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COMPARISON OF FIELD AND LABORATORY FOREST FUEL IGNITION ENERGIES AND EXTRAPOLATION TO HIGH-YIELD WEAPONS

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COMPARISON OF FIELD AND LABORATORY FOREST FUEL IGNITION ENERGIES AND EXTRAPOLATION TO HIGH-YIELD WEAPONS

by

F. M. Sauer

Interim Technical Report AFSWP-870
March 1956

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U. S. Department of Agriculture
Forest Service
Division of Fire Research
Washington, D. C.
A. A. Brown, Division Chief

Project Leader: W. L. Fons
California Forest and Range Experiment Station
P. O. Box 245
Berkeley, California

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Agriculture--Berkeley

[redacted]

ABSTRACT

Comparisons are made between ignition energies of forest fuels, including newspaper, determined during Operations BUSTER, SNAPPER and UPSHOT-KNOTHOLE and laboratory exposures made utilizing the Forest Service thermal source. Agreement is excellent for fuels exposed normal to the radiant flux when fuel moisture content is considered. Ignition of fuels exposed at attitudes other than normal to the radiant flux is not discussed. Ignition energy-moisture content relationships which include the effect of weapon yield are presented. Although presented relationships lack complete scientific verification they appear valid for thin homogeneous fuel types, such as newspaper and grass, within ±5 to 15 per cent for a range of yield of 1 KT to 10 MT. For more heterogeneous fuels, such as punk and litter, results are believed to be within ±25 ~~per~~ % cent for yields of 1 to 100 KT.

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INTRODUCTION

Ignition energies, i.e., the minimum thermal energy required for sustained ignition, have been determined for a variety of forest fuels and newspaper during Operations BUSTER (1),[1] SNAPPER (2), and UPSHOT-KNOTHOLE (3). These fuels, plus others, have been exposed to the Forest Service thermal source by the Department of Engineering, University of California, Los Angeles (4) and the Forest Products Laboratory (5,6), and their ignition energies determined over a wide range of moisture contents.

Previous comparisons of field and laboratory data (1,2) have indicated general agreement; however, field ignition energies were usually based on preliminary thermal data and at times laboratory experiments were incomplete. Furthermore, an examination by the author of ignition data on newspaper and ponderosa pine needles (3) indicated that moisture content sampling procedures during BUSTER and SNAPPER lead to high moisture values, equilibrium moisture content corresponding to shot-time relative humidity being nearer the correct value.

Recent work on ignition of black alpha-cellulose paper (7) indicates an increase in ignition energy for thin fuels proportional to the 1/4-power of the pulse time, provided $0.8 \leqslant \sqrt{a t_s}/L$, where a is the thermal diffusivity, t_s is the pulse time, and L is the thickness of the fuel particle in consistent units. Although this result is based on square wave exposure, dimensionless correlation of ignition data allows one to assume the same scaling equation holds for the time base in the case of the field pulse,[2] leading to the conclusion that ignition energy scales as the 1/8-power of the weapon yield.

With these considerations in mind it appeared worthwhile to re-examine all available forest fuel ignition data on the basis of final thermal yields (8,9,10) and shot-time relative humidities, and compare

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1/ Underlined numbers in parentheses refer to Literature Cited, page 31.
2/ Cf. page 21.

field values with laboratory results. Once the validity of these nominal yield relationships have been established, extrapolation to high-yield weapons may be effected utilizing the above-mentioned scaling equation.

SUMMARY OF IGNITION DATA

Operation BUSTER data are summarized in table 1 for those fuels exposed in their natural vertical configuration, such as grasses, and those exposed normal to the incident radiant flux.[3/] Usually, only those listings which bracket ignition are presented since data gathered at higher or lower energies have little significance. In some cases where data are inconsistent (as madrone, table 2) all energies and effects are tabulated. Interpolation between these energies is a difficult and hazardous procedure since ignition is a liminal process. In some cases lower limits (nonignition) were not determined, as indicated. Thermal energies of table 1 were re-estimated from the final operation thermal report (8).

Experience subsequent to Operation BUSTER indicates that fine fuels which are heavily charred most probably ignite and are blown out by blast (3), a condition which does not accompany laboratory exposures. Blowout or extinguishment must then be treated separately in the analysis of field data since it will occur only at special combinations of overpressures and thermal energies. Consequently several entries of (1) listed as "char" appear in table 1 as "extinguished by blast" as reanalysis of field data indicates this was the probable effect. "Extinguished by blast" observations should be considered "burned" in comparing field and laboratory results.

Similar data for Operations SNAPPER and UPSHOT-KNOTHOLE are shown in tables 2 and 3.

Table 4 presents final yield, air temperature, and relative humidity data for all shots on which fine fuel ignition data were gathered. Moisture contents for the various natural fuel types were

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3/ Ignition of fuels exposed other than normal to radiant flux is discussed in some detail in (3).

Table 1.- Operation BUSTER data for fuels exposed vertical or normal to radiant flux

Fuel	Shot	Energy (cal/cm^2)	Energy÷(KT)$^{1/8}$	Effect
Sedge grass	BAKER	7.3	6.2	Extinguished by blast
		4.8	4.1	Slight char
	CHARLIE	8.5	6.1	Extinguished by blast
		5.2	3.7	None
	DOG	7.1	4.8	Extinguished by blast
		4.0	2.7	None
	EASY	6.2	4.0	Burn
		4.5	2.9	None
Desert stipa	DOG	5.3	3.6	Limit of ignition
	EASY	4.9	3.2	Limit of ignition
Punk 1/	BAKER	4.8		Burn
		2.5		None
	CHARLIE	8.5		Char or extinguished
		5.2		None
	DOG	4.0		2/ Burn
	EASY	4.5		2/ Burn
Ponderosa pine needles	EASY	14.5	9.4	2/ Burn
Madrone leaves	EASY	10.0	6.5	2/ Burn
Wheat straw	EASY	6.2	4.0	2/ Burn

1/ White fir punky log
2/ No exposures made below this value

determined from the equilibrium moisture content-relative humidity data of Dunlap (14,15) on conifer and hardwood fuels, and Bartholomew and Norman's (16) data on grasses. Data on paper were taken from the International Critical Tables (17). These data are shown graphically in figures 1 and 2.

Table 2.- Operation SNAPPER data for fuels exposed normal to radiant flux

Fuel	Shot	Energy (cal/cm^2)	Energy÷(KT)$^{1/8}$	Effect
Ponderosa pine needles	3	8.8	5.8	Burn
	3	7.3	4.8	Char
	4	10.8	7.4	Burn
	4	8.4	5.8	Char
Madrone leaves	3	8.8	5.8	Char
	3	7.3	4.8	Burn
	3	6.0	3.9	Char
	3	5.2	3.4	Char
	3	4.6	3.0	None
	4	10.8	7.4	Burn
	4	8.4	5.8	Char
	4	6.6	4.6	Burn
	4	5.3	3.7	None
Beech leaves	3	4.6	3.0	Char
	3	3.5	2.3	1/ Burn
	4	5.3	3.7	Burn
	4	4.3	3.0	Char
Rhododendron leaves (dry)	3	11.0	7.2	Extinguished by blast
	3	8.8	5.8	Char
	4	21.0	14.5	Extinguished by blast
	4	8.4	5.8	Char
Wheat straw	3	8.8	5.8	2/ Char
	3	7.3	4.8	Char
	3	6.0	3.9	Char
	3	5.2	3.4	None
	4	8.4	5.8	Extinguished by blast
	4	5.3	3.7	Char
Cheat grass	3	4.6	3.0	Burn
	3	3.5	2.3	None
	4	6.6	4.5	Burn
	4	5.3	3.7	Char
	4	3.6	2.5	None
Horsehair (brown) lichen	3	5.2	3.4	Extinguished by blast
	3	4.6	3.0	Char
	4	5.3	3.7	Burn
	4	4.3	3.0	Char
Punk (hardwood)	3	4.6		2/ Char
	4	3.6		1/ Burn

1/ No exposures made below this value
2/ No exposures made above this value

Table 2 (continued)

Fuel	Shot	Energy (cal/cm^2)	Energy÷$(KT)^{1/8}$	Effect
Punk (fir)	3	3.5		Burn
	3	2.2		None
	4	3.0		Burn
	4	2.4		None
Punk (black oak)	3	3.5		Burn
	3	2.9		None
	4	3.0		Burn
	4	2.4		None
Punky log (black oak)	3	5.2		Burn
	3	4.6		3/ Burn; char
	3	3.5		None
	4	5.3		Burn
	4	4.3		Char
Punky log (fir)	3	5.2		Burn
	3	4.6		3/ None; burn
	3	3.5		3/ None; burn
	3	2.9		None
	4	5.3		Burn
	4	4.3		3/ Burn; char
	4	3.6		3/ Burn; none
	4	3.0		3/ Burn; none
	4	2.4		None

3/ Two samples exposed

Table 3.- Operation UPSHOT-KNOTHOLE data for fuels exposed normal to radiant flux

Fuel	Shot	Energy (cal/cm^2)	Energy÷$(KT)^{1/8}$	Effect
Crumpled newspaper	4	4.0	3.0	Burn
		3.4	2.5	Slight char
	9	4.3	2.8	Burn
		3.1	2.0	Slight char
Ponderosa pine needles	4	5.4	4.0	1/ None
	9	7.7	5.1	Burn
		6.3	4.2	Char

1/ No exposures made above this value

Table 4.- Summary of yield, shot-time humidity and temperature, and corresponding fuel moisture

Operation	Shot	Yield (KT)	Ref.	$(KT)^{1/8}$	Relative humidity (per cent)	Temperature °F	Ref.	Estimated fuel moisture (per cent): Grasses 1/	Hardwood 2/ leaves and punk	Conifer 3/ needles and punk	Newsprint 3/
BUSTER	BAKER	3.49	(11)	1.17	65	56	(1)	13.0	17.5	12.0	6.5
	CHARLIE	14.0	(11)	1.39	80	40	(1)	19.0	22.0	17.0	8.5
	DOG	21.0	(11)	1.49	50	53	(1)	9.5	14.5	9.5	5.5
	EASY	31.4	(11)	1.54	27	55	(1)	6.5	11.0	6.5	4.0
SNAPPER	3	30.0	(12)	1.53	30	66	(12)	7.0	11.5	6.5	4.0
	4	19.6	(12)	1.45	4/ 47	4/ 63	(12)	9.0	14.0	9.0	5.0
UPSHOT-KNOTHOLE	4	10.8	(13)	1.35	25	60	(13)	6.5	11.0	6.0	3.5
	9	26.4	(13)	1.51	19	62	(13)	6.0	10.0	5.5	3.0

1/ Desorption curve used since relative humidity falling
2/ ±1 per cent
3/ ±0.5 per cent
4/ Weather station at 20,000 ft ground range indicated 43 per cent relative humidity and 64°F (2)

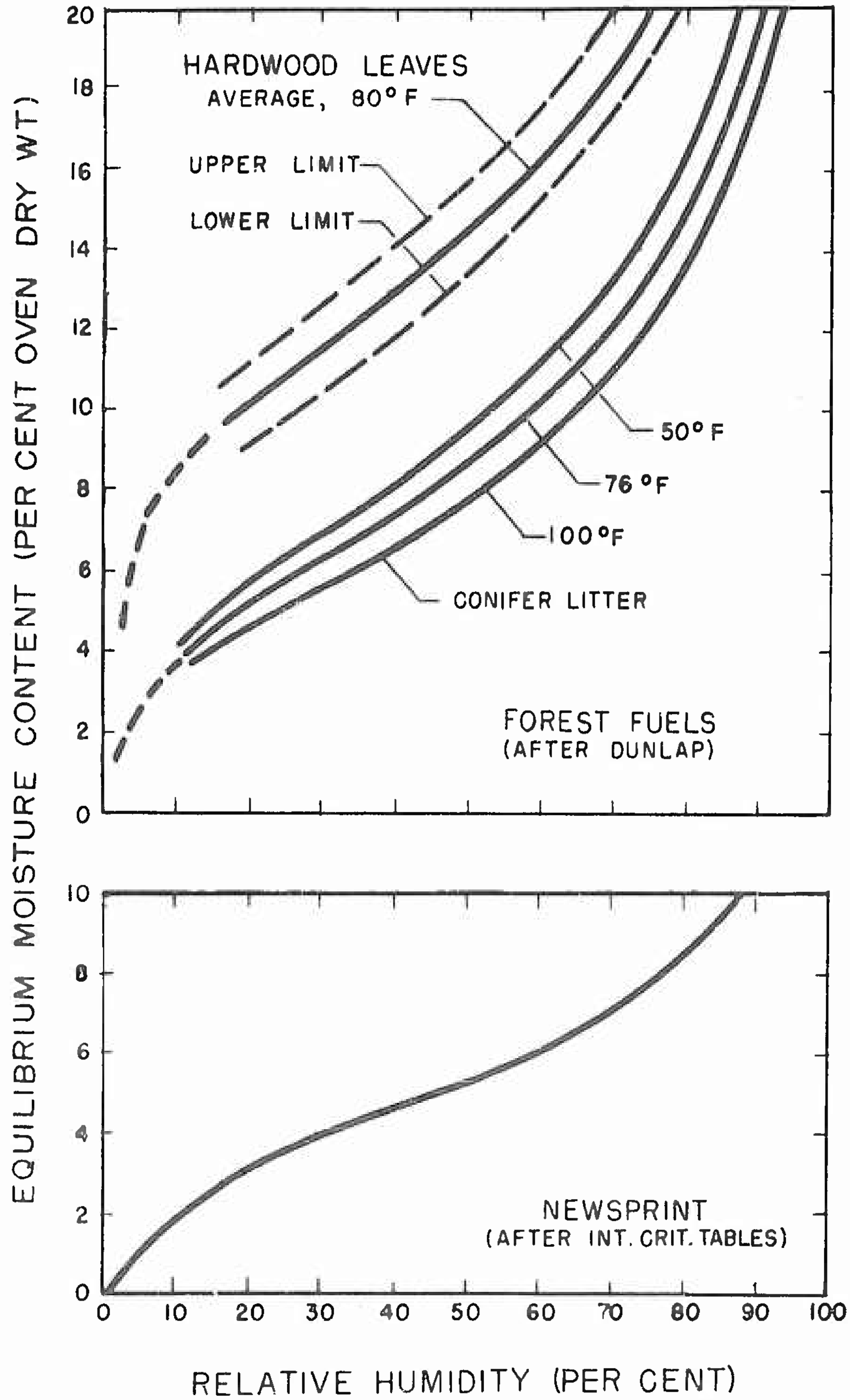

Figure 1.--Equilibrium moisture content-relative humidity relationships for forest fuels and newspaper

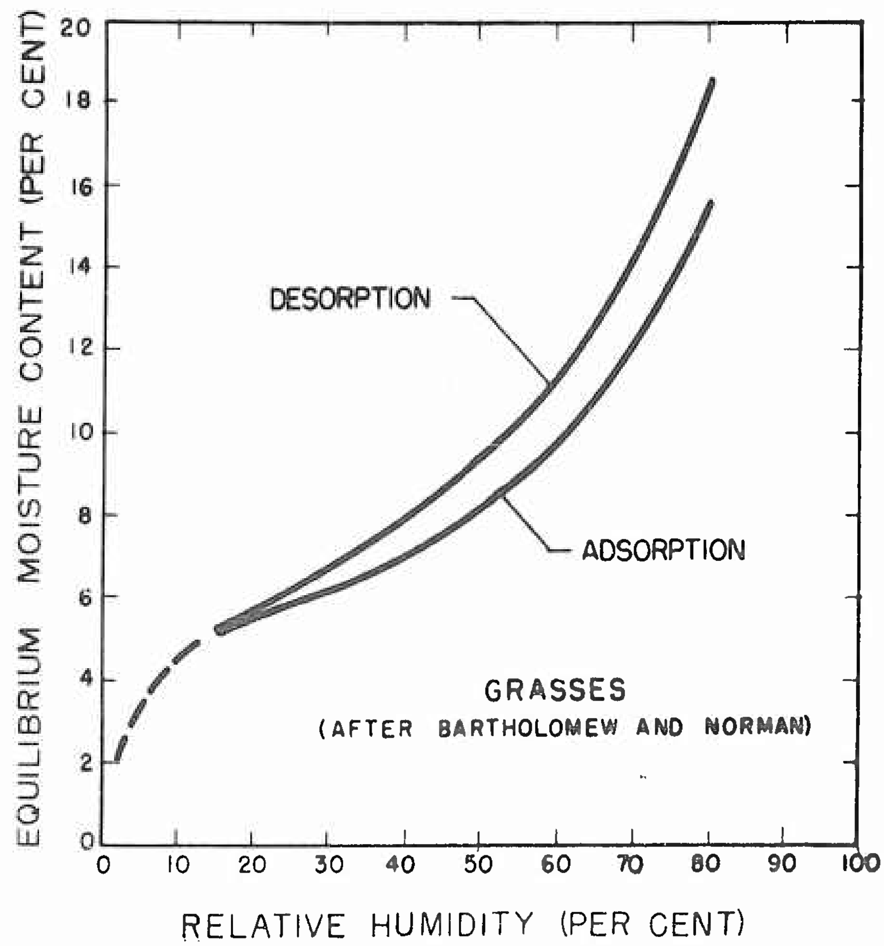

Figure 2.--Equilibrium moisture content-relative humidity relationships for grasses

Thermal effects determined from field observations are compared in figures 3a, b, c, and d with laboratory determinations of ignition energy for all fuels where both data are available. Figure 4 displays laboratory ignition data for which corresponding field data are not available. Laboratory determinations were made using the Forest Service source "1 second" pulse (figure 5). The agreement between field and laboratory data is evident when consideration is given the limited number and finite spacing of field exposures. In view of the many theoretical hypotheses to the contrary (18, sheet 7c.6) this juxtaposition of data appears fortuitous; however, examination of other types of thermal damage data presents supporting evidence as to why this result occurs. These arguments are discussed in the following section.

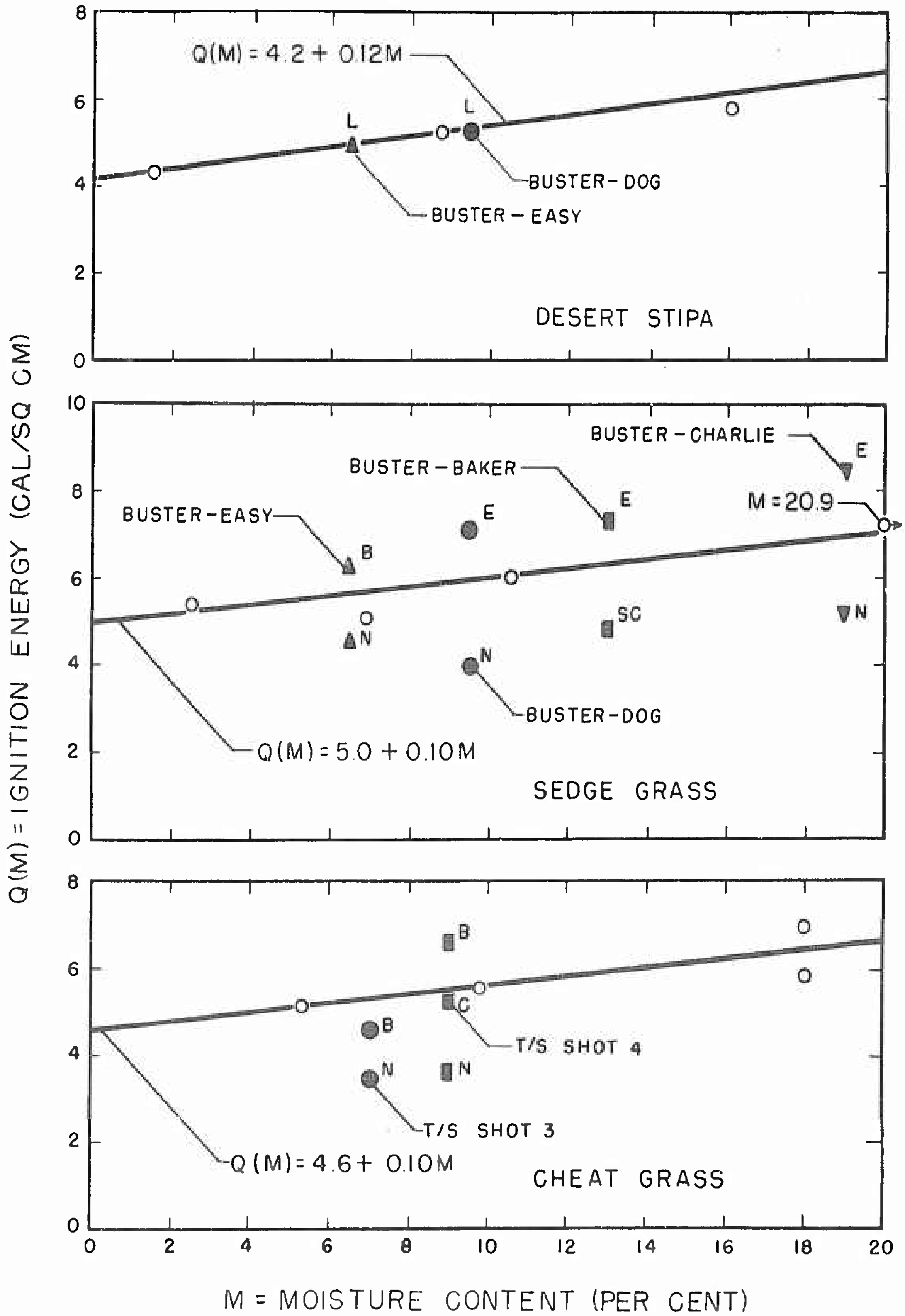

Figure 3a.--Comparison of field and laboratory ignition energies. (Open circles represent ignition energies determined by Forest Service source. Letters adjacent field data points indicate effect noted in tables 1, 2, and 3.)

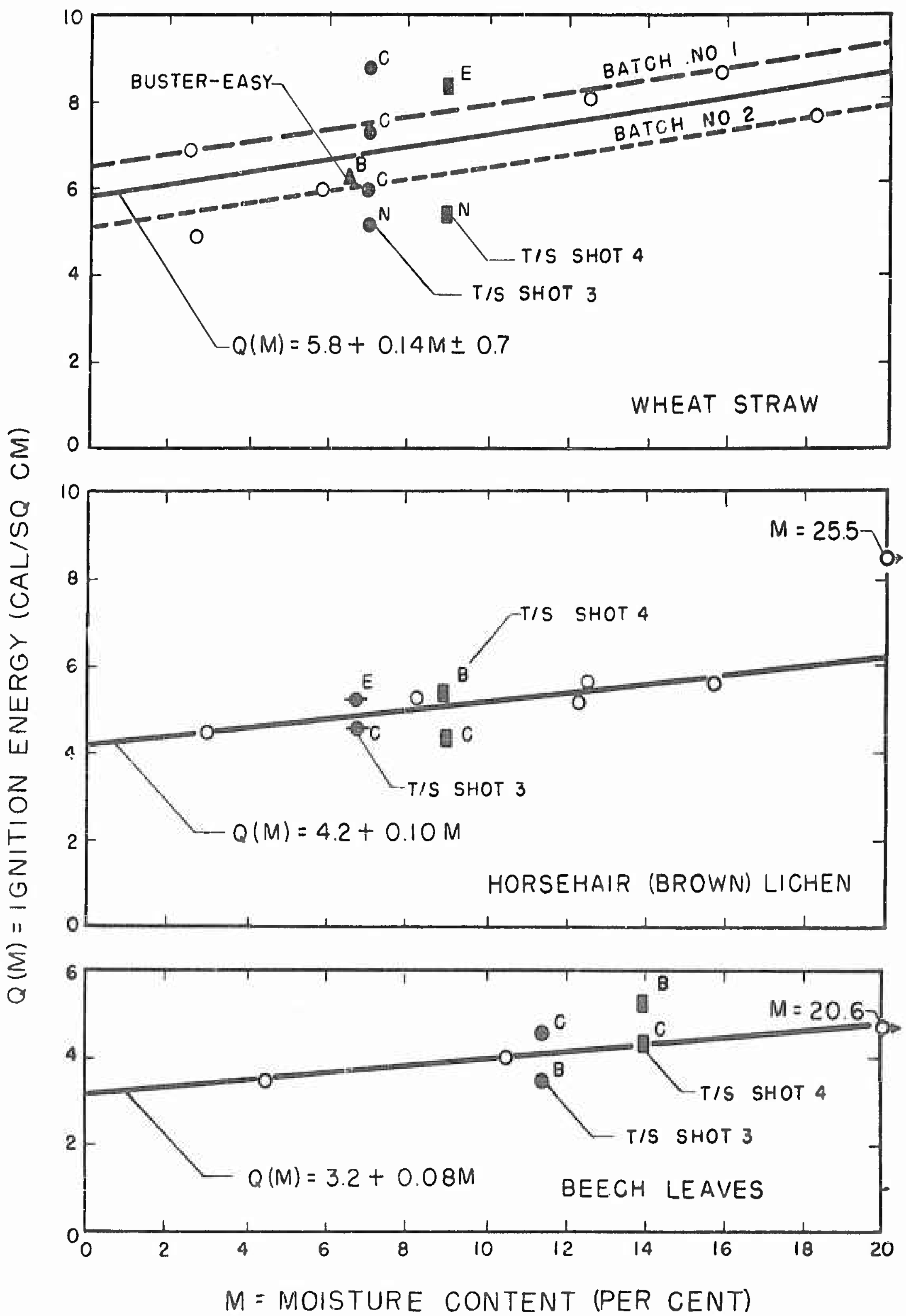

Figure 3b.--Comparison of field and laboratory ignition energies. (Open circles represent ignition energies determined by Forest Service source. Letters adjacent field data points indicate effect noted in tables 1, 2, and 3.)

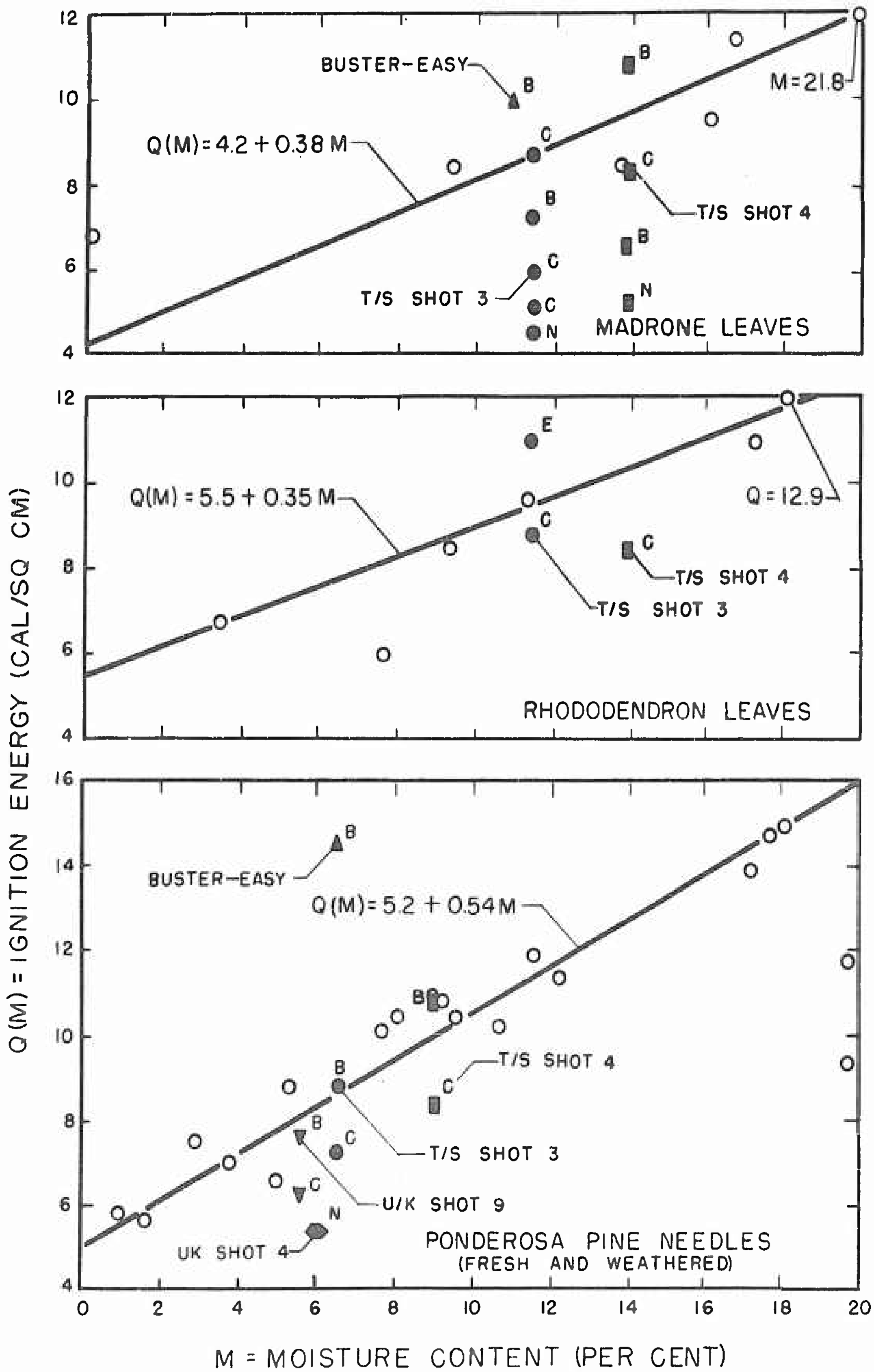

Figure 3c.--Comparison of field and laboratory ignition energies. (Open circles represent ignition energies determined by Forest Service source. Letters adjacent field data points indicate effect noted in tables 1, 2, and 3.)

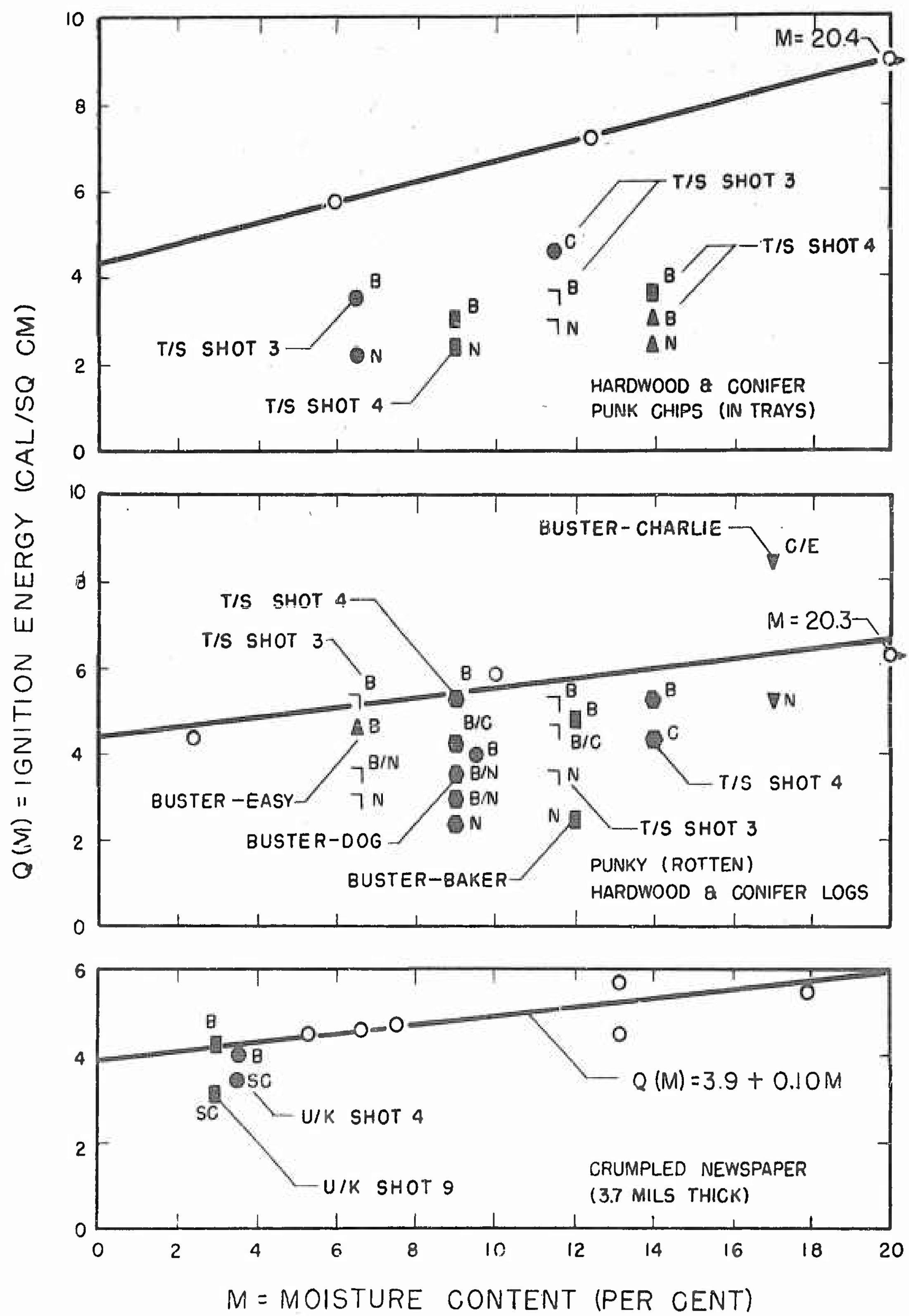

Figure 3d.--Comparison of field and laboratory ignition energies. (Open circles represent ignition energies determined by Forest Service source. Letters adjacent field data points indicate effect noted in tables 1, 2, and 3.)

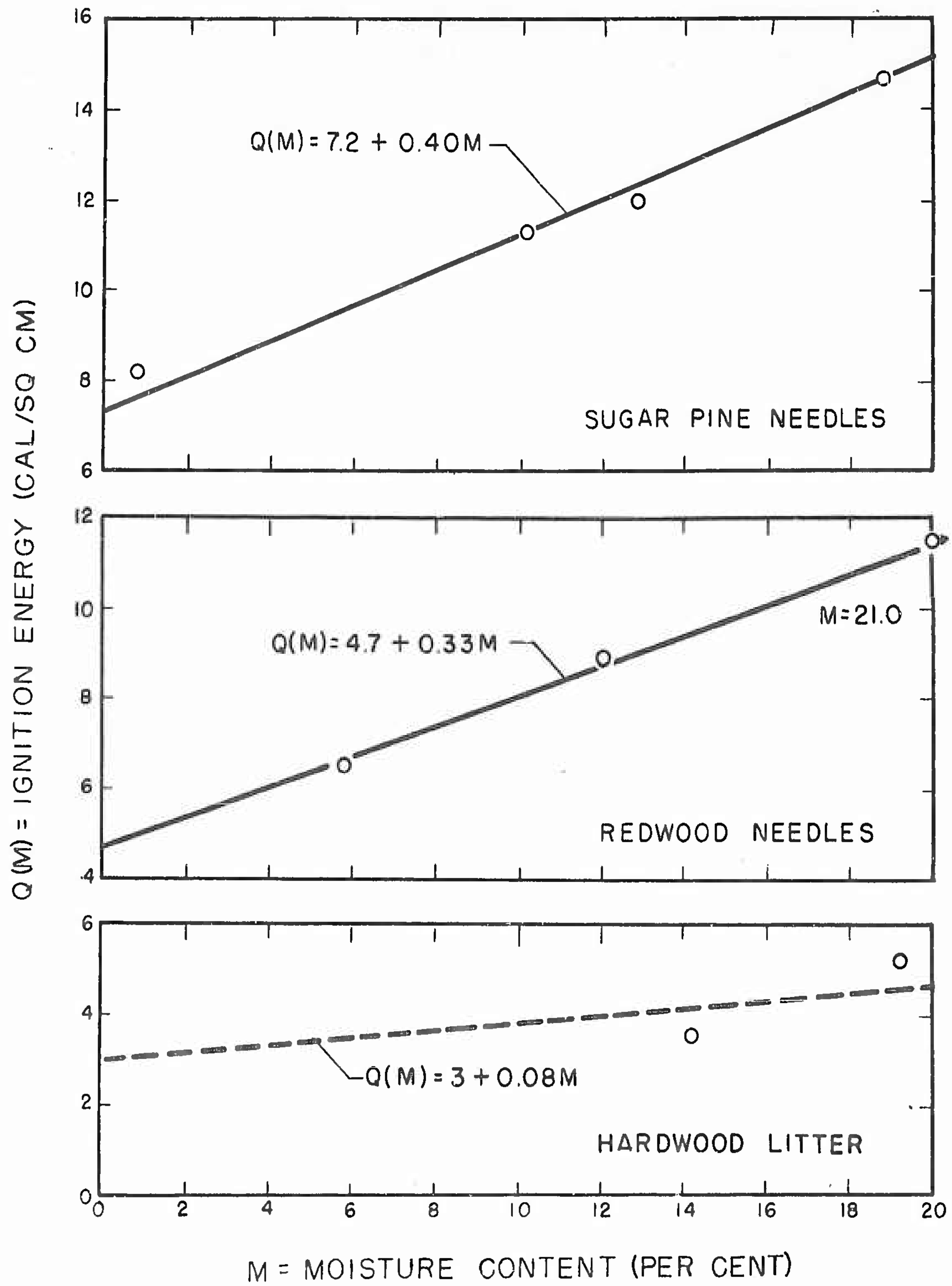

Figure 4.--Laboratory ignition energies for fuels not exposed during field operations--Forest Service source data

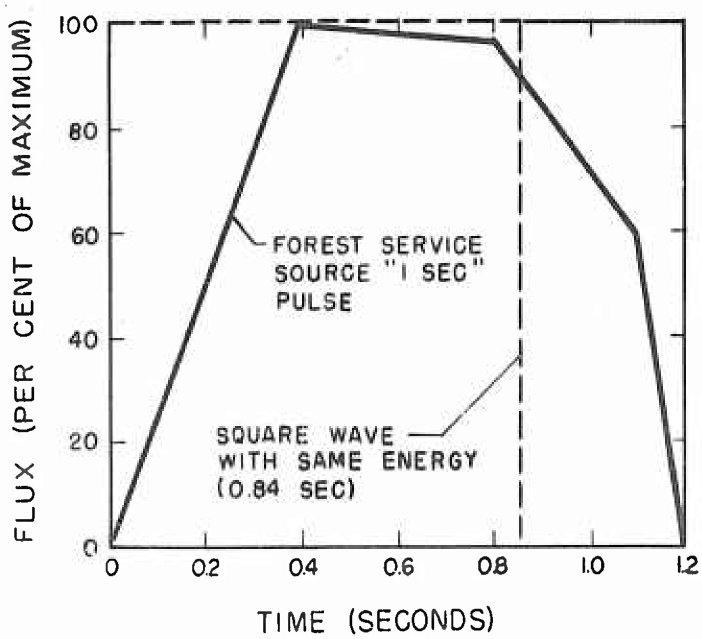

Figure 5.--Radiant intensity-time characteristics of Forest Service source "1 second" pulse (after H. D. Bruce)

VARIATION OF IGNITION ENERGY WITH YIELD

Dimensionless correlation of results occurring during thermal damage to cellulosic materials has brought forth results which appear basic in regard to timewise scaling of these effects. While these studies are not entirely complete, i.e., the effects of moisture content and diathermancy have not been completely studied, they provide information which may be used to effect an engineering extrapolation of presented ignition energies to large-yield weapons. Hence, due to obvious lack of scientific confirmation in several instances the following presentation should be viewed in the light of final results.

The author has shown (19) the depth of char and weight loss during exposure to a square wave radiant pulse are identical to those experienced during exposure to the NRDL simulated (laboratory) field pulse provided the square wave flux equals 0.60 times the maximum flux (second maximum) of the field pulse, and the square wave exposure time equals 4.0 times the time of second maximum. This equivalence holds for all char depths, excepting incipient charring (threshold), and checks well against available field data (20). Visual color variation from the light color of sugar pine to the dark color of mahogany appeared to have no discernible effect on this relationship. This does not imply that white materials behave as do black materials since white paper and cloth are usually highly diathermous, a property which has not been investigated.

Investigation of the ignition of black alpha-cellulose papers (7) indicates that ignition is just sustained only when the rear surface of the paper shows signs of incipient charring. The phenomena of charring, weight loss, and persistent ignition are apparently closely related. With some assurance the same pulse shape equivalence may be assumed to hold for ignition as for charring and weight loss, viz., the field pulse ignition energies correspond to those determined utilizing a square wave exposure of four times the time of the second maximum.[4/]

Correlation of black alpha-cellulose ignition energies for square wave exposures at a moisture content of 4 to 5 per cent results in the dimensionless equation[5/]

$$\frac{Q_s}{\rho C L T_o} = 3.5 \left(\frac{\sqrt{a t_s}}{L}\right)^{1/2} \quad ; \quad 0.8 \leqslant \frac{\sqrt{a t_s}}{L} \tag{1}$$

within a maximum error of ±15 per cent. The constant 3.5 holds when T_o is approximately equal to 300°K. Below 0.8 ignition energies increase in a more complex manner as time decreases.

One expects then that for the field pulse

$$Q_p \propto t_p^{1/4} \quad ; \quad 0.4 < \frac{\sqrt{a t_p}}{L} \tag{2}$$

Since the time of the second maximum, t_p, is related to the weapon yield by $t_p = 3.2 \times 10^{-2}(KT)^{1/2}$ (21), then one has the result the ignition energy should be proportional to $(KT)^{1/8}$ provided the

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4/ Actually the NRDL simulated field pulse requires 13 per cent less energy under these conditions. However, this difference is within the limits of reported field pulse shape measurements (18,sheet 1a.1) and within the error of Eq. (1).

5/ See Nomenclature, page 33.

inequality of Eq. (2) holds. At present the constant of proportionality cannot be specified in a general manner due to the more complex structure of natural fuels compared to that of the alpha-cellulose paper.

In figure 6 the inequality of Eq. (2) is plotted in terms of weapon yield. Diffusivity of wood is 16×10^{-4} cm^2/sec or greater and for paper is 9×10^{-4} cm^2/sec or greater (7). Below 10 KT dashed lines are shown as there exists some doubt as to the dependence of t_p on KT in this region. Thickness measurements (table 5) on exposed fuels indicate that the thinner fuels, newspaper, grasses, etc., will follow Eq. (2) for yields greater than 1 KT while the thicker group will probably have a lower limit to 10 KT.

The Forest Service source "1 second" pulse (figure 5) does not yield a square wave pulse; thus we must make the *a priori* assumption the equivalent square wave has the same maximum flux and total energy leading to an equivalent square wave pulse time of 0.84 sec (22). From the previously deduced equivalence between square wave and field pulse exposures $t_p = 0.84 \div 4 = 0.21$ sec, corresponding to a yield of 45 KT (21). Thus, the Forest Service source ignition energies appear to correspond to those of a weapon of 45 KT. Since the majority of field data result from yields ranging from 10 to 30 KT (a maximum difference of 15 per cent in $(KT)^{1/8}$ from 45 KT), the juxtaposition of field and laboratory results in figures 3a, b, c, and d is for the most part explained. This does not, however, consider the effect of different spectral characteristics of the two sources, an area of which little is known.

Data on ignition of ponderosa pine needles and newspaper have been determined (23) using the Forest Service source modified to produce the flux-time characteristics of a field pulse having a time of second maximum of 3 seconds (9 MT). These results are compared with the "1 second" pulse data by dividing ignition energies by their respective $(KT)^{1/8}$ [6/] as shown in figure 7.

6/ $45^{1/8} = 1.61$, $9000^{1/8} = 3.12$.

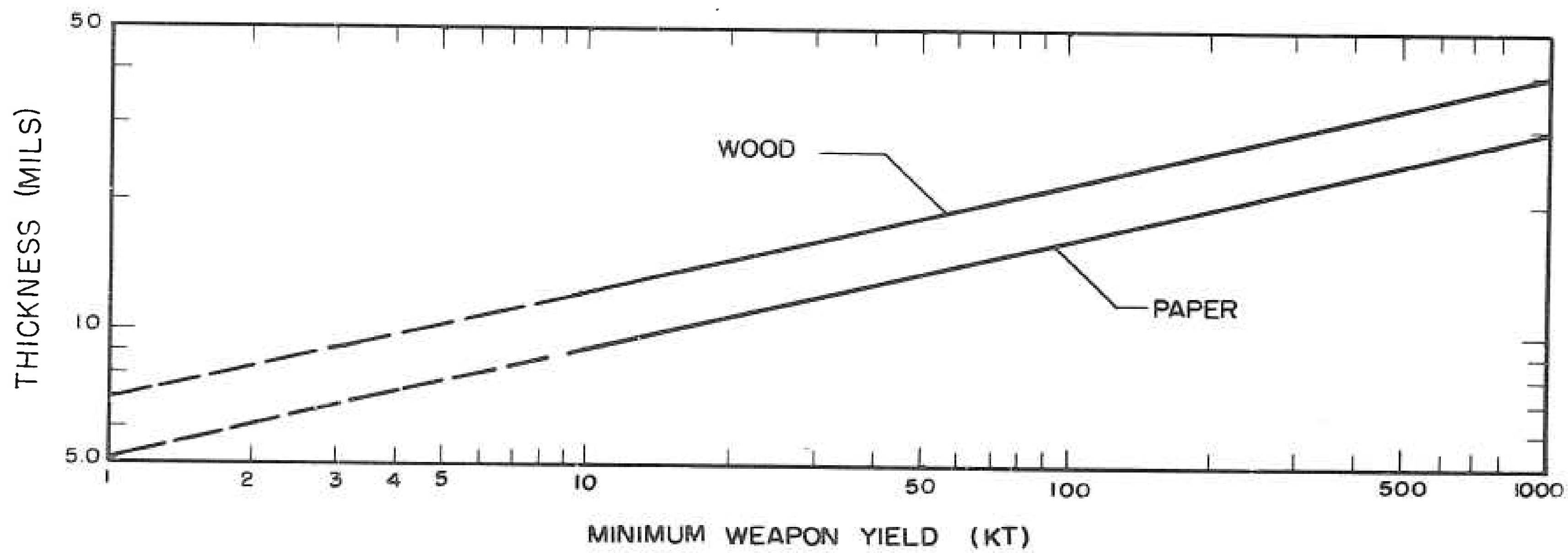

Figure 6.--Minimum weapon yields for which $(KT)^{1/8}$ scaling applies vs fuel particle thickness and material

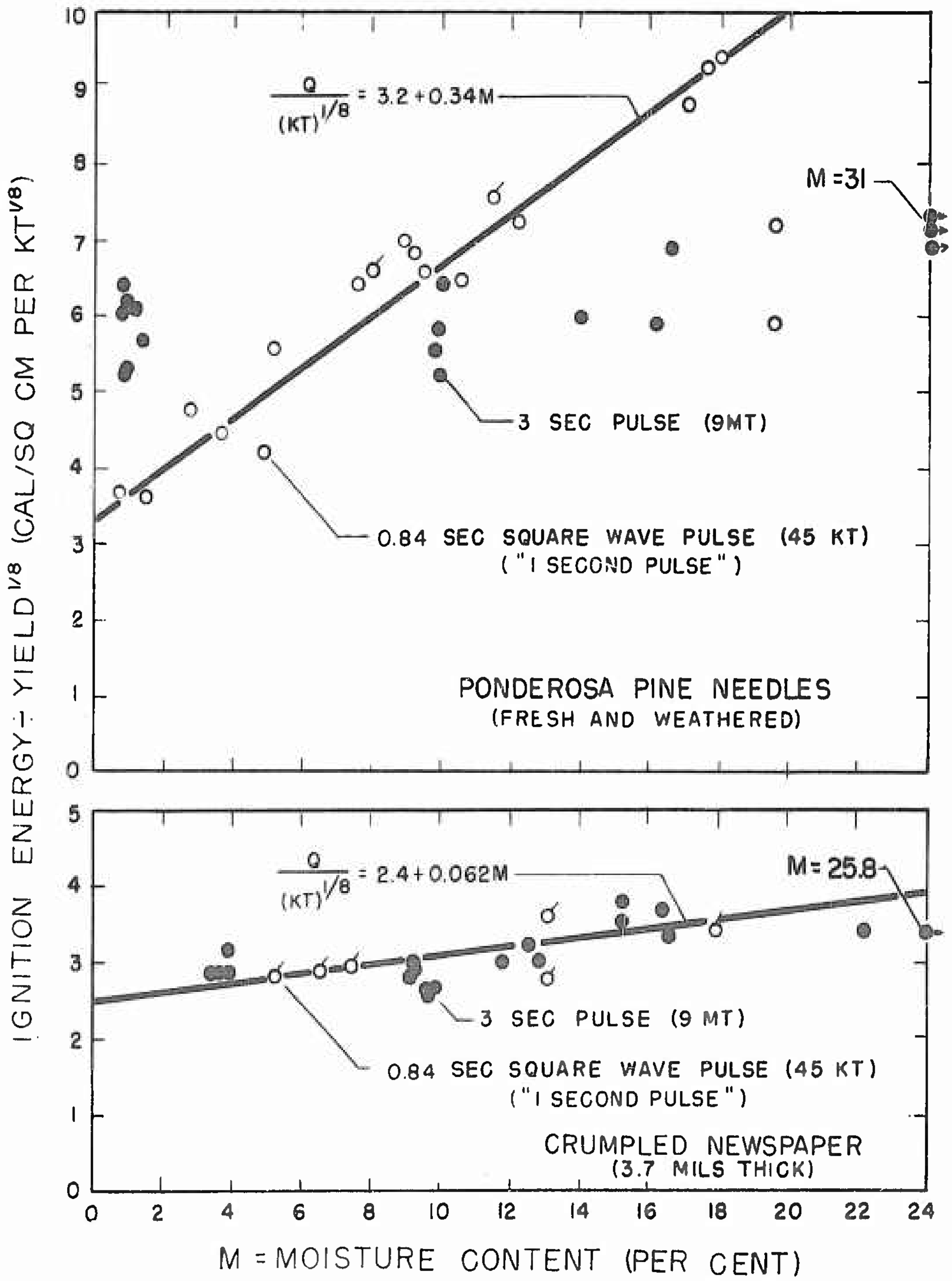

Figure 7.--Comparison of "1 second" and 3 second pulse ignition energies--Forest Service source data (♂ indicates Forest Products Laboratory "1 second" pulse data, o indicates UCLA data)

The excellent agreement among the newspaper data is obvious considering the 2:1 correction, and needs no further comment.

Although the above scaling procedure normalizes the ponderosa pine needle data in the usual range of moisture content (7 to 9 per cent) the slope appears considerably less steep for the higher yield exposure, in contradiction of the proposed hypothesis. This result is not conclusive, however, since there remain two possible explanations for this behavior.

Examination of fuel shipping records definitely shows two separate batches of needles--the first gathered in a pure pine stand, the second gathered in a mixed hardwood and pine region. The first batch, used during the experiments conducted at the University of California at Los Angeles and for the "1 second" pulse at the Forest Products Laboratory,[7/] contained no foreign material while the second batch used for all 3 sec exposures contained "catkins, broadleaves, grasses, etc. -- which were removed before conditioning" (23). The effect of small amounts of such impurities remaining would be to make ignition energy less dependent on moisture content as in the thinner materials.

The second postulate is that samples equilibrated at low relative humidities tended to gain moisture at the exposed surface during preparation for exposure. Bulk moisture determinations would then result in lower moisture content than true surface values. Samples conditioned at relative humidities higher than ambient would lose surface moisture producing the opposite effect. Such behavior would be most serious in cases where ignition energy is most dependent on moisture, i.e., ponderosa pine needles, and least serious with such fuels as newspaper. This consideration is apparently absent from the UCLA tests wherein the fuel tray remained sealed until just prior to the radiant exposure (4). For this reason additional exposures should be made under controlled ambient humidity conditions.

7/ Indicated by tagged circles in figure 7.

COMPARISON OF FIELD AND LABORATORY NORMALIZED IGNITION ENERGIES

Thermal effects noted during field operations are compared with laboratory ignition energies on a normalized basis in figures 8a, b, and c by dividing energies by their respective $(KT)^{1/8}$. Laboratory pulse corresponds to 45 KT as previously noted. Careful examination indicates somewhat better correspondence than shown in figure 3 (note newspaper and pine needles); however, due to the small variation of $(KT)^{1/8}$ between exposures (a maximum of 37 per cent between Baker and "1 second" pulse) these results do not constitute a proof of the proposed scaling equation. Absolute convergence of field and laboratory data is of course unobtainable due to the finite spacing of fuels during field exposures (excepting desert stipa).

Data for punk are not shown because of the inherent inconsistency of ignition energies due to the variability of the thermal properties and particle thickness of punk.

The linear dependence of ignition energy with moisture content suggests use of an equation of the form

$$Q \div (KT)^{1/8} = A + BM \qquad (3)$$

Constants A and B for all fuels exposed are displayed in table 5. Accuracy corresponding to "excellent" comparison with field data is believed to be in the order of ±5 per cent, "good" ±10 per cent, and "fair" ±15 per cent. Data on newspaper suggest that, excepting heterogeneous fuels such as punk and litter, the presented relationships are valid to yields of 10 MT.

The estimating equations set forth in table 5 should be regarded as extrapolations until more exacting scientific confirmation results from tests on specific fuels or from future results of controlled experiments on alpha-cellulose paper.

SUMMARY

Comparisons made between field and laboratory ignition energies indicate close correlation, in most cases, when the effects of moisture content and weapon yield are considered. The Forest Service source

"1 second" pulse is deduced to correspond to a yield of approximately 45 KT. The proposed scaling equation, i.e., ignition energy proportional to $(KT)^{1/8}$, appears valid within the limitations of available ignition data. Ponderosa pine needle laboratory data corresponding to large yield (9 MT), however, indicate a change in the energy-moisture content relationship which is not apparent in the case of newspaper. Estimating equations are presented for all tested forest fuels, including newspaper, which appear valid for thin homogeneous fuel types within ±5 to 15 per cent for a range of yield of 1 KT to 10 MT. Presented relationships should be considered in the light of lacking complete verification.

Table 5.- Summary of constants in equation, $Q \div (KT)^{1/8} = A + BM$

Fuel	Thickness 1/ (mils)	A	B	Comparison of equation with field data
Thin fuels (equation valid for yields greater than 1 KT)				
Horsehair lichen	1	2.6	0.062	excellent
Desert stipa	2/ 3	2.6	0.075	excellent
Cheat grass	2/ 3	2.8	0.062	good
Beech leaves	3/ 3.5	2.0	0.047	fair
Newspaper (crumpled)	3/ 3.7	2.4	0.062	excellent
Sedge grass	6.7	3.1	0.062	excellent
Hardwood litter	--	2.0	0.05	none
Thick fuels (equation valid for yields greater than 10 KT)				
Rhododendron leaves	10	3.4	0.22	fair
Madrone leaves	2/ 11	2.6	0.24	fair
Sugar pine needles	2/ 12-15	4.5	0.25	none
Wheat straw	15	3.6	0.087	fair
Ponderosa pine needles	15	3.2	0.34	excellent
Redwood needles	18	2.9	0.20	none
Miscellaneous				
Punk	--	2.5±0.7	--	fair within limits specified

1/ From Thermal Properties of Forest Fuels, Byram, G. M., and others, AFSWP-404, U.S. Forest Service, Fire Res. Div. 1952.
2/ Estimated.
3/ Reference (23).

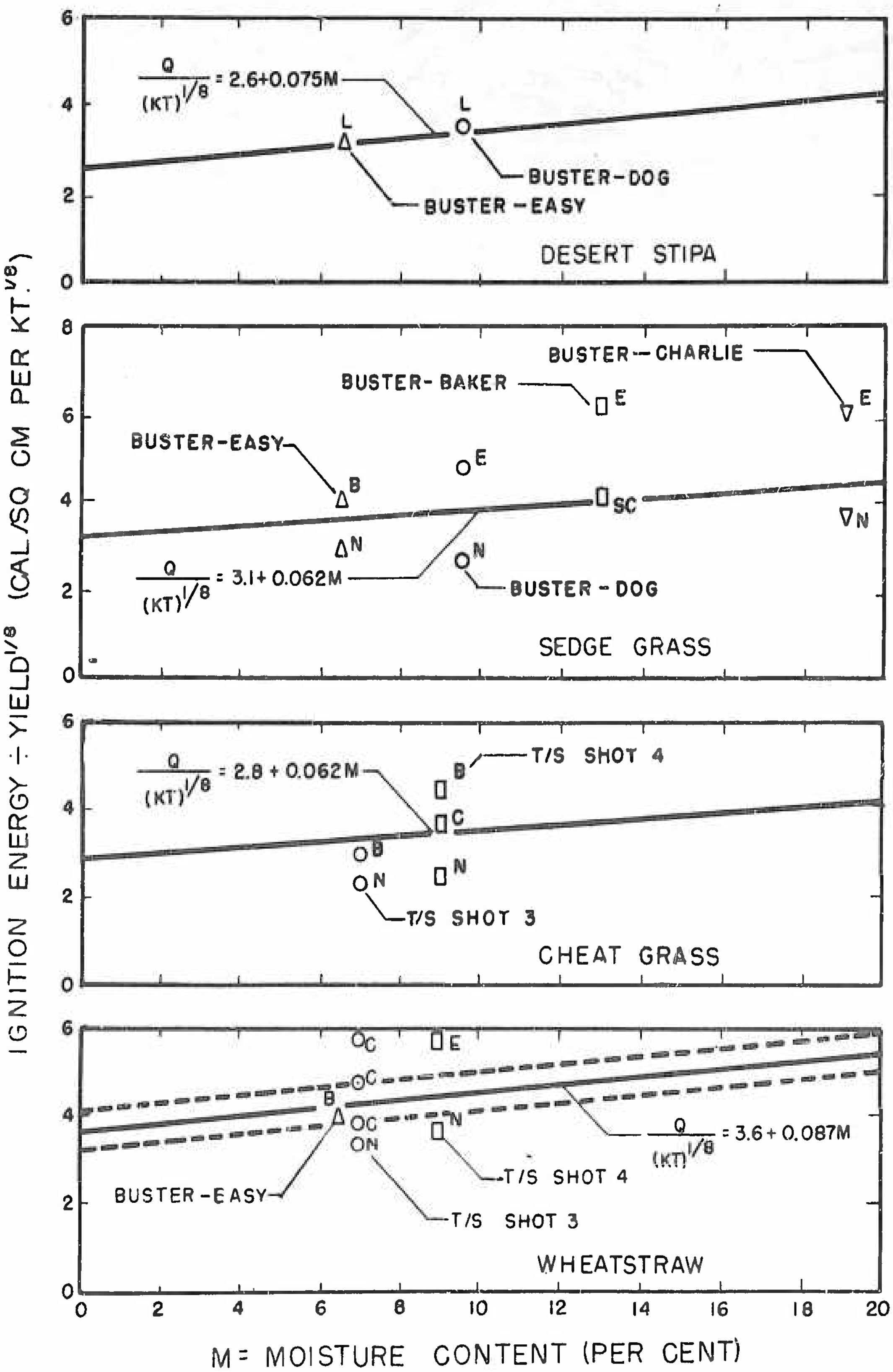

Figure 8a.--Comparison of field and laboratory reduced ignition energies. (Solid line represents ignition energies determined by Forest Service source. Letters adjacent field data points indicate effect noted in tables 1, 2, and 3.)

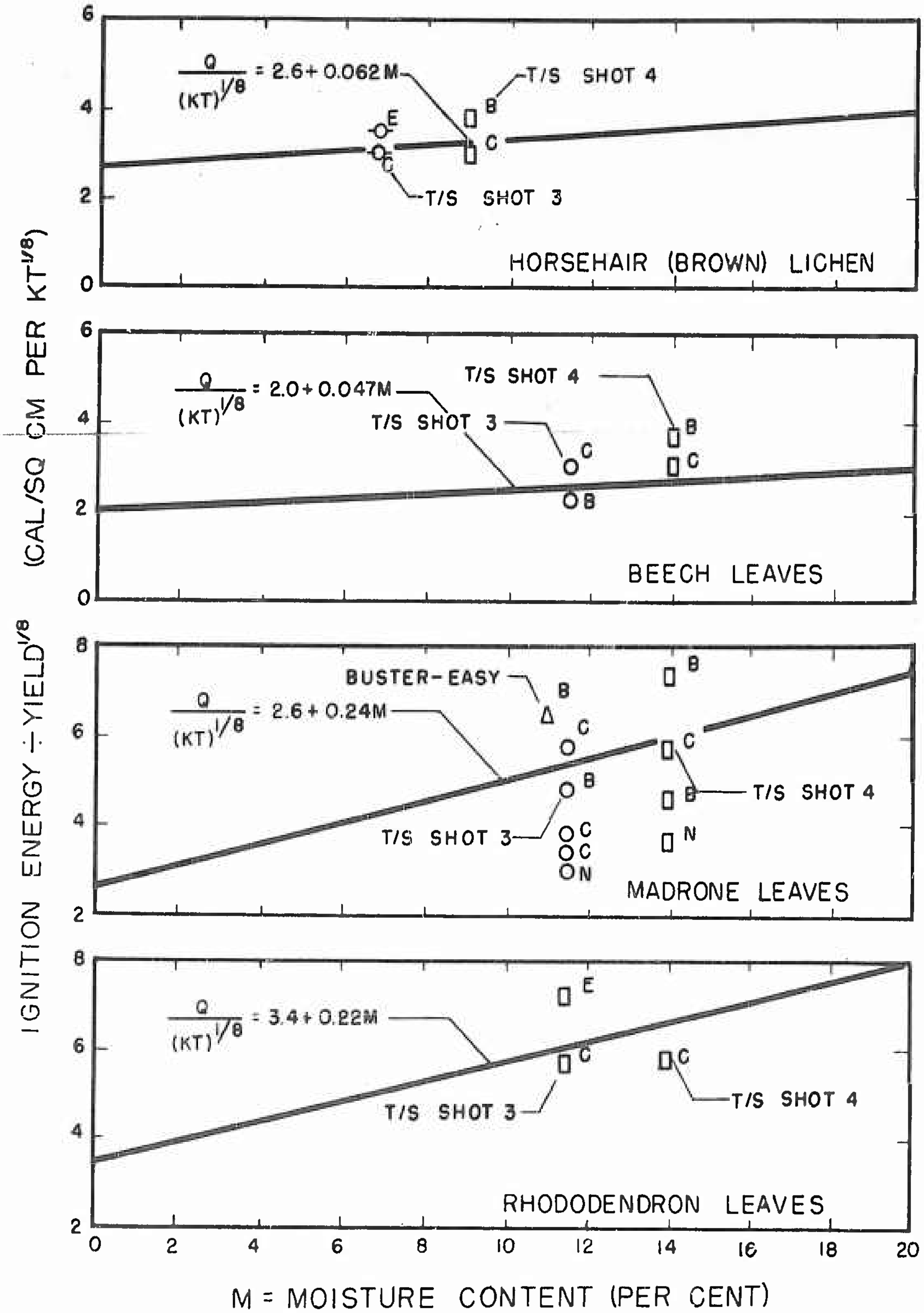

Figure 8b.--Comparison of field and laboratory reduced ignition energies. (Solid line represents ignition energies determined by Forest Service source. Letters adjacent field data points indicate effect noted in tables 1, 2, and 3.)

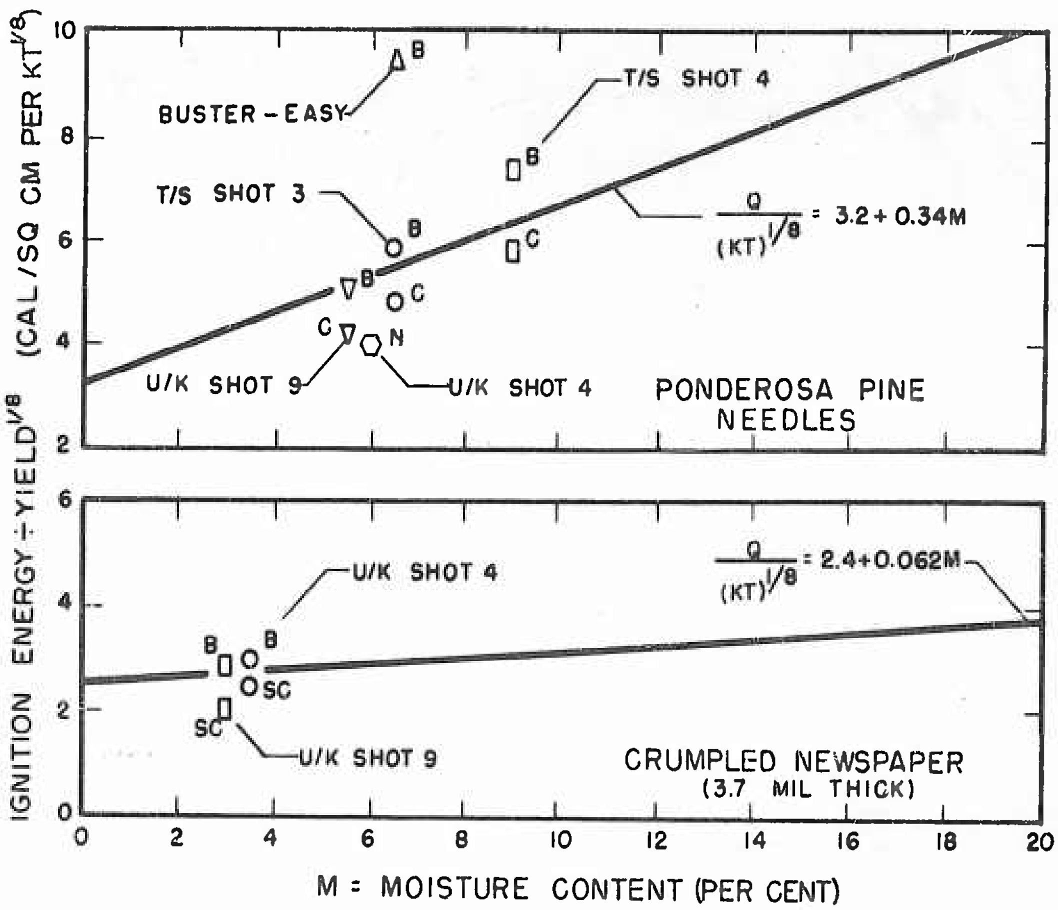

Figure 8c.--Comparison of field and laboratory reduced ignition energies. (Solid line represents ignition energies determined by Forest Service source. Letters adjacent field data points indicate effect noted in tables 1, 2, and 3.)

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NOMENCLATURE

a	thermal diffusivity of fuel	cm^2/sec
A	a constant in Eq. (3)	
B	a constant in Eq. (3)	
C	heat capacity of fuel	cal/gm^oC
L	fuel particle thickness	cm
M	moisture content	per cent dry weight
Q	ignition energy	cal/cm^2
Q_p	ignition energy for field pulse	cal/cm^2
Q_s	ignition energy for square wave pulse	cal/cm^2
t_p	time of second thermal maximum	sec
t_s	square wave pulse time	sec
T_o	absolute ambient temperature	^oK
ρ	fuel density	gm/cc