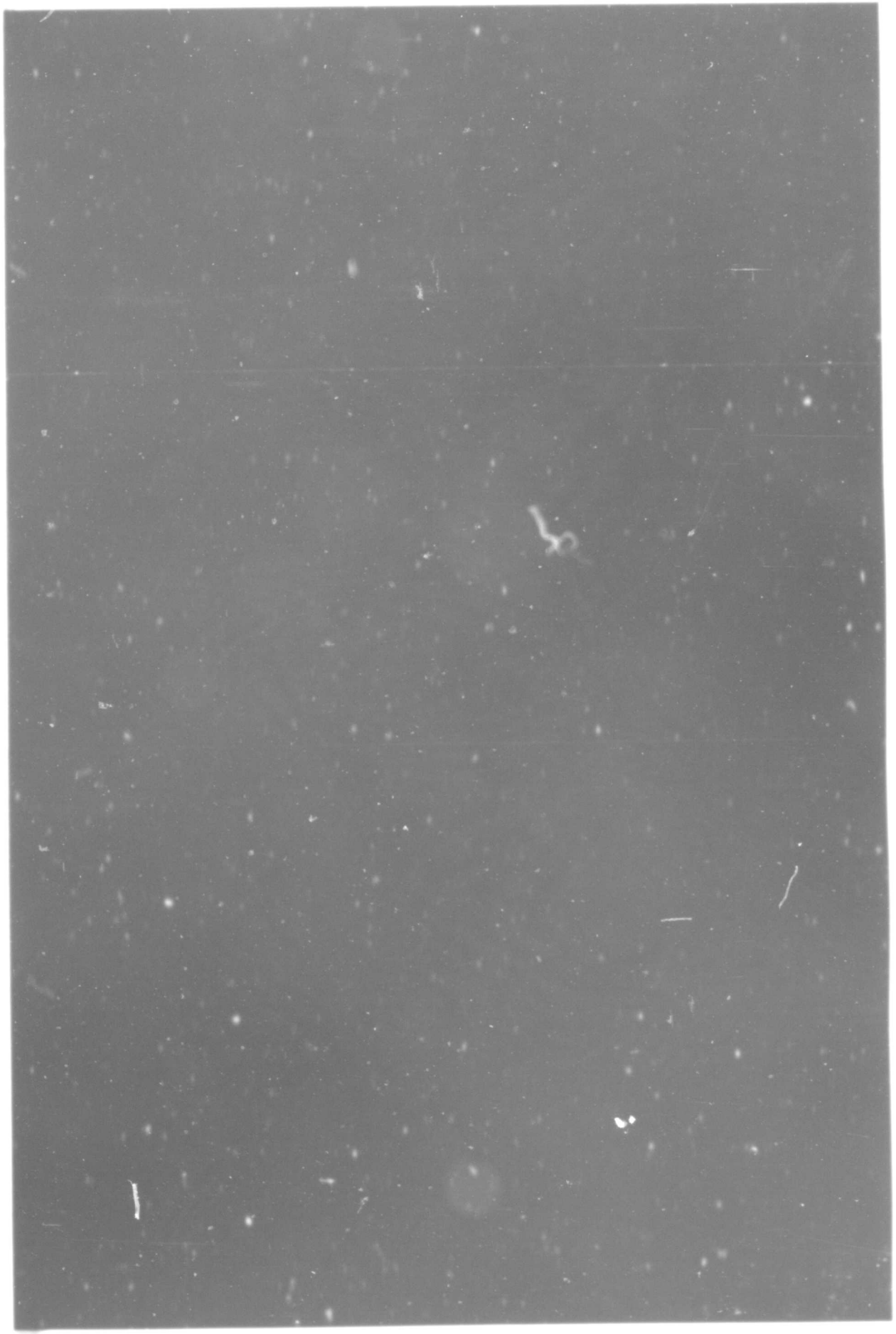
Interim Technical Report
AFSWP - 869
September 1956

IGNITION OF BLACK ALPHA-CELLULOSE PAPERS BY THERMAL RADIATION

SQUARE WAVE PULSE

DIVISION OF FIRE RESEARCH
FOREST SERVICE
U. S. DEPARTMENT OF AGRICULTURE



ACKNOWLEDGMENTS

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ABSTRACT

Available data on critical energies for sustained ignition of black alpha-cellulose paper in the absence of forced convective heat losses are correlated against exposure time on a nondimensional basis. Investigations cover a range of irradiance from 2 to 25 cal/cm^{2}sec, exposure time from 0.1 to 4 seconds, and paper thickness from 2 to 30 mils. Ignition energies for papers of two nominal densities were determined. Results are presented in terms of an energy modulus, $Q_R/\rho cLE$ and the Fourier modulus, $\sqrt{at}/L$ for a constant value of E/RT_o equal to 44.

For Fourier moduli less than 0.4, the energy modulus approaches a constant value of approximately 0.11. As the Fourier modulus increases, the energy modulus decreases to a minimum value of 0.068 at a Fourier modulus of 0.8. For Fourier moduli above 0.8, the energy modulus increases with exposure time according to the equation

$$\frac{Q_R}{\rho cLE} = 0.080\left(\frac{\sqrt{at}}{L}\right)^{0.5}$$

These results are valid for paper moisture contents of 4 to 5 percent, initial paper temperatures between 0 and 60°C, and irradiance levels above the critical irradiance, estimated to be 2 cal/cm^{2}sec. Presented correlations are within a maximum error of ±15 percent.

Regions of ignition, transient flaming, destruction (without flame), and nondestruction are illustrated in terms of the above-mentioned dimensionless moduli.

IGNITION OF BLACK ALPHA-CELLULOSE PAPERS BY THERMAL RADIATION

--Square Wave Pulse--

By

F. M. Sauer,

Interim Technical Report, AFSWP-869
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ABSTRACT

Available data on critical energies for sustained ignition of black alpha-cellulose paper in the absence of forced convective heat losses are correlated against exposure time on a nondimensional basis. Investigations cover a range of irradiance from 2 to 25 cal/cm^{2}sec, exposure time from 0.1 to 4 seconds, and paper thickness from 2 to 30 mils. Ignition energies for papers of two nominal densities were determined. Results are presented in terms of an energy modulus, $Q_R/\rho cLE$ and the Fourier modulus, at/L for a constant value of F/RT_o equal to 44.

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INTRODUCTION

General

Ignition of thin fuels by direct thermal radiation has been recognized for some time as the source of initiation of primary fires during nuclear attack (1,2,3).[1/] Numerous investigations of ignition energy, both laboratory and field, have been made on particular fuels under particular exposure conditions (4,5,6,7,8,9,10). Those fuels whose ignition energies are less than 20 cal/cm^2 are of special interest and have been identified as "kindling fuels." Ignition energies at one or more values of moisture content for approximately 100 kindling fuels have been determined for a 1-second (approximately) square wave exposure and 22 for a 3-second field pulse exposure.

These results demonstrate that ignition energy increases with fuel moisture content and thickness, and generally increases between the 1-second and 3-second pulses. However, apparently anomalous results were obtained by Bruce (10) in the latter case in which ignition energies for some materials failed to increase for the longer pulse. Complete ignition energy-moisture relationships are known for 22 fuels for the 1-second pulse and 2 fuels for 3-second pulse. The task of filling gaps in knowledge for these fuels, aside from others not yet tested, represents a substantial experimental program.

The number of required tests may be considerably reduced through dimensionless correlation of results. Such correlations provide means for evaluation of unknown ignition energies from known physical properties and also information on variations of ignition energy with pulse time (scaling equations).

Use of previously determined ignition data on naturally occurring fuels for correlation purposes was considered inadvisable due to the lack of data over a range of pulse times and, more fundamentally, due to the inability to vary physical properties independent of one another. For the latter reason alpha-cellulose paper was chosen as a material

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1/ Underlined numbers in parentheses refer to Literature Cited, page 29.

which would most nearly represent an idealized fuel of constant chemical properties with some latitude for variation in physical properties.

The Forest Products Laboratory at Madison, Wisconsin prepared, from a single batch of wood pulp, alpha-cellulose papers of maximum quality in two nominal densities, 0.55 and 0.75 gm/cc, and in thickness ranging from 2 to 30 mils. A description of the raw pulp and other paper-making data is reported elsewhere (11). These variations in density and thickness represent the extremes which can be produced by paper-making machinery. White and black (carbon filled) papers were produced in each density. Thus one has independent control over density, thickness, surface absorptance, and/or diathermancy.

Reflectance measurements (12) indicated that papers with 2.5 percent by weight of carbon black added were sufficiently "black" so that additional carbon did not substantially increase absorptivity. Felt side absorptivity was 92-93 percent (0.40-0.75μ) for this paper. It appeared desirable to eliminate any effect of absorptivity and/or diathermancy during initial phases of the experimental program, hence this paper was chosen for test.

Since exposures were made normal to the flat paper surface and using a square wave radiant pulse, the most ideal ignition model was secured. Idealization, as far as practicable, has the virtue of being perhaps amenable to theoretical attack. In addition the square wave exposure provides a means of comparison with the majority of previous data. From an experimental standpoint square wave exposures are more expeditious than field pulse exposures. Correlation of field pulse data is intuitively similar to the square wave correlation and, as in depth of char and weight loss (13), correlations should lead to an equivalent square wave pulse. Square wave exposure data then may be used effectively to program field pulse exposures so that a minimum of experimentation will be required.

Ignition and Destruction--Definitions

Various types of thermal degradation occur during exposure of a cellulosic material to radiant energy. There are, in general, five

identifiable regions dependent on irradiance level and time which in the absence of other ignition sources[2] define these effects.

If the irradiance is lower than a certain value, the "critical irradiance," degradation takes place without the appearance of flame or glowing. If exposure time is insufficient the material will not be destroyed. If the exposure continues until the material is destroyed, the effect is called simply "destruction." Destruction is accompanied by heavy smoke and substantial amounts of liquid products.

At greater than critical irradiance flame may momentarily appear and die as soon as the radiant exposure ceases and the material will not be consumed. This effect is called "transient flaming" and corresponds to that previously described as transient or spurious ignition.[3] If the exposure is continued for longer time the flame establishes itself after cessation of the pulse and consumes the remaining material. In some instances, glowing combustion persists which continues until the fuel is consumed. These latter effects are defined herein as "ignition" and are those previously described as sustained (7), persistent, and/or primary ignition (3). Since ignitions are considered to be the only cause of primary fires, they are of major importance. It should be noted that destruction by either flaming or glowing ignition or destruc- without flaming or glowing are indistinguishable under field conditions where direct observations are not made.

THERMAL PROPERTIES OF ALPHA-CELLULOSE PAPER

Weight per unit area and thickness measurements were made by the Forest Products Laboratory on all papers before shipment to NRDL (11). Weight measurements represent the average of 500 sheets, 25 x 40 inches in size after conditioning for at least 24 hours at 50 percent relative humidity and 72°F (15). The papers appeared to have a tendency to swell during storage, hence thickness was measured at NRDL during the

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2/ Lawson and Simms (14) define "pilot flame ignition" wherein a small pilot gas jet was held adjacent the surface during irradiation. In the absence of any pilot flame, ignition is termed "spontaneous."

3/ The author suggests that the term "ignition" be reserved for sustained ignitions as defined below just as the term "destruction" is reserved for destruction without flame.

experimental period. Measurements were made using a large anvil paper micrometer. Variations in thickness were approximately ±5 percent on the thinner papers and ±3 percent on the thicker papers. Weight and thickness data used during correlation are presented in Table 1.

Table 1.--Black alpha-cellulose paper properties (2.5 percent carbon black)

Paper number	Weight per unit area[1/]	Thickness[2/]	Density	Paper number	Weight per unit area[1/]	Thickness[3/]	Density
	(10^{-2} gm/cm^2)	(mils)	(gm/cc)		(10^{-2} gm/cm^2)	(mils)	(gm/cc)
4097	0.379	2.4	0.62				
4090	0.768	4.8	0.63	4098	0.557	4.4	0.50
4091	1.12	6.8	0.65	4099	0.856	6.4	0.53
4092	1.54	9.3	0.65	4100	1.12	8.3	0.53
4093	1.91	11.0	0.68	4101	1.41	10.1	0.55
4094	2.28	13.1	0.68	4102	1.68	12.4	0.53
4095	3.74	21.5	0.68	4103	2.81	20.9	0.53
4096	5.48	31.3	0.69	4104	4.18	30.2	0.55

1/ FPL data at 50 percent relative humidity and 72°F.
2/ NRDL data at 32-42 percent relative humidity and 71-79°F.
3/ NRDL data at 45-52 percent relative humidity and 71-79°F.

Thermal conductivity of the alpha-cellulose paper was determined experimentally using stacked sheets of 30 mil paper compressed to a known thickness. Since this procedure resulted in variations from the original density these data were compared with conductivity data of similar cellulosic materials in order to check the relationship of conductivity to density (see Appendix). The literature seldom reports moisture content, hence the latter conductivities may not be corrected for moisture. The specific heat of cellulose was taken as 0.35 (16). The resulting calculated diffusivity is shown plotted against density in figure 1. The diffusivity for dry wood is shown for comparison.

Addition of carbon black to the cellulose appears to increase the conductivity somewhat over that of pure cellulose. This difference is not, however, significant for the 2.5 percent carbon content (of figure 6). The carbon content quoted (2.5 percent) is at most a nominal

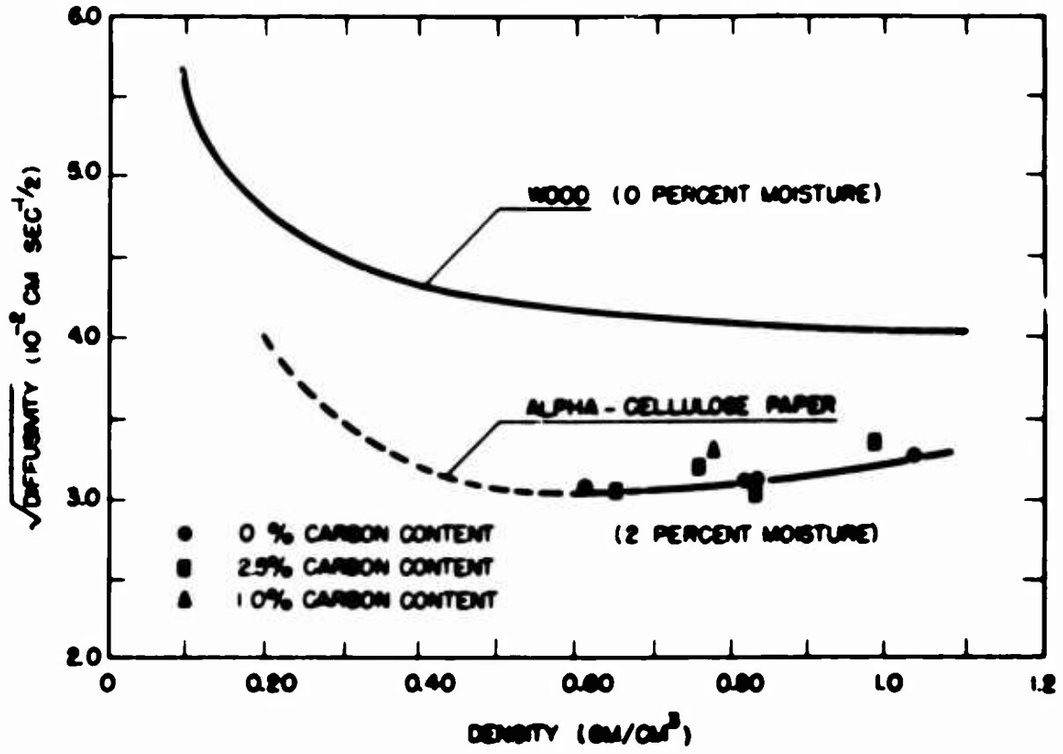

Figure 1.--Thermal diffusivity-density relationship for wood and alpha-cellulose paper

figure since this amount of carbon blac was that added to the pulp. A certain amount of carbon is retained in the process water which drains from the pulp on the paper-making screen. Denser and thicker papers retain more carbon black than thinner papers, resulting in lower actual carbon contents for the latter papers.

One equilibrium moisture content was determined on scrap material from the 0.75 density papers. Resulting moisture was 4.8 percent at 50 percent relative humidity and 75°F. These values check well with those quoted for newsprint (17,p.323) (5.3 percent at 50 percent relative humidity), hence the latter data may be used for estimating purposes.

TEST CONDITIONS AND PROCEDURES

Paper specimens in the form of disks 3/4 inches in diameter were cut using a special die, care being taken to avoid rough edges or "feathers" around the circumference. Papers were held at three points

on the circumference by a special fixture previously described (12). Exposures were made using the NRDL Mitchell Source (18). The radiant flux was apertured at a slightly larger diameter than the specimen. This procedure minimized heat losses to the fixture and edge effects, resulting in most nearly unidirectional heat flow.

Exposures were made at constant irradiance and the exposure time increased until sustained ignition occurred. Sufficient exposures (generally 4 to 6) were made at somewhat shorter and longer times in order to check the consistency of the critical exposure time. Measurement of irradiant flux and exposure time were made in the same manner as during charring experiments (12).

Tests were conducted under prevailing ambient relative humidity and temperature conditions. Hygrothermograph data show the following ranges in ambient conditions during the test period: 0.75 density paper, relative humidity 32-42 percent; 0.55 density paper, relative humidity 45-50 percent. Ambient temperatures were 75±4°F. These conditions correspond to estimated changes in moisture content of 4 to 4.5 percent for the denser paper and 4.5 to 5 percent for the lighter paper. Although moisture represents one of the important variables in ignition the above variations appeared to be sufficiently small that the additional complication of a controlled humidity chamber was not warranted.

Ignition and other effects were determined by visual examination. All exposures were recorded and effects noted. From subsequent examination of these records the critical exposure time was chosen such that ignition occurred about 80 percent of the time although statistical measures were not applied. Sufficient overlap on exposure times were obtained so that the critical time could be estimated to within at most 10 percent.

Rather complete data were obtained on the 0.75 density paper. Irradiance levels were varied from 2 cal/cm^{2}sec to 25 cal/cm^{2}sec. Determinations at the lower irradiance levels became increasingly difficult as the critical irradiance level was approached. Exposures less than 10 times of the least count of the timing circuit (0.01 sec) were not made. Exposures using the 0.55 density paper were used primarily as

a check against correlation of the 0.75 density paper ignition data and therefore are not extensive. For some papers only 2 or 3 points were determined for this purpose.

CORRELATION OF DATA

Previous analysis by the author of depth of char and weight loss data (13) showed that the rate of thermal degradation of cellulosic material exposed to thermal radiation was governed primarily by the diffusion of heat into the interior of the solid as opposed to a kinetic reaction controlled process. Integration of the differential equation for degradation of cellulose material expressed as a first order kinetic reaction, with the boundary conditions that temperature profiles are those of the irradiated semi-infinite solid, lead to specification of the usual transient heat flow grouping of parameters with the temperature rise replaced by the initial absolute temperature of the solid and a second parameter containing the activation energy for the rate of isothermal degradation. Specification of charring (or ignition) temperature was eliminated from consideration. Natural woods are known to be somewhat diathermanous; however, this consideration is probably not necessary for the black alpha-cellulose papers.

For a nondiathermanous (opaque) cellulosic material, depth of char data may be correlated over a wide range of irradiance levels and exposure times by the relationship (13)

$$\frac{QR}{\rho c d E} = f\left(\frac{\sqrt{at}}{d}\ ,\ \frac{E}{RT_o}\ ,\ M\right) \qquad (1)$$

where

a = thermal diffusivity in cm^2/sec

c = specific heat in cal/gr per ^oC

d = depth of char in cm

E = activation energy for isothermal degradation in cal/mole

M = moisture content in percent oven dry weight

Q = ignition energy in cal/cm^2

R = gas constant, 1.9864 cal/mole ^oK

t = exposure time in sec

T_o = initial absolute temperature of the paper in ^oK

ρ = density in gr/cm^3

The activation energy E relates the rate of weight loss during isothermal degradation to the absolute temperature through the equation

$$\frac{dw}{dt} = \mu w \exp\left(-\frac{E}{RT}\right) \tag{2}$$

where

T = temperature of sample during exposure (constant) in ^oK

w = weight of sample at time t in gm

μ = the velocity constant in sec^{-1}

Observations on the behavior of the alpha-cellulose paper confirmed other results (9) that charring of the rear surface of materials takes place just prior to ignition. In some instances small holes appeared, and flame was initiated at the rear surface. Although transient flaming may take place without char penetrating through, a necessary condition for sustained ignition appears to be that the specimen be charred through. From this statement one may arrive at a series of dimensionless groupings by replacing depth of char by the thickness in equation (1).

On this basis one expects that ignition data will be correlated through use of the function relationship

$$\frac{QR}{\rho cLE} = f\left(\frac{\sqrt{at}}{L}, \frac{E}{RT_o}, M\right) \tag{3}$$

where L equals the paper thickness in cm. For the purpose of identification the following nomenclature has been adopted for these groupings of parameters

$\frac{QR}{\rho cLE}$; the energy modulus

$\frac{\sqrt{at}}{L}$; the Fourier modulus

$\frac{E}{RT_o}$; the isothermal degradation modulus

Ignition data (flaming ignition only) for 0.75 nominal density papers are presented on a dimensionless basis in figure 2. Ambient temperature was chosen as 297^oK, the mean value for all determinations.

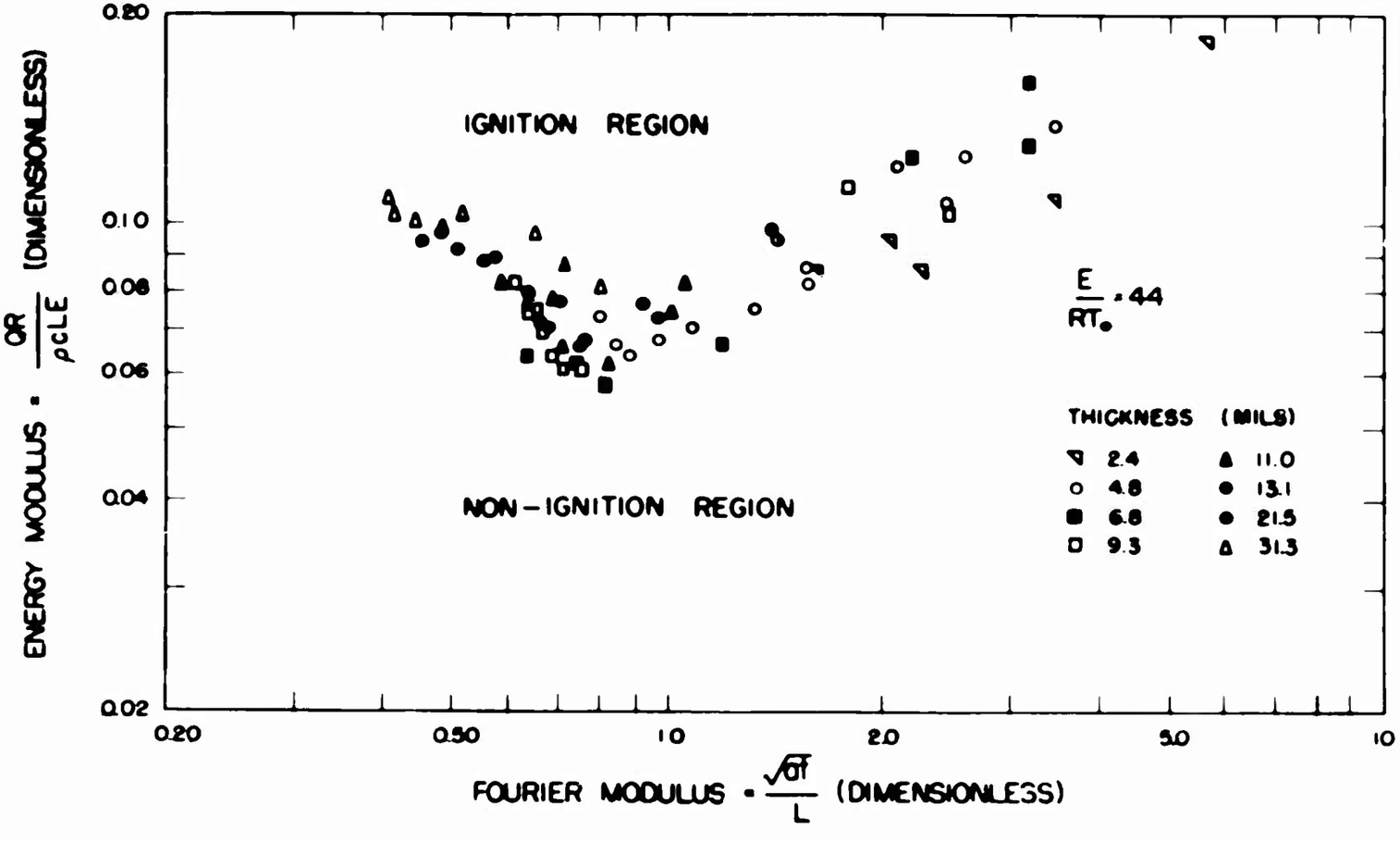

Figure 2.--Correlation of flaming ignition data, 0.75 nominal density black alpha-cellulose paper (4 to 4.5 percent moisture content)

Density and thermal properties are uncorrected for moisture content. The value of activation energy used was that reported by Stamm (19) for alpha-cellulose, i.e., $E = 26 \times 10^3$ cal/mole, so that $E/RT_o = 44$ for the present investigations. Figure 3 displays similar data for 0.55 nominal density papers. All ignition data are summarized in figure 4.

For irradiance levels less than approximately 2 cal/cm^{2}sec, the critical irradiance, destruction occurred without flame. The correlation in figure 4 is limited to irradiance levels above this critical value. Pulse times for destruction at an irradiance of 1.5 cal/cm^{2}sec were determined for four 0.75 density papers and are shown in figure 5. Values of the Fourier modulus were computed from the energy modulus given by the correlation equation and the condition that the irradiance equals 2 cal/cm^{2}sec. The dashed lines of figure 5 were then drawn between this computed value of the Fourier modulus and the corresponding destruction data. These lines illustrate the expected behavior during destruction. The proposed ignition correlation obviously does not correlate destruction data.

DISCUSSION

Ignition energies of black alpha-cellulose papers have been correlated over a Fourier modulus range from 0.35 to 5.5 within an over-all accuracy of ±15 percent. The spread of data is somewhat less for individual papers; thus it appears that errors in the choice of thermal properties were contributory to the inaccuracies of the correlation. The correlation should be considered satisfactory in view of the 13:1 thickness range and the 40:1 range in pulse time covered by the correlation and the degree of limited control exercised over other parameters, particularly moisture content, during experimentation.

Glowing ignition data (figure 4) appear to be indistinguishable along with flaming ignition data within the limits of over-all accuracy. One can readily distinguish between these ignition types during test of a single paper; however, the difference in energy is not sufficiently great to warrant a separation of data according to these ignition types.

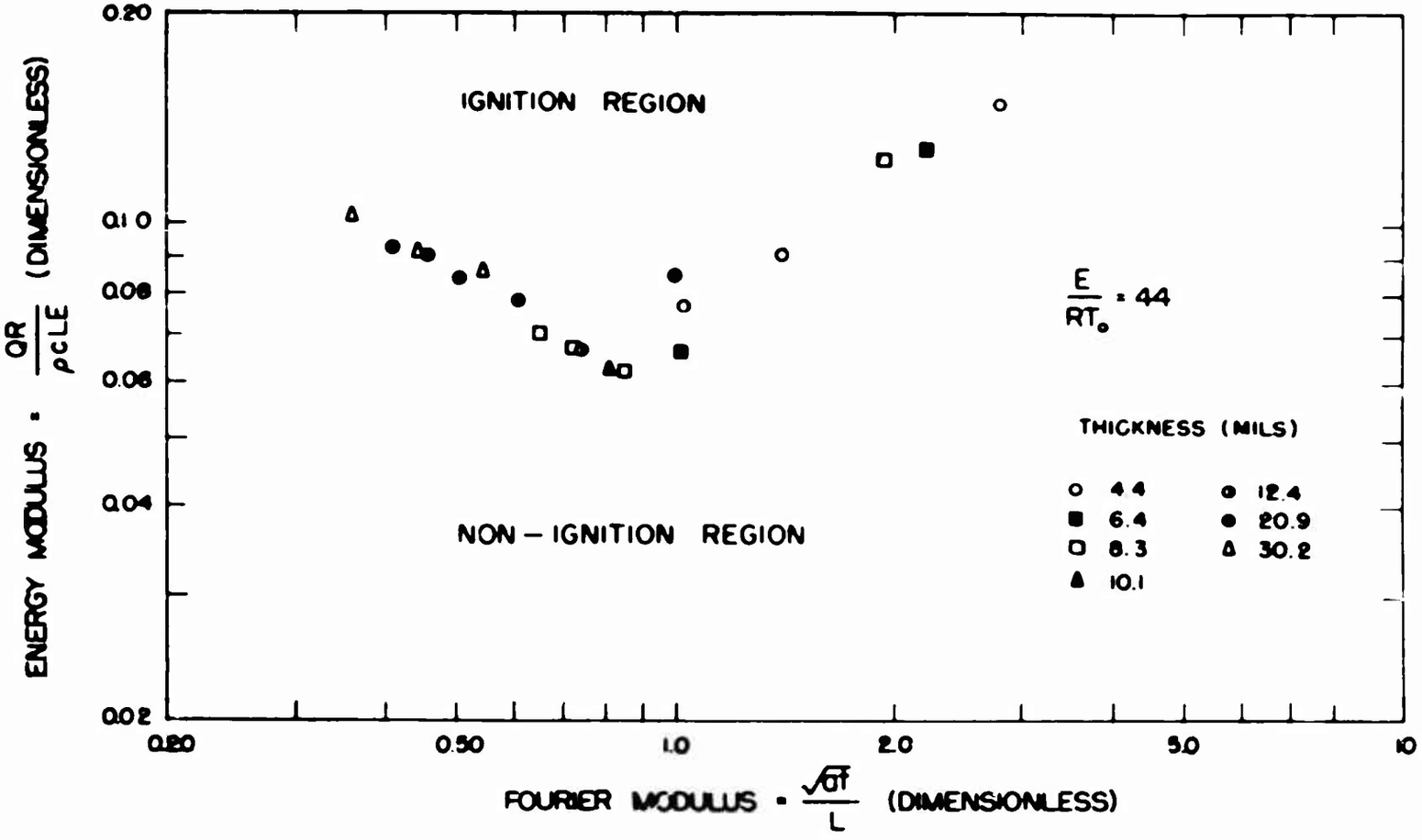

Figure 3.--Correlation of flaming ignition data, 0.55 nominal density black alpha-cellulose paper (4.5 to 5 percent moisture content)

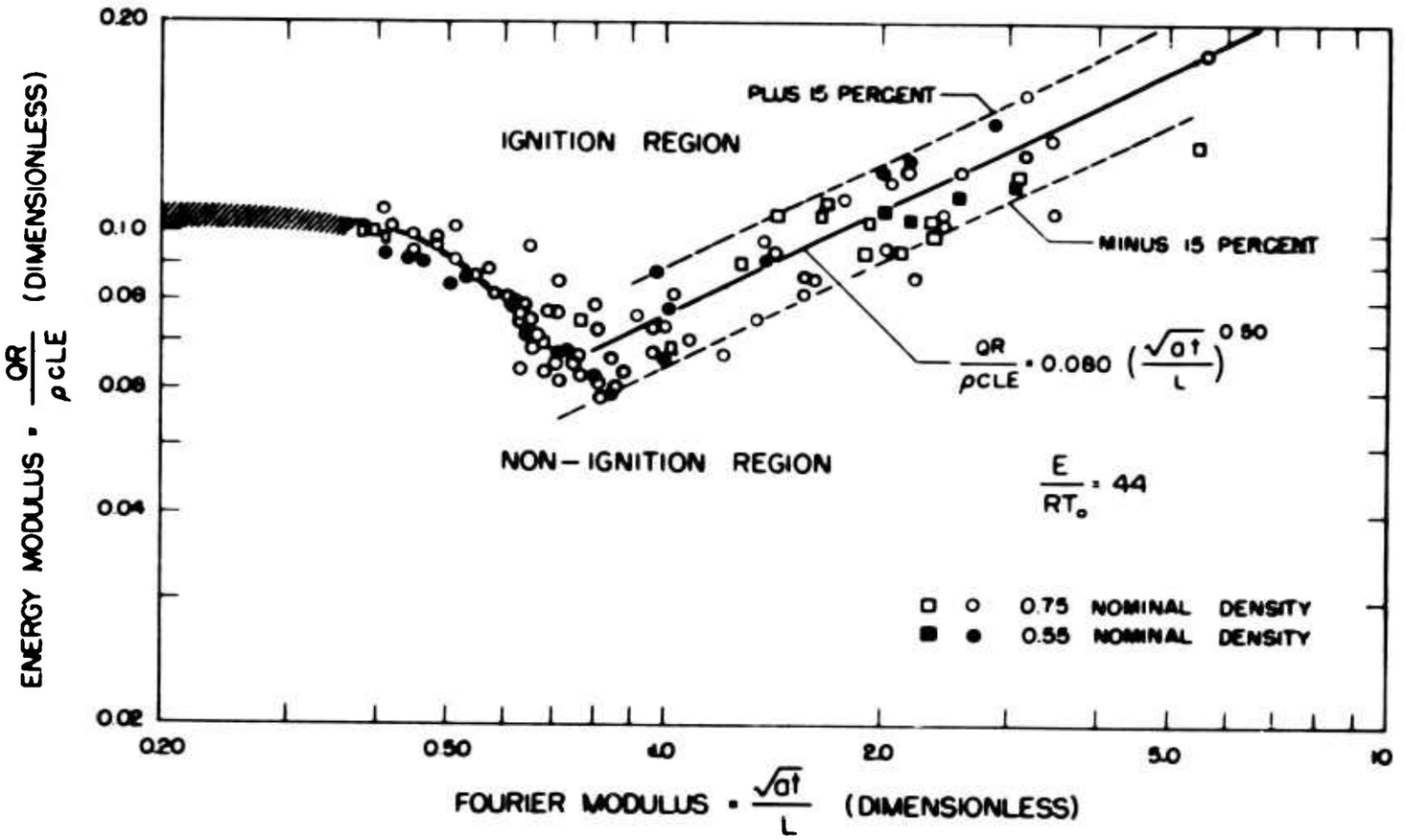

Figure 4.--Correlation of ignition data for irradiance greater than cal/cm^{2}sec, black alpha-cellulose paper, 4 to 5 percent moisture content (circles represent flaming ignition, squares glowing ignition)

FRAMES

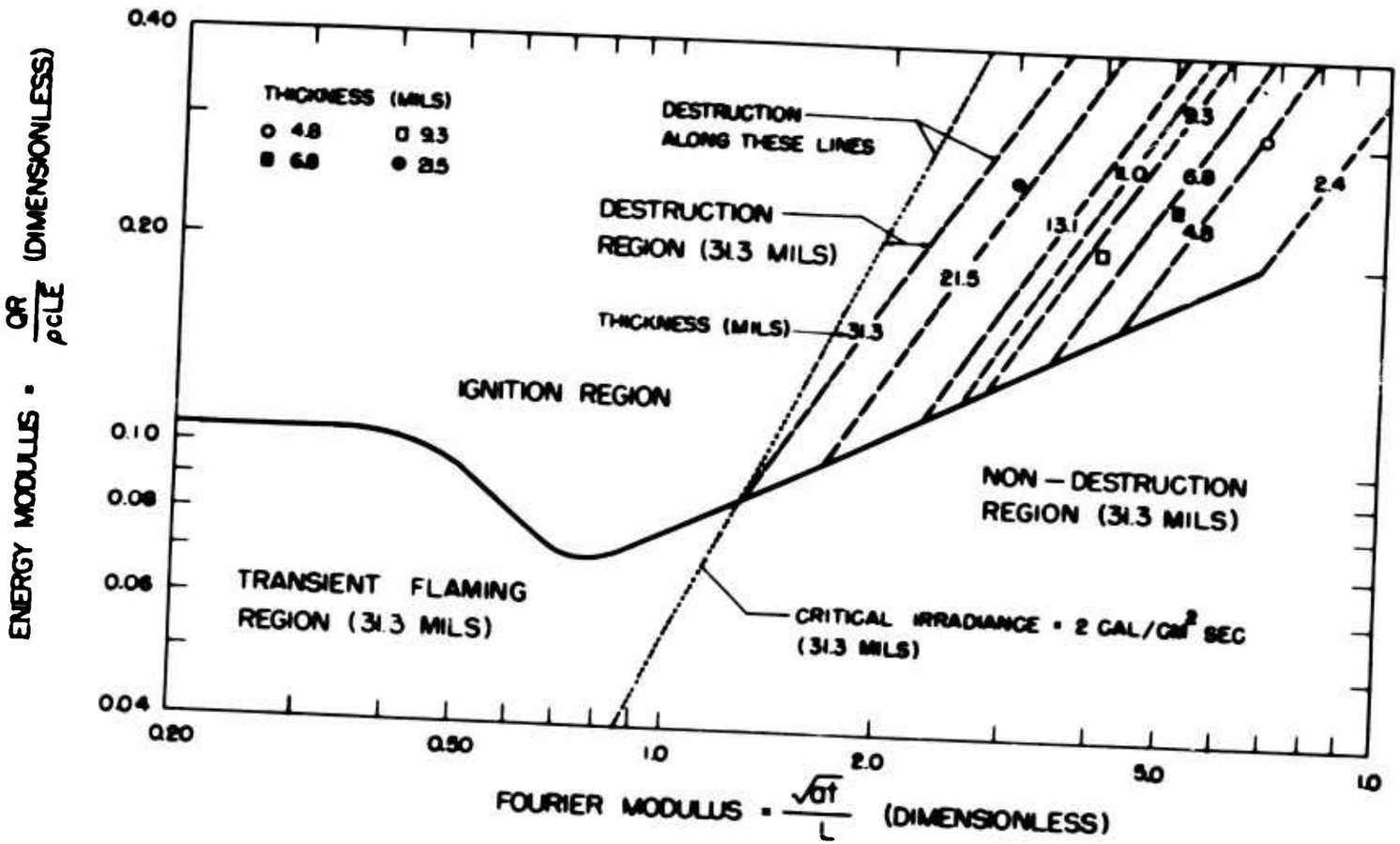

Figure 5.--Destruction data, 0.75 nominal density black alpha-cellulose paper

At this point it is well to consider the dependence of ignition energy on the initial temperature T_o. The critical temperature appears only in the isothermal degradation modulus. As indicated by equation (3) the presented correlations represent but one of the family of curves generated by varying the degradation modulus and moisture content. It is well known that ignition will occur, unaided by thermal radiation, if one raises the initial temperature to the so-called "ignition temperature." Consequently as T_o increases (or E decreases) the required energy Q will decrease. It is obvious that the initial temperature plays an inverse role to the activation energy; however, the presented data do not clarify the role of this relationship since variations in initial absolute temperature were insignificant during these experiments.

The author wishes to emphasize that the presented analysis does not condone specification of an "ignition temperature." In fact it is known that the "ignition temperature" for a specified material depends to a large extent on the testing procedures used and hence is fundamentally a dependent parameter. The isothermal degradation modulus is purely an independent parameter and will, when sufficient data are available, adequately define the dependence of ignition energy on initial temperature.

A comparison of activation energies for various species of wood (13) leads to the conclusion that this quantity probably can be specified within an accuracy of ±10 percent. Since the effect of variations in E are the same as those in T_o it is doubtful that variations of ±10 percent in T_o are significant within the limitations of present data.

Hence it is suggested that where the initial temperature varies within the limits, 300°K ±10 percent ($0 < T_o < 60$°C), then the presented correlations are valid within the ±15 percent.

Spread of Data

When the initial temperature is less than 300°K then the correlation will underestimate the ignition energies somewhat, and energies will be overestimated for temperatures greater than 300°K. This procedure is, however, consistent with the accuracy of the assumption of constant E as discussed above.

For Fourier moduli less than 0.4 the energy modulus approaches constant value. Available irradiance levels unfortunately were too low to explore this region thoroughly. A close inspection of the 31.3 mil paper data (figure 2) reveals a pronounced trend towards a constant ignition energy. Masters' analysis (20,sheet 4c.5) of NML data on the destruction[4/] or burn-through of fabric samples shows conclusively that for $\sqrt{at}/L$ less than 0.4, the critical energy is constant. Similar data of Bates and Monahan (21) also show that at short (relatively) times energy is a constant. Little doubt exists that for short times the energy modulus approaches a constant value which is approximately 0.11 for the black alpha-cellulose.

For Fourier moduli greater than 0.4 the energy modulus decreases as time increases until the Fourier modulus reaches 0.8. At this point the material theoretically is dimensionally too thin to support a temperature gradient (19,part III,p.4). In the absence of heat losses the energy modulus would be expected to again become a constant. At this point, however, heat losses become controlling and since the losses increase with time the energy now becomes greater as the exposure time increases. For Fourier moduli greater than 0.8 with $E/RT_o = 44$ the energy modulus increases according to the equation

$$\frac{Q_R}{\rho c L E} = 0.080 \left(\frac{\sqrt{at}}{L}\right)^{0.50} \qquad (4)$$

For constant pulse time and for a given material, energy is proportional to the square root of the thickness. In the former case, $\sqrt{at}/L < 0.4$, energy was proportional to the thickness. For a given material energy increases as the one-quarter power of pulse time. The one-half power exponent of equation (1) was chosen primarily as a visual fit which portrayed the time dependence of individual data (cf., 4.8 mil data of figure 2) and the constant as the visual average for the data as a whole.

4/ Most probably not destruction in the sense used by the author. Irradiance levels are not identified nor is the critical irradiance for the material known.

The decrease and subsequent increase in energy is a true phenomenon since a majority of the data may be followed around the "bend," i.e., the character of the curve does not result from the joining together of portions of two separate curves. This behavior offers an explanation for the results of Bruce (10) where some materials show very little increase in ignition energy as pulse time increases. Consider a material of such thickness that for a 1-second pulse $\alpha t/L = 0.5$. If the pulse time is increased to 9 seconds, $\alpha t/L = 1.5$ and the ignition energy will not have appeared to change. However, if the same material were to have half the original thickness the 9-fold increase in pulse time would result in an increase in ignition energy of 75 percent.

Bates and Monahan (20) show a dependence of energy with time for pulse times greater than 1 second. They arrive at a 0.27 power for the time dependence as the statistical fit to a rather limited number of data. In their abstract they modify this to the one-quarter power. It is interesting to note that the above-mentioned and the presented analysis arrived at the same result independently.

The author wishes to point out that since the region of Fourier moduli greater than 0.8 appears to be that in which heat losses are controlling, further experimentation should consider the effect of convective losses. In the present work, convective losses are primarily those associated with free convection and are of the order of magnitude of the radiative losses. The presence of even a slight wind will increase convective losses materially and probably will increase the constant in equation (4), and possibly change the time dependence.

Further effort should be made to specify the critical irradiance and define the dimensionless correlation of the destruction energy-time or irradiance-time dependence. The author suggests that the destruction correlation first be found, then by the intersection of destruction and ignition lines, as in figure 5, the critical irradiance may be specified for each paper.

The importance attached to defining the destruction relationships is stressed under conditions where pulse times are long or thickness relatively large and irradiance levels low. Knowledge of whether ignition or destruction takes place may also be important in biomedical aspects of burn protection.

Density and thermal properties are uncorrected for moisture content. The value of activation energy used was that reported by Stamm (19) for alpha-cellulose, i.e., $E = 26 \times 10^3$ cal/mole, so that $E/RT_o = 44$ for the present investigations. Figure 3 displays similar data for 0.55 nominal density papers. All ignition data are summarized in figure 4.

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For Fourier moduli less than 0.4 the energy modulus approaches a constant value of approximately 0.11. This behavior is consistent with the results of other investigators. For Fourier moduli greater than 0.4 the energy modulus decreases to a minimum value of 0.068 at a Fourier modulus of 0.8. Above this value ignition energy can be represented by the equation

$$\frac{Q_R}{\rho c L E} = 0.080 \left(\frac{\kappa a t}{L}\right)^{0.5}$$

provided the irradiance exceeds the critical irradiance.

For 31 mil black alpha-cellulose paper the critical irradiance appears to be approximately 2 cal/cm^{2}sec.

The time dependence of the scaling equation, i.e., Q proportional to $t^{1/4}$, is in agreement with other investigators.

Regions of ignition, transient flaming, destruction without flame, and nondestruction are illustrated in terms of the above-mentioned dimensionless moduli. Additional work, however, is necessary to define the correlation for destruction and to improve the estimate of critical irradiance on a dimensionless basis.

APPENDIX

THERMAL CONDUCTIVITY-DENSITY RELATIONSHIP FOR ALPHA-CELLULOSE PAPER AND OTHER HOMOGENEOUS CELLULOSIC MATERIALS

Thermal conductivities of all alpha-cellulose papers used during this investigation were not separately determined. Limitations in measuring temperature difference prohibited using single sheets of paper for conductivity determination. Consequently it was necessary to stock sufficient sheets under pressure, to produce a thickness of about 1/4 inch. These data are shown in table 2 and plotted in figure 6.

Table 2.--Thermal conductivity at room temperature of alpha-cellulose paper (moisture content of 2 percent)

Paper Number	Percent Carbon	Density during Test (gm/cc)	Conductivity (10^{-4} cal/cm^{2}sec$^\circ$C/cm)
4204	0	0.62	2.1
4211	0	0.84	3.0
4204	0	0.83	3.0
4211	0	1.04	4.1
4204	2.5	0.65	2.2
4104	2.5	0.76	2.8
4096	2.5	0.82	2.8
4096	2.5	0.99	3.4
4089	10	0.77	3.3
4082	5	0.81	3.0

The above procedure resulted in increasing density somewhat and it became necessary to determine the variation of conductivity with density. The literature reveals little such data on paper; however, a large number of data are summarized on various types of cellulosic insulating materials. These data were carefully selected to exclude nonhomogeneous sheet material, i.e., felt between two sheets of paper, as such materials may lead to extraneous results due to included air films. The selected data are tabulated in table 3 and plotted in

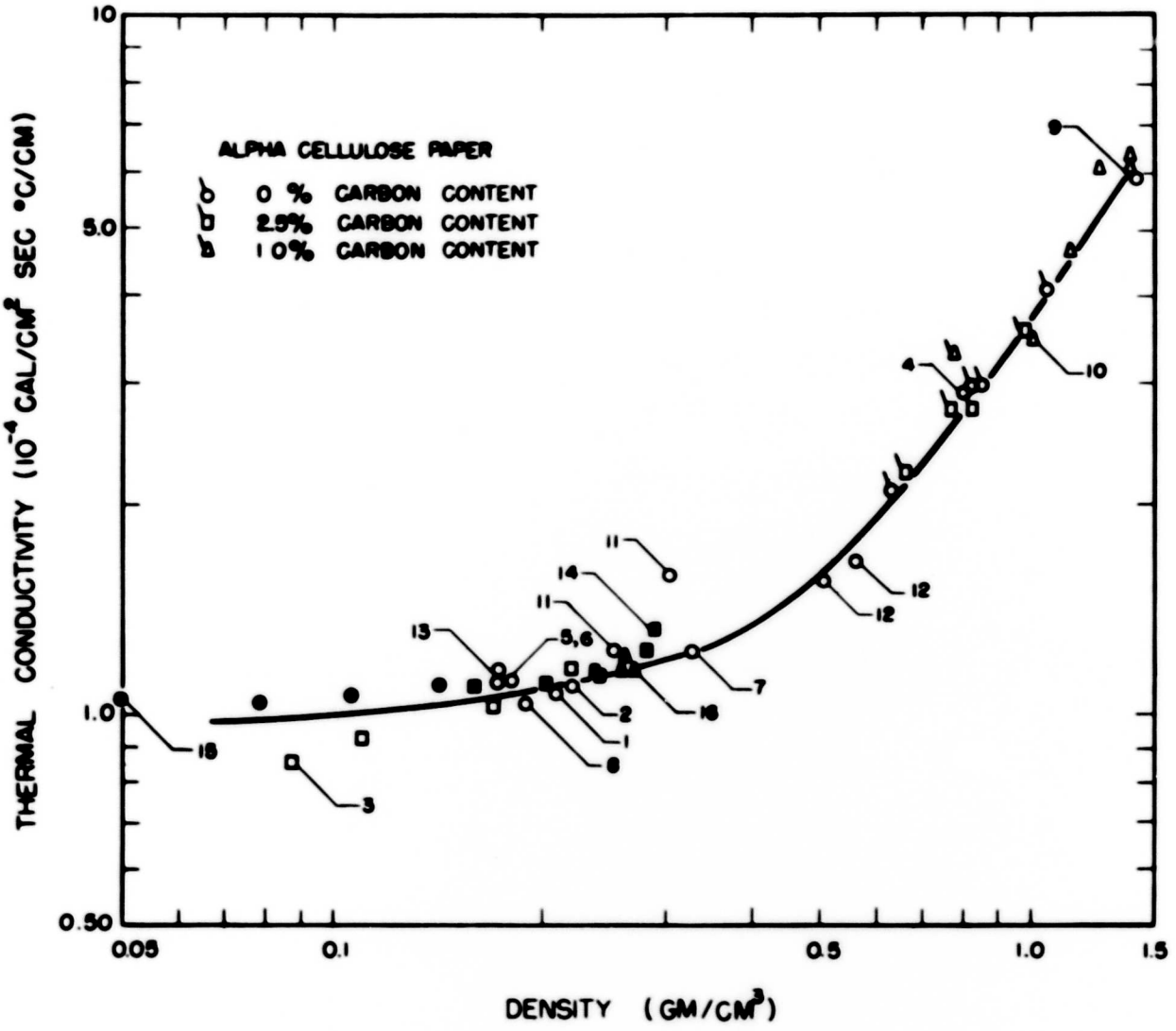

Figure 6.--Thermal conductivity-density relationship for cellulosic insulating materials in sheet form. (Numbers correspond to listing in table 3. Closed symbols represent measurements at zero moisture content, open symbols at 4 to 8 percent or unknown moisture content, alpha-cellulose values from table 2 at 2 percent moisture content.)

figure 6. The agreement of measured conductivities with these data is readily apparent. The addition of 2.5 percent carbon does not increase the conductivity significantly; however, at 10 percent carbon content the conductivity appears to be increased about 15 percent.

Table 3.--Thermal conductivity at room temperature of various cellulosic insulating materials in sheet form

	Material	Reference	Density (gm/cc)	Conductivity (10^{-4} cal/cm^2 sec °C/cm)
1	Flax fiber sheet	(22)	0.21	1.07
2	Flax and rye fiber sheet	(22)	0.22	1.10
3	Cork board	(22)	0.087	0.86
			0.11	0.93
			0.17	1.03
			0.22	1.17
4	Manila paper	(17,p.312)	0.8	2.87
5	Felted flax fibers	(17,p.312)	0.18	1.12
6	Felted vegetable fibers	(17,p.312)	0.18	1.12
7	Wood felt	(17,p.312)	0.33	1.24
8	Pressed wood pulp board	(17,p.312)	0.19	1.03
9	Cellulose (compressed)	(17,p.312)	1.42	5.84
10	Fuller board (20°C)	(17,p.312)	1.01	3.47
			1.15	4.66
			1.26	6.10
			1.38	6.40
			1.39	6.22
11	Wood fiber-board	(23)	0.31	1.59
			0.26	1.23
12	Card board	(23)	0.51	1.55
			0.56	1.67
13	Flax waste mat	(23)	0.17	1.11
			0.17	1.15
14	Wood fiber-board	(24)	0.16	1.10
			0.20	1.11
			0.24	1.14
			0.24	1.15
			0.28	1.31
			0.29	1.23
15	Wood pulp board	(24)	0.05	1.05
			0.08	1.03
			0.11	1.06
			0.14	1.10
16	"Insulite" (wood pulp)	(24)	0.26	1.16
			0.27	1.20
			0.27	1.17

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