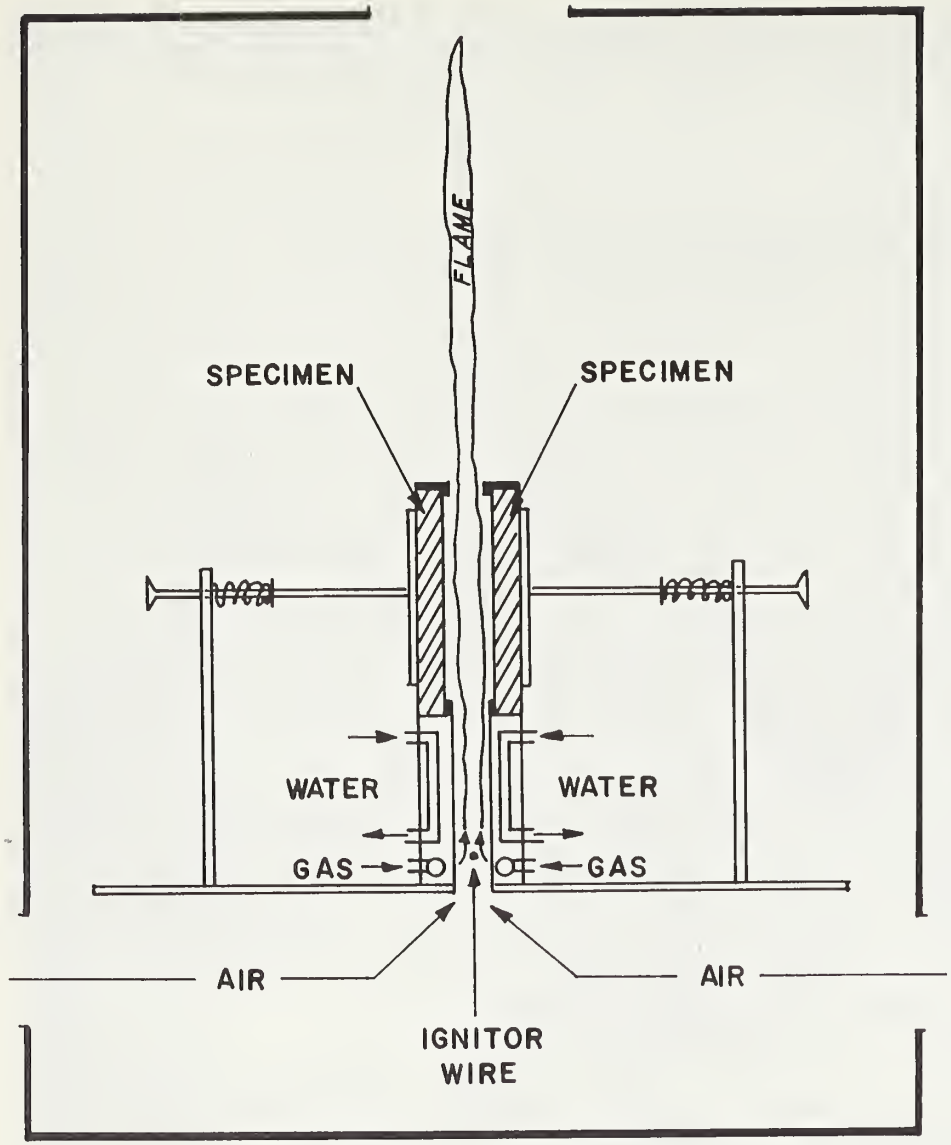
(2) "Study of Fire Development in a Room," J. B. Fang, July 1971.

(3) Carslaw and Jaeger, "Conduction of Heat in Solids," Second Edition, (Oxford 1959).



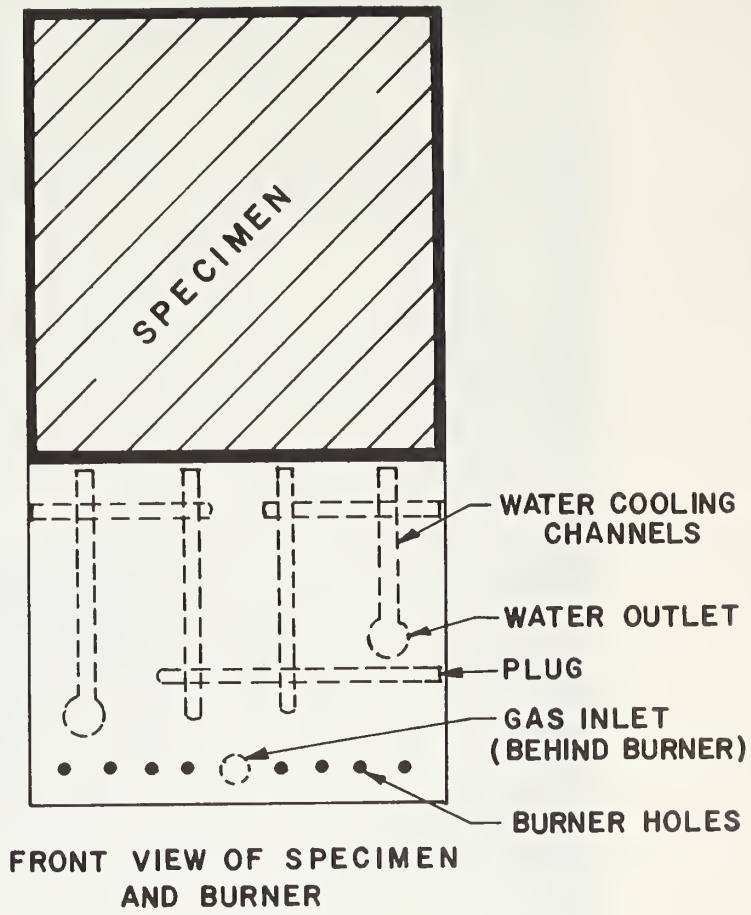


Figure I Sketch of Ignition Apparatus

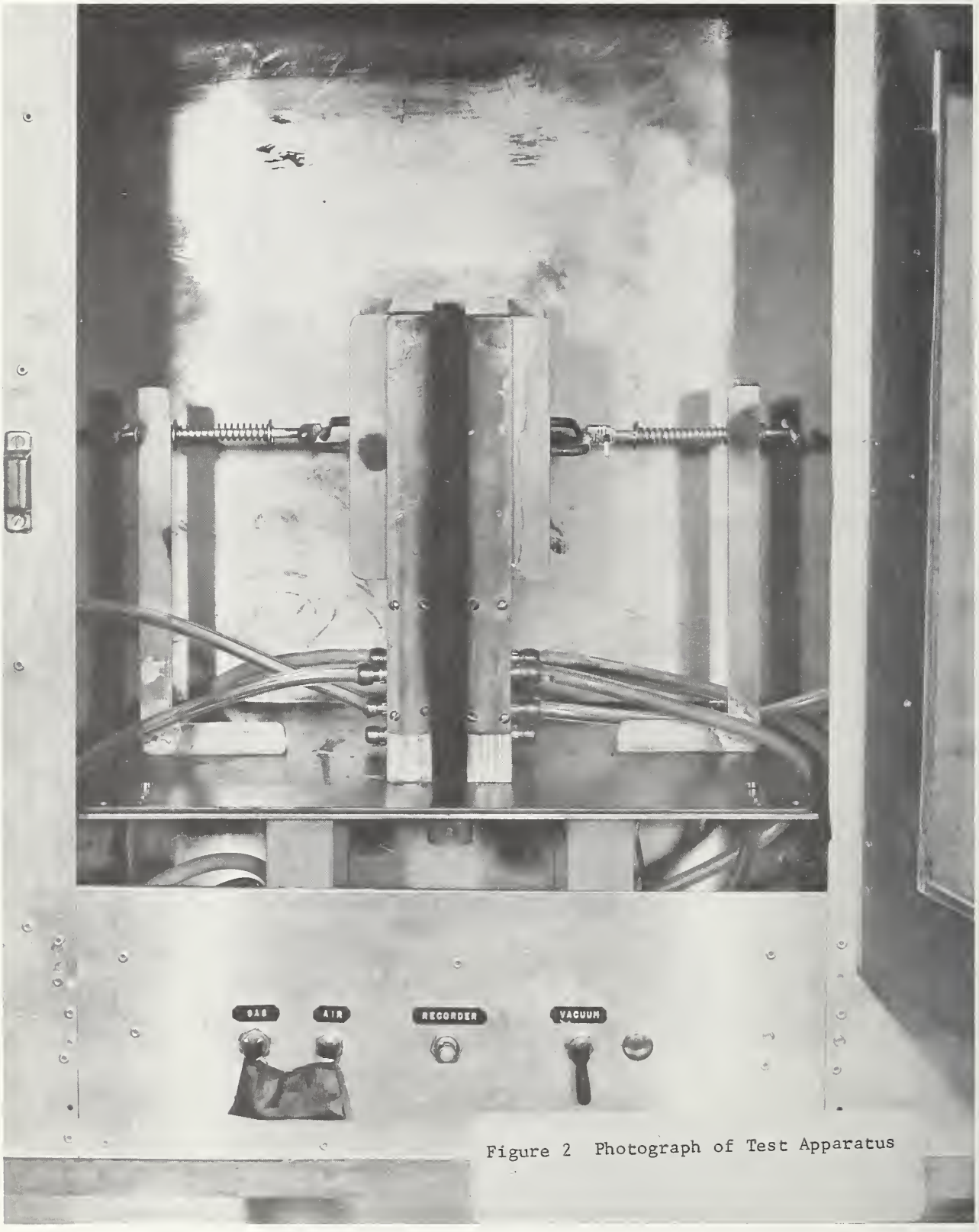


Figure 2 Photograph of Test Apparatus

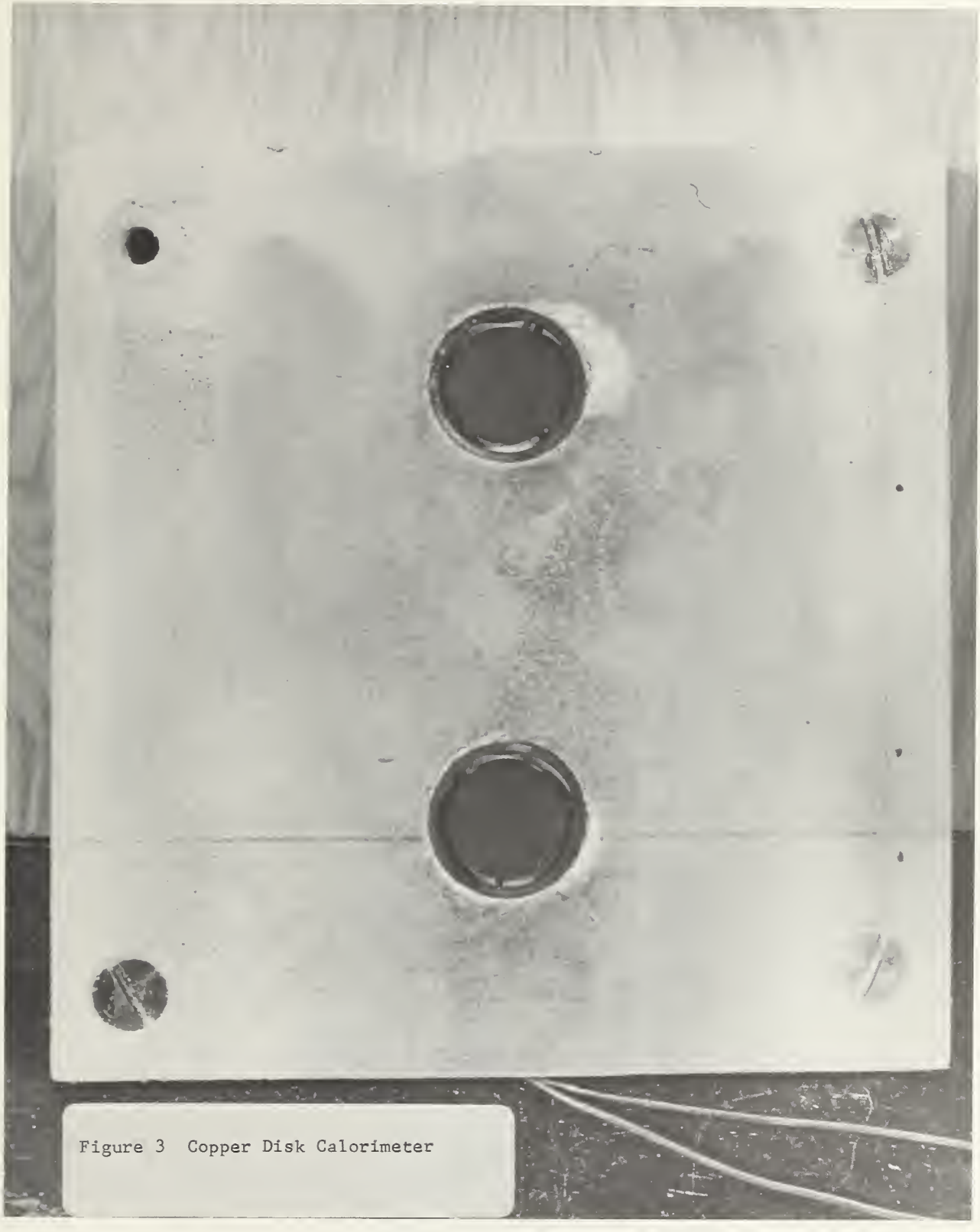


Figure 3 Copper Disk Calorimeter

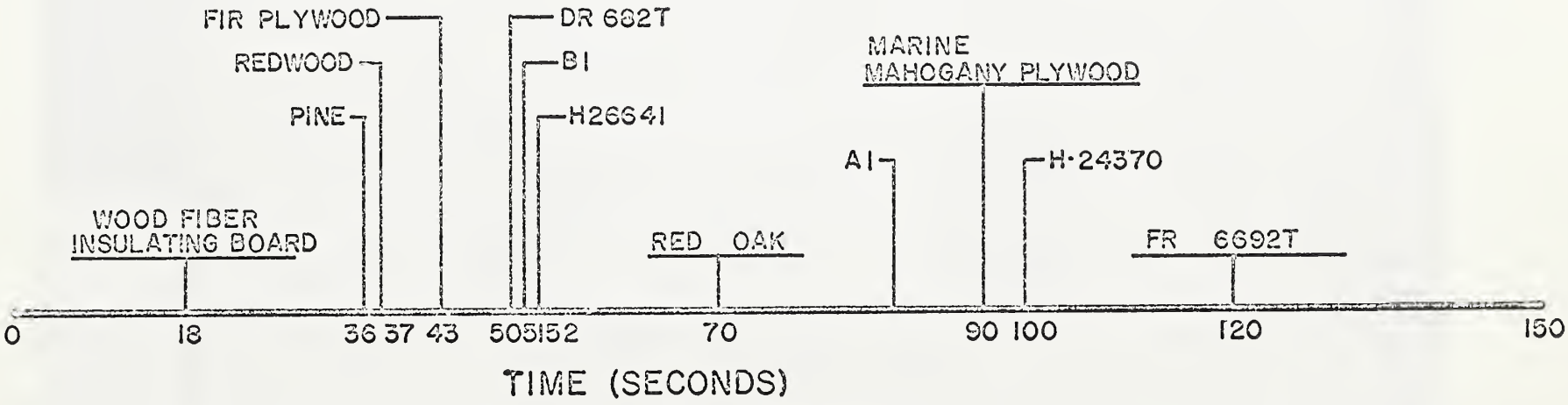


Figure 4 Ignition Times for Initial Tests

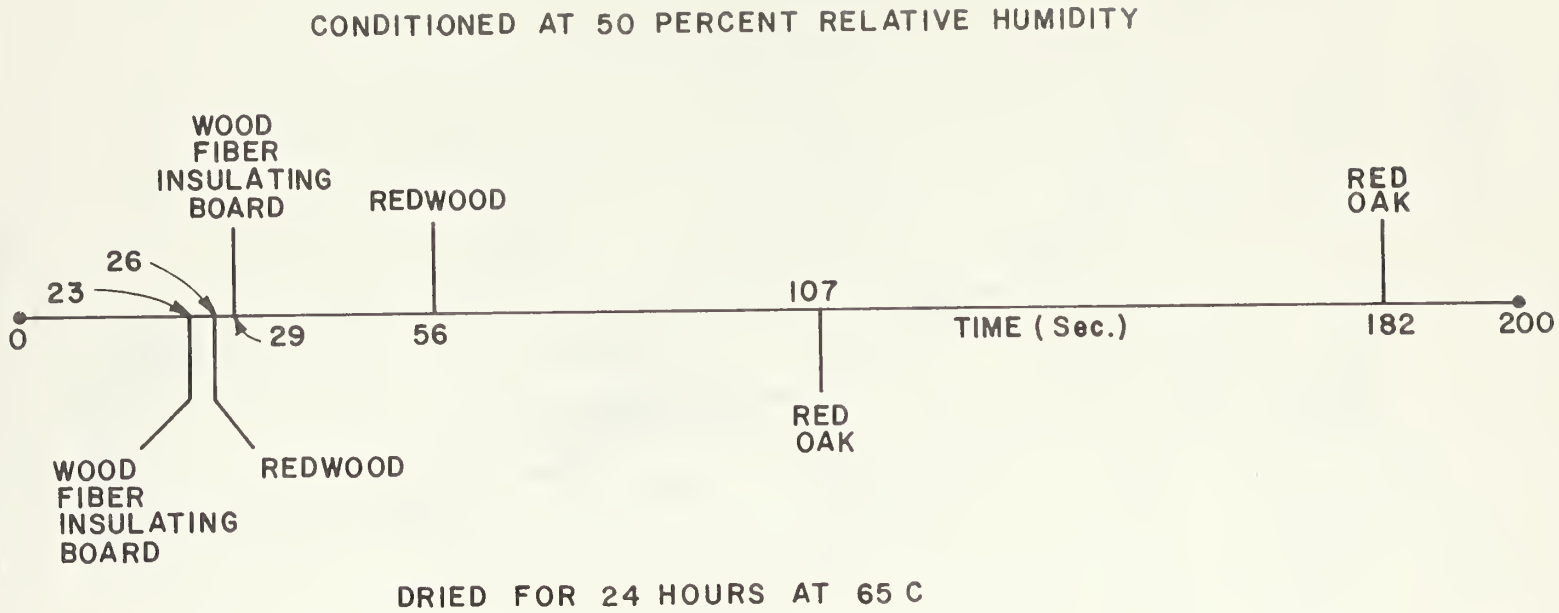


Figure 5 Ignition Times for Present Tests

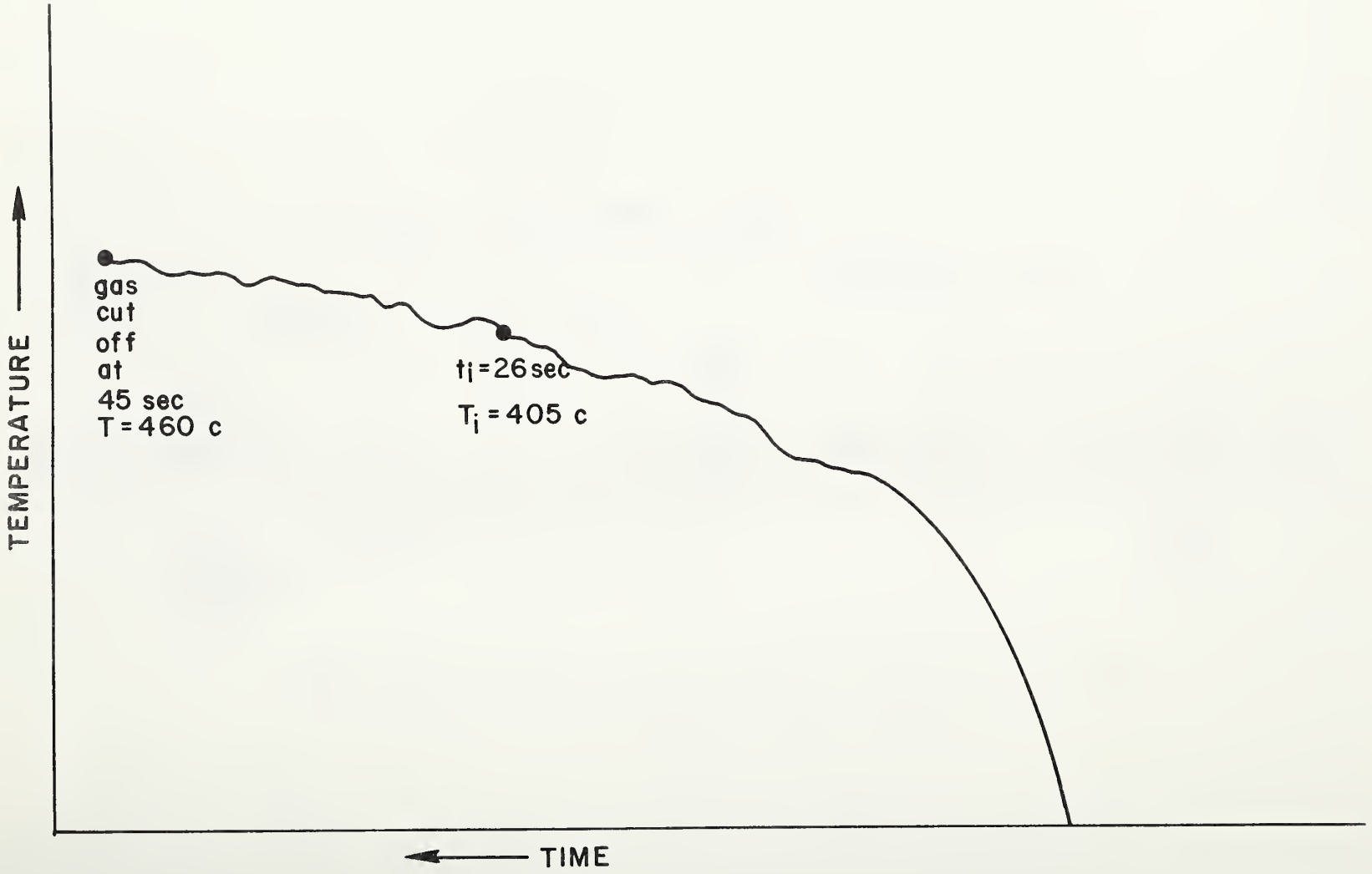
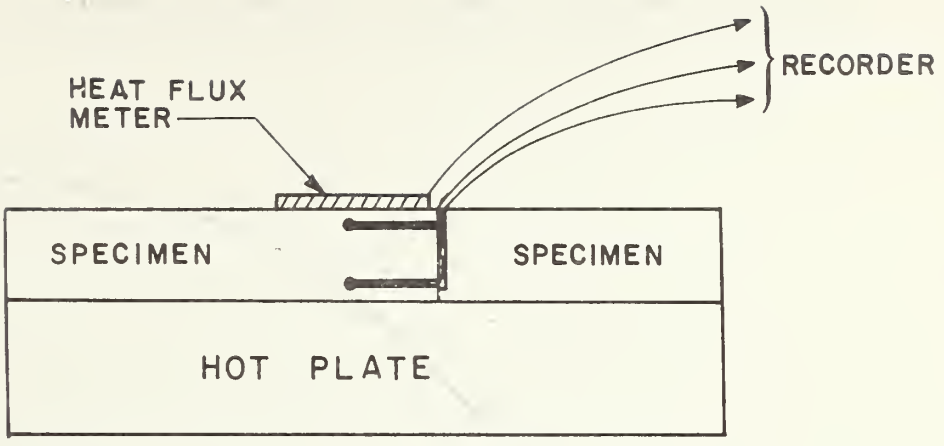
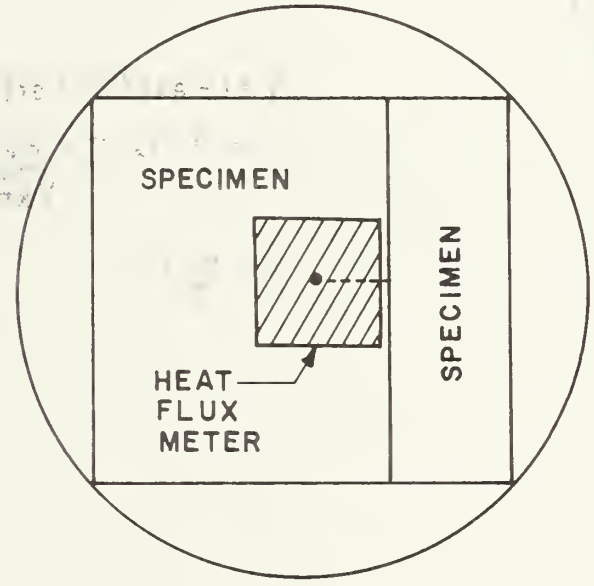


Figure 6 Front Surface Temperature History for Redwood Specimen



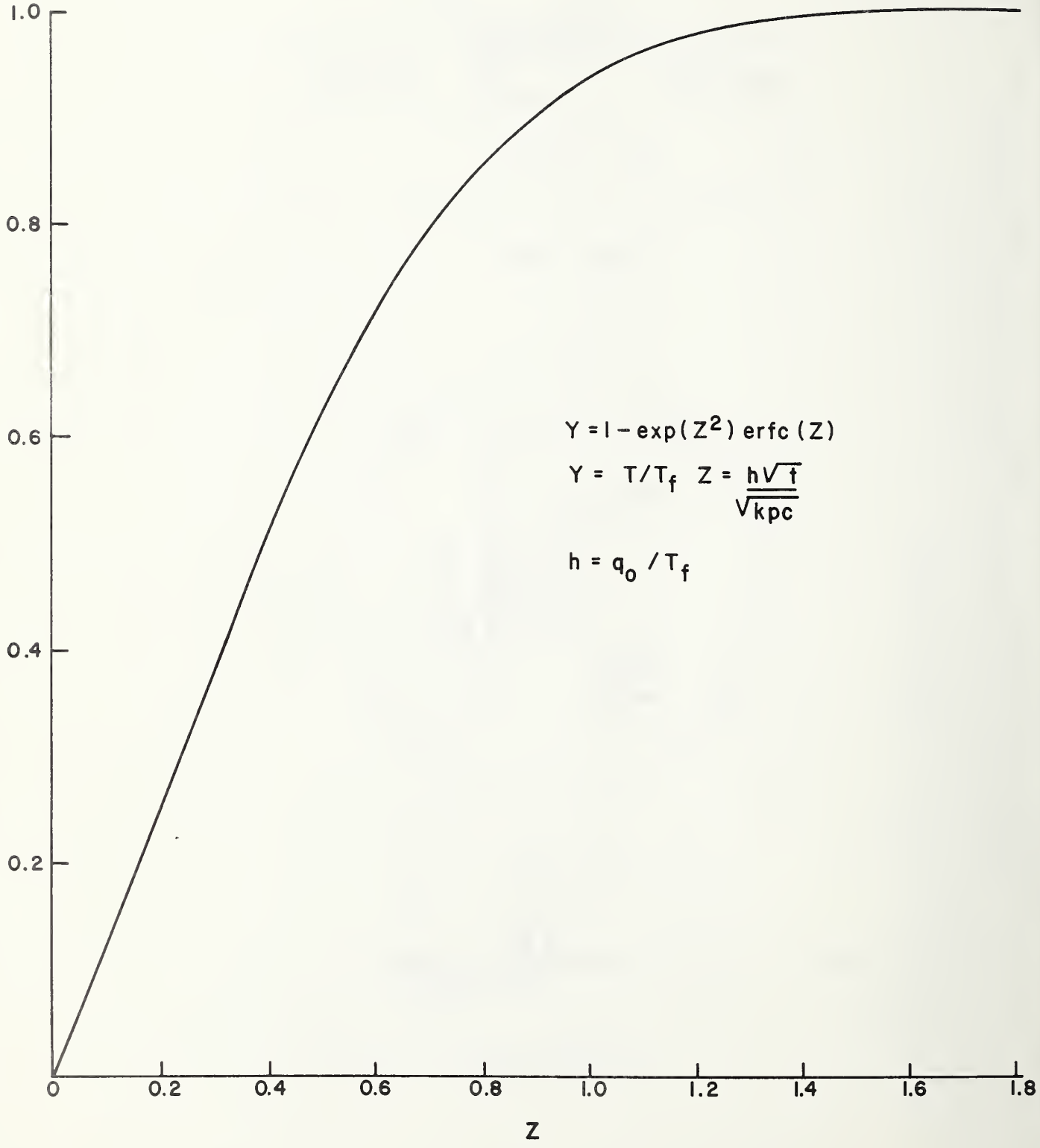
SIDE VIEW



TOP VIEW

Figure 7 Thermal Conductivity Measurement

Figure 8 Theoretical Curve for Front Surface Temperature

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