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Surface Flame Propagation on Cellulosic Materials Exposed to Thermal Radiation

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The results of a series of flame-spread tests are summarized and analyzed to delineate the importance of the physical and thermal properties in surface flame propagation on simple and composite slabs. The data are in accordance with relationships for the transient surface temperature rise for irradiated opaque and chemically inert slabs and support a simple concept for the spread of flame on the surfaces of cellulosic materials exposed to thermal radiation; viz, that flame propagation consists of progressive ignition of the solid when a characteristic temperature is reached.

1. Introduction

The result of a standardized flame-spread test [1][1] performed on a single material or on a composite assembly is reported in terms of an arbitrary flame-spread index. This index is defined as zero for noncombustible asbestos-cement board and may range in the hundreds or even thousands for materials of very rapid flammability. It has been shown [2] that the flame-spread index is composed of two multiplicative factors: (a) a flame-spread factor representing the ignition sensitivity of the material, and (b) a heat evolution factor representing the maximum rate of heat generation. Although flame-spread index values for a wide variety of typical building finish materials have been published [3, 4, 5, 6], a systematic evaluation of the important physical and thermal properties which govern the surface propagation of flames is incomplete. This paper summarizes the results of tests performed to define the significance of ignition sensitivity for cellulosic materials and to analyze and delineate some important parameters in flame propagation. The primary objective of the analysis was to extend a simple surface ignition concept to a flame propagation situation by considering the propagation of flames as a series of progressive surface ignitions of thermally irradiated material. In actual fires, the predominant mode of heat transfer is by radiation, generally from adjacent flaming surfaces. Although all tests were performed using the radiant panel test method, the analysis and interpretation are considered likely to be applicable to surface propagation of flame on most irradiated combustible materials.

2. Apparatus and Test Procedure

The apparatus used for the tests has been described in detail [1, 3]. As shown in schematic form in figure 1, it consists of a radiant panel heat source, a frame for support of the test specimen, and associated measuring equipment.

[1] Figures in brackets indicate the literature references at the end of this paper.

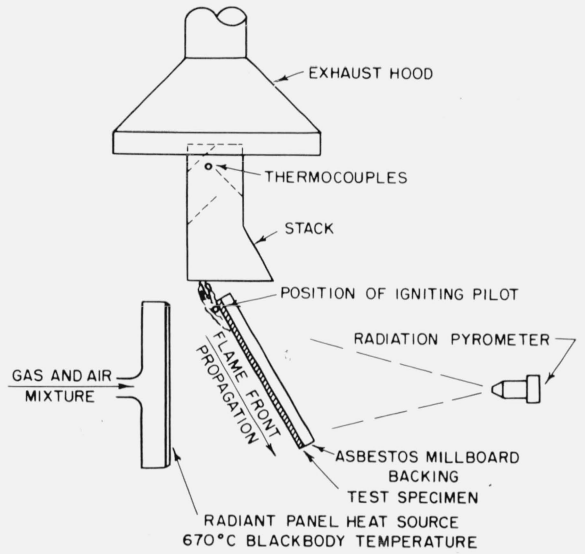


FIGURE 1. *Schematic diagram of radiant panel apparatus for flame-spread measurement.*

The radiant panel consists of a cast iron frame enclosing a 12-in. wide by 18-in. high porous refractory material. The panel is mounted in a vertical plane, and a premixed gas-air mixture supplied from the rear is burned in intimate contact with the refractory surface to provide a radiant heat source. The energy output of the panel, which is maintained by regulating the gas flow according to the indication of a radiation pyrometer, is that which would be obtained from a blackbody of the same dimensions operating at a temperature of 670 °C (1,238 °F). A stack placed under an exhaust hood and above the test specimen receives the hot products of combustion and smoke.

For test, the 6- by 18-in. specimen backed by a sheet of asbestos millboard was placed in a metal holder and mounted on a supporting frame, facing the radiant panel and inclined 30 deg to it. A pilot igniter fed by an air-acetylene mixture served both

to initiate flaming at the upper edge of the test specimen and to ignite combustible gases rising from the specimen. Observations were then made of the progress of the flame front, the occurrence of flashes, etc., as well as the temperature rise of the stack thermocouples. For some tests, an electrical timer calibrated in minutes and decimal fractions to hundredths was used for recording the time of occurrence of events during the tests. However, for tests involving very rapid flaming, a hand-operated switch was used to actuate an event marker on a high-speed recorder. The test duration was 15 min, or until sustained flaming had traversed downward the entire 18-in. length of specimen, whichever time was less.

The flame-spread index, I_s, was computed as the product of the flame-spread factor, F_s, and the heat evolution, Q, thus:

$$I_s=F_sQ \tag{1}$$

where

$$F_s=1+\frac{1}{t_3}+\frac{1}{t_6-t_3}+\frac{1}{t_9-t_6}+\frac{1}{t_{12}-t_9}+\frac{1}{t_{15}-t_{12}}. \tag{2}$$

The symbols t_3 . . . t_{15} correspond to the times in minutes from specimen exposure until arrival of the flame front at a position 3 . . . 15 in., respectively, along the length of the specimen and

$$Q=0.1\Delta\theta/\beta \tag{3}$$

where 0.1 is an arbitrary constant, $\Delta\theta$ is the observed maximum stack thermocouple temperature rise for the specimen minus the maximum temperature rise observed with a thick asbestos-cement board substituted for the specimen, and β is a calibration constant representing the maximum stack thermocouple temperature rise per unit heat input rate using a calibrating diffusion-type gas burner placed near the top of an asbestos-cement board specimen during normal operation of the radiant panel [1, 3]. To maintain the established numerical consistency of eq (1), and for convenience, English units (Btu, °F, min) were employed in eqs (1), (2), and (3).

Prior to test, all specimens and composite assemblies were conditioned by placing them in an oven at 140 °F for a 24-hr period and then allowing them to reach moisture equilibrium (constant weight) at 73 °F and at one of three relative humidities (17%, 50%, and 86%). The low and high humidity conditions were achieved by placing a tray containing an appropriate saturated salt solution at the bottom of each of two closed containers into which the specimens were suspended. Each container lid was fitted with a fan to provide adequate air circulation and a hygrometer element for measuring relative humidity. A room maintained at 73 °F and 50 percent rh by a conventional central air conditioning system was used for achieving moisture equilibrium at this intermediate relative humidity in all other specimens.

3. Analysis

A rigorous analysis of the radiation-induced ignition process would require consideration of chemical decomposition reactions, surface charring and contraction, variation in thermal properties with temperature, diffusion and mixing of combustible volatiles, and other complex conditions. Fortunately, the ignition behavior of cellulosic materials appears to closely follow the most simple theoretical postulate for temperature variation; i.e., the opaque, constant property, and chemically inert solid [7]. Thus, no consideration is given to the possible effects of absorptance and diathermancy, chemical decomposition, supply of volatiles, etc., the primary objective being to extend the simple postulate to a better understanding of the propagation of flames along surfaces.

The equation for the temperature rise, θ, of an opaque inert slab of thickness l, density ρ, thermal conductivity k and heat capacity c, subjected to constant irradiance I on one face and losing heat by Newtonian cooling through a coefficient H from both faces is complex [8].

However, the solution is of the form

$$\theta=\frac{I}{H}f\left(\frac{x}{l}, \frac{kt}{\rho cl^2}, \frac{Hl}{k},\right), \tag{4}$$

where x is the distance in the slab measured from the irradiated surface and t is time. Simms [7] has given approximations for the two cases of interest, namely thin and thick materials.

3.1. Thin Materials

For thin materials (in which a linear temperature gradient exists) and for very small values of the Nusselt number Hl/k, an approximation to the rise in temperature of the irradiated surface, θ_s, is given in reference [7] as

$$\theta_s=\frac{I}{2H}\left[1-e^{-\frac{Ht}{\rho cl}}\right]. \tag{5}$$

The term $Ht/\rho cl$ is the ratio of the energy lost by cooling to the heat content of the material, and is termed a cooling modulus.

3.2. Thick Materials

For thick materials, the surface temperature rise is the same as that for a semi-infinite solid and the relation [7, 9] is

$$\theta_s=\frac{I}{H}\left[1-e^{b^2}\operatorname{erfc} b\right] \tag{6}$$

where

$$b=H\sqrt{\frac{t}{k\rho c}} \tag{7a}$$

and the complementary error function is

$$\text{erfc}\ (b)=1-\text{erf}\ (b)=\frac{2}{\sqrt{\pi}}\int_b^\infty e^{-\xi^2}d\xi \qquad (7b)$$

In the radiant panel flame-spread test, the irradiance varies along the surface of the specimen with the distance from the top [3]. If ignition of a given material may be represented by a characteristic surface temperature [7], then, for thin materials, this temperature is reached at the same position along the length of the specimen (same I and H) at exactly the same time, if the ρcl product is the same. For thick materials a similar situation exists if the $k\rho c$ product is the same. In other words, the ignition time (at each position) should be directly related to either ρcl or $k\rho c$. The product $k\rho c$ is commonly referred to as the thermal inertia for surface heating. Since the flame-spread factor F_s consists of a series of reciprocal time periods, inverse relationships of hyperbolic form are to be expected between F_s and ρcl for thin materials and between F_s and $k\rho c$ for thick materials.

3.3. Composite Materials

A solution for the surface temperature rise of a composite slab, in which the surface of the upper finite skin is irradiated in a spatial nonuniform manner (with or without surface heat loss), is unknown to the authors. However, examination may be made of the governing parameters in the following equation derived in reference [10] for the temperature rise, θ_s, on the surface of a composite material consisting of a finite skin of thickness l_1 (thermal properties k_1, ρ_1, c_1, where the thermal diffusivity $\alpha_1=k_1/c_1\rho_1$) over a substrate extending to infinity (thermal properties k_2, ρ_2, c_2, α_2) as the surface is heated without losses by constant irradiance I:

$$\theta_s=\frac{2I\sqrt{\alpha_1 t}}{k_1}\left[\frac{1}{\sqrt{\pi}}+2\sum_{n=1}^{\infty}\left(-\frac{1}{\gamma}\right)^n \text{ierfc}\ \frac{nl_1}{\sqrt{\alpha_1 t}}\right], \qquad (8)$$

where

$$\gamma=\frac{\sqrt{k_2\rho_2c_2}+\sqrt{k_1\rho_1c_1}}{\sqrt{k_2\rho_2c_2}-\sqrt{k_1\rho_1c_1}}=f\left(\frac{k_2\rho_2c_2}{k_1\rho_1c_1}\right)=f(\sigma). \qquad (9)^2$$

From this equation, the time, t, for a given surface temperature rise to be accomplished is a complicated function of $k_1\rho_1c_1$, l_1^2/α_1 and $\frac{k_2\rho_2c_2}{k_1\rho_1c_1}$. Griffith and Horton [10] illustrate that for a given skin material and for each time of heating, a critical thickness exists such that for greater thickness the composite assembly behaves essentially as a wall of infinite thickness of the skin material. For such cases, the substrate may be ignored so that the equation for the surface temperature reduces to that for a homogeneous thick wall, namely,

$$\theta_s=\frac{2I}{\sqrt{\pi}}\sqrt{\frac{t}{k_1\rho_1c_1}}, \qquad (10)$$

and the critical thickness is given very closely by

$$l_1'=\sqrt{\pi\alpha_1 t}. \qquad (11)$$

It is important to note from eqs (8), (10), and (11) that the surface temperature rise depends upon the thermal inertia $k\rho c$ while the critical thickness depends upon the thermal diffusivity, $\alpha=k/\rho c$.

4. Results and Discussion

While the analytical expressions for simple slabs listed in section 3 are strictly applicable only to uniformly irradiated slabs, the form in which the thermal and physical parameters appear is useful in interpreting the present data. These data were obtained using an experimental setup in which there is a nonuniform spatial irradiation, and interest has been confined to the travel of flames from the region of higher to the region of lower irradiance. While the expressions do not take into account heat flow in the direction of flame travel, this will occur in the actual test, particularly for highly conductive veneers and substrates, and for sandwich constructions. In addition, variations in the surface heat transfer coefficient are to be expected for the experimental arrangement used.

4.1. Thin Materials

To examine the effect of board thickness on flame propagation, veneers of balsa wood and hardboard were obtained or prepared in various thicknesses. These ranged from 0.071 to 1.26 cm for the balsa veneers and from 0.081 to 0.635 cm for the hardboard veneers. These materials were chosen because of their readily measurable rates of flame propagation, uniformity in structure (especially the hardboard) and availability. The hardboard veneers were cut from a single large sheet and planed to constant thickness. The density was uniform to ± 10 percent for all veneer thicknesses. However, the balsa wood sheets, obtained from a commercial source, varied in density by a factor of more than 2. In contrast to the standard flame spread test procedure, for this test series the veneers were supported at the edges only, leaving an enclosed air space of 1.27 cm between the back of the veneer and a backing sheet of 1.27-cm-thick asbestos millboard.

The ranges of measured thickness and densities, and average values of F_s and I_s are given in table 1 for specimens conditioned to equilibrium in relative humidities of 17, 50, and 86 percent. The average coefficient of variation for the F_s values listed was 4 percent for the hardboard specimens and 16 percent for the balsa specimens. Generally, four replicate tests were performed.

The effect that the relative humidity of the conditioning atmosphere has on surface flammability of materials has been given [2] for thick specimens of spruce, fiberboard, and hardboard. Since moisture vapor is readily dissipated from thin unsupported veneers, the relative change in F_s (and I_s) was not as large for the thin as for the thick hardboard specimens.

[2] As corrected.

TABLE 1. *Surface flammability test results for balsa and hardboard veneers*

Material	Thickness range	Density range	Flame spread factor, F_s^*			Flame spread index, I_s^*		
			17% rh	50% rh	86% rh	17% rh	50% rh	86% rh
	cm	*g/cm³*						
Balsa	0.071–0.081	0.206–0.279	67.7	55.9	54.4	410	317	325
	.147– .155	.120– .150	63.3	70.8		417	404	
	.300– .305	.157– .221	41.1	35.7		442	392	
	1.25 –1.26	.083– .147	62.6	45.3		457	284	
Hardboard	0.081–0.086	0.975–1.04	17.5	18.5	15.4	314	302	255
	.150– .155	1.00 –1.04	10.9	10.2		254	232	
	.297– .318	0.986–1.08	6.64	5.97		207	175	
	.584– .635	.865–1.00	5.47	4.80	3.64	160	154	84

*All F_s and I_s values represent averages for 4 individual test specimens.

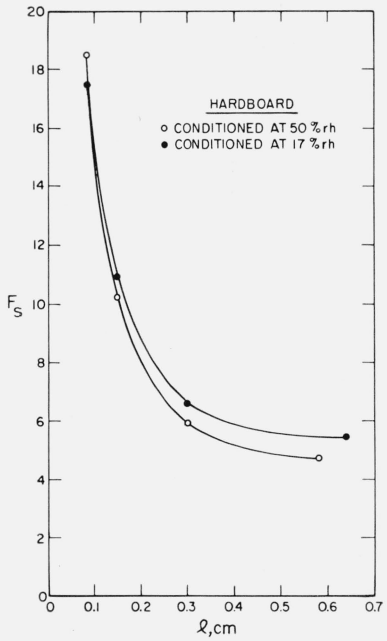


FIGURE 2. *Effect of veneer thickness on flame-spread factor for hardboard.*

An inverse relationship between the flame-spread factor and the thickness of veneer was found to hold for the hardboard specimens, as shown in figure 2. A thickness of approximately 0.4 cm may be taken as the approximate dividing region between thin and thick hardboard specimens, inasmuch as further increases in thickness appear to produce very little change in F_s.

Account was taken of the large density variations of the thin (0.08 to 0.30 cm) balsa specimens in the plot of F_s versus ρcl of figure 3. Individual values (rather than averages of four) were plotted for two conditioning humidities. Also included are the average values for thin (0.08 to 0.32 cm) hardboard specimens. Using a generalized CGS system of units [3] the data may be approximated by a relation of hyperbolic form:

$$F_s = 5 + \frac{1.5}{\rho cl}. \qquad (12)$$

[3] l: cm, ρ: g/cm³, c: w sec/g °C, k: w/cm °C.

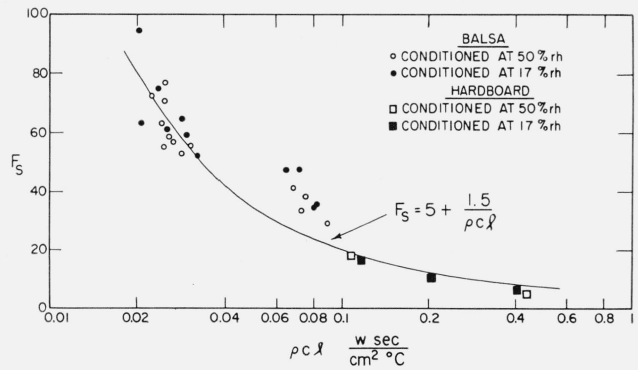
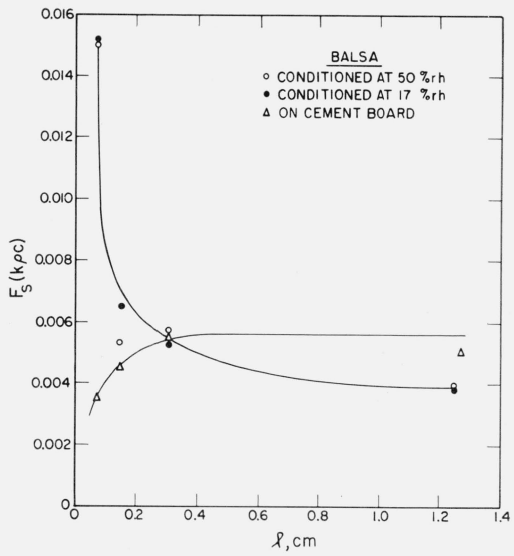


FIGURE 3. *Flame-spread factor* versus *ρcl for thin balsa and hardboard veneers.*



GU 4 *Effect of veneer thickness on modified flame-spread factor for balsa.*

Because of the inverse relationship between F_s and thermal inertia for thick materials, a second method for examining the combined effects of thickness and density is illustrated in figure 4. Here, the modified flame-spread factor, F_s $(k\rho c)$, for balsa (with no substrate) is seen to decrease with increasing thick-

ness and to approach a limiting value at a thickness of about 0.6 cm. The thermal conductivity values were taken at the measured density from room temperature values of cross-grain thermal conductivity of dry balsa [11, 12]. The effect of using an asbestos-cement board substrate with varying thickness of balsa veneer is also illustrated in figure 4 and will be discussed later.

4.2. Thick Materials

A survey of previous flame-spread data for thick cellulosic materials revealed a good correlation between flame-spread factor and thermal inertia (fig. 5). The data shown include the 1.2-cm-thick balsa woods conditioned at 17 and 50 percent rh, the 0.6-cm-thick hardboard, and a wide variety of other cellulose-base materials all conditioned at 50 percent rh. The specific heat and thermal conductivity values were taken from handbook sources and refer to dry material at room temperature. For materials which ranged from balsa (ρ=0.08 g/cm^3) to hardboard (ρ=1.08 g/cm^3), and including paper, cotton, fiberboard, plywood and nine varieties of natural wood, the data were closely represented by the relation

$$F_s=5+\frac{0.003}{k\rho c}. \qquad (13)$$

The fact that cellulosic materials do vary in their surface temperatures for ignition may explain part of the departure of the empirical relationships obtained experimentally (figs. 3 and 5) from that of a true hyperbola. On the basis of measured times for pilot ignition of woods exposed to uniform low-level irradiance [13], it was found that the calculated surface temperatures for ignition of cellulosic materials varied from 300 °C for hardboard to 390 °C for balsa, approximately, and the calculated surface temperatures were definitely related to thermal properties. Furthermore, the actual gaseous ignition process, not considered in this analysis, must likewise be a function of material properties.

4.3. Composite Materials

Another series of tests was performed to examine the effect of the type of substrate on the flame-spread factor of composite assemblies. The test specimens consisted of thin veneers (0.08 cm thick) of both balsa and hardboard cemented to a variety of relatively thick noncombustible substrates ranging from felted calcium silicate, a very good insulator, to conductive aluminum alloy. A thin coating of fire-retardant adhesive was used and sufficient pressure was applied during the drying process to ensure good thermal contact. Except for the thickest composite assemblies, all assemblies were backed up with the standard 1.27-cm-thick asbestos millboard backing. As shown in table 2 and in figure 6, the thermal inertia of the substrate has a very strong effect on the flame-spread factor of composite assemblies with thin surface veneers.

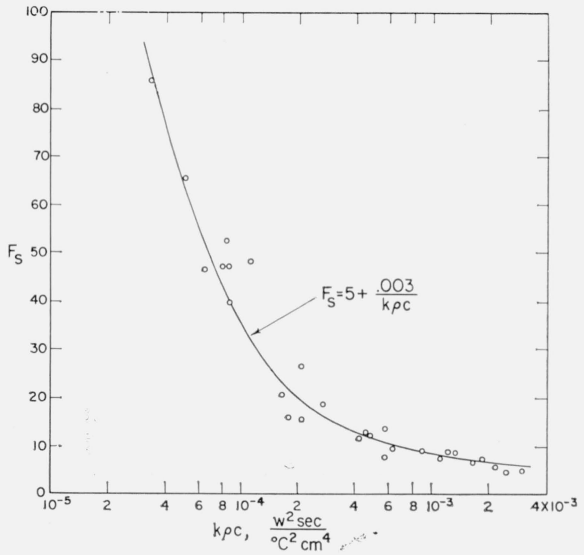


FIGURE 5. *Effect of thermal inertia on flame-spread factor for thick cellulosic materials.*

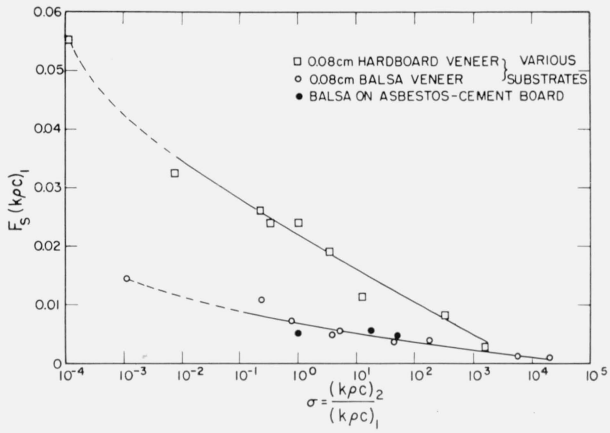


FIGURE 6. *Effect of thermal inertia ratio on modified flame-spread factor for a composite assembly with thin surface veneer.*

Although this was noted in previous studies [4, 6], neither the range of substrate properties nor the importance of the thermal inertia parameter had been fully explored. Furthermore, analysis of previous data on the basis of thermal inertia is complicated by the combustible nature of most of the substrates used in the earlier studies and their contribution (of heat) to flame propagation.

For example, it may be noted that a replot of previous flame-spread index data (fig. 3 of reference 4) on the basis of the F_s ratio rather than the I_s ratio results in an equally good (or better) correlation (see fig. 7). In addition, the F_s ratio approaches unity very closely for a finish thickness of 0.4 cm. That the ratio is higher than unity for composite materials with thin veneers even when the heat contribution of the substrate is not a factor, is obvious

TABLE 2. *Effect of substrate on surface flammability of composite assemblies with balsa and hardboard veneers*

Substrate	Thickness l	Density ρ	Thermal conductivity k	Specific heat c	Thermal inertia $k\rho c$	Balsa*		Hardboard*	
						F_s	I_s	F_s	I_s
	cm	*g/cm³*	*w/cm °C*	*w sec/g °C*	*w² sec/°C² cm⁴*				
None (air)	1.27	0.0012	0.000260	1.01	3.16×10^{-7}	55.9	317	18.5	302
Calcium silicate	0.635	.40	.000649	0.837	2.17×10^{-4}	28.2	142	10.9	172
Gypsum board	.698	.82	.00107	.837	7.35×10^{-4}	33.2	34	8.79	154
Asbestos millboard	1.27	.86	.00121	1.05	1.09×10^{-3}	25.1	47	8.08	75
Asbestos cement	0.474	1.88	.00745	0.837	1.17×10^{-2}	15.3	17	6.39	57
Granite	2.54	1.68	.0218	.795	2.91×10^{-2}	17.4	25	3.88	20
Stainless steel	0.670	8.00	.260	.502	1.04	7.18	13	2.74	10
Stainless steel	.061	7.94	.260	.502	1.03	20.1	85	10.1	166
Alluminum alloy	2.54	2.70	2.03	.921	5.05	4.22	3	1.00	0.2
Alluminum alloy	0.635	2.69	2.03	.921	5.03	12.0	19	4.98	40
Aluminum alloy	.051	2.69	2.03	.921	5.03	23.4	85	12.3	190

*Veneer 0.08 cm thick.

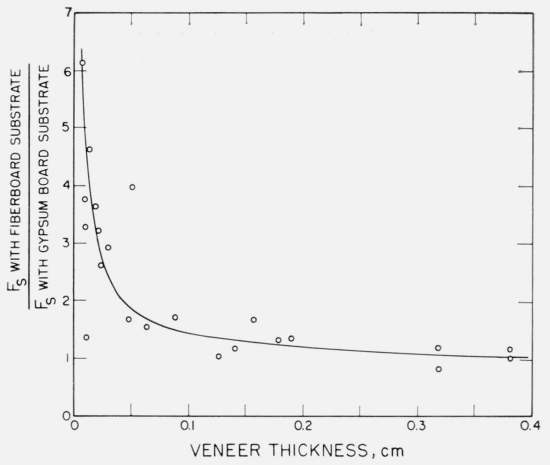


FIGURE 7. *Effect of veneer thickness on flame-spread factor ratio for two substrates.*

in terms of the findings of figure 6, namely, that for a composite material with a thin veneer, the value of F_s is higher with a substrate of lower $k\rho c$. Since $k\rho c$ (gypsum board substrate)$>k\rho c$ (fiberboard substrate) for composite materials with thin veneers,

$$\frac{F_s \text{ with fiberboard substrate}}{F_s \text{ with gypsum board substrate}}>1.$$

Several additional tests were performed to illustrate the effect of (a) the thickness of veneer and (b) the thickness of substrate on the flame-spread factor of composite assemblies. The first effect is clearly shown in figure 4 for various thicknesses of balsa veneers applied to an asbestos-cement board substrate. The substrate is most effective in reducing the (F_s) $(k\rho c)$ product for the thin veneers, but its influence becomes insignificant when the veneer thickness exceeds the critical thickness (0.6 cm).

Account may also be taken of the veneer thickness in the plot of figure 6 if the substrate is considered to consist of the portion of the balsa veneer exceeding 0.08 cm (but less than 0.6 cm) in combination with a thick asbestos-cement substrate. An "effective" thermal inertia, $(\overline{k\rho c})_2$, was calculated from the equation

$$(\overline{k\rho c})_2=\left(\frac{l-0.08}{0.6-0.08}\right)k_1\rho_1c_1+\left(\frac{0.6-l}{0.6-0.08}\right)k_2\rho_2c_2 \tag{14}$$

where $0.08\leq l\leq 0.6$ cm.

The effective thermal inertia reduces to that of the substrate, $k_2\rho_2c_2$, when the veneer thickness is 0.08 cm. It becomes equal to that of the veneer, $k_1\rho_1c_1$, for a veneer thickness of 0.6 cm. Using the effective thermal inertia of the substrate, these data, shown as closed circles, were plotted along with the bulk of the data for 0.08-cm-thick balsa and hardboard veneers in figure 6.

Using eq (8), typical curves were calculated and are shown in figure 8 for "specific temperature rise" θ_s/I on the surface of a composite material in terms of the thickness l_1 of the veneer and the thermal inertia ratio $\sigma=k_2\rho_2c_2/k_1\rho_1c_1$ of substrate to veneer. It may be seen that, for veneers less than the critical thickness $(\sim\sqrt{\pi\alpha_1 t})$, the specific temperature rise will

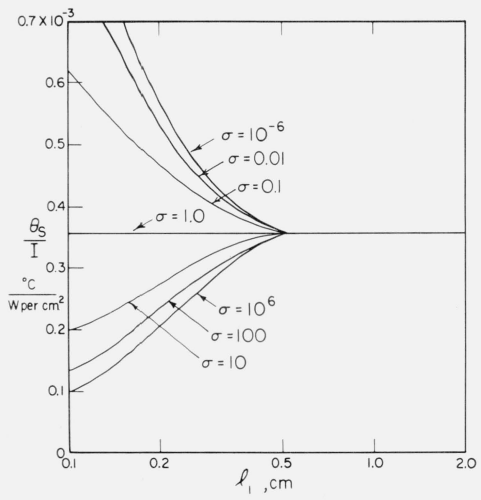


FIGURE 8. *Specific surface temperature rise for a composite material in terms of the veneer thickness* (l_1) *and the thermal inertia ratio* (σ).

Time: 100 sec, $k_1=.001$, $\alpha_1=.001$.

be greater than or less than the semi-infinite value (i.e., $\sigma=1$) according as the thermal inertia ratio is less than or greater than 1. It is clear that no finite amount of insulating or conductive substrate will permit attainment of the same surface temperature rise at the same time as the semi-infinite material. However, it is possible by employing the relationship of eq (11) to estimate the equivalent thickness of substrate which, when combined with a thin (i.e., less than critical) veneer, will yield the equivalent critical veneer thickness. If the critical thickness of balsa is taken to be 0.6 cm, then, for the same time and a balsa veneer thickness of 0.08 cm, the equivalent thickness of substrate may be estimated by

$$l_2'=\sqrt{\frac{\alpha_2}{\alpha_1}}\,(l_1'-l_1)=\sqrt{\frac{\alpha_2}{\alpha_1}}\,(0.6-0.08). \qquad (15)$$

Equivalent substrate thicknesses based upon a critical thickness of 0.6 cm for balsa and 0.4 cm for hardboard are listed in table 3. It may be noted that the thickness of the asbestos-cement substrate and the thickest stainless steel and aluminum alloy substrates used were each less than the equivalent thickness. Consequently, the limiting values of F_s for such assemblies were not fully reached. As expected, a wide range in the flame-spread factor was observed for composite assemblies of 0.08 cm balsa and hardboard veneers on varying thicknesses of aluminum alloy and stainless steel substrates (see table 2). In fact, for the hardboard veneer on 2.54-cm-thick aluminum alloy, the flame-spread factor was reduced to 1.0, corresponding to the complete absence of surface flaming. It should be mentioned that the application of a thin combustible veneer on a relatively thin, highly conductive substrate with an insulating backing board forms a unique sandwich construction. In the orientation of the flame-spread test, this type of construction is ideally suited to longitudinal rather than normal heat flow in the substrate, and this may have increased the rate of flame travel (and therefore F_s) for the thin metallic substrates.

TABLE 3. *Equivalent substrate thickness for thin (0.08 cm) veneers of balsa and hardboard*

Substrate	Actual thickness l_2	Thermal diffusivity α_2	Equivalent substrate thickness	
			Balsa veneer $\alpha_1=0.00223$	Hardboard veneer $\alpha_1=0.000892$
	cm	*cm²/sec*	$l_2'=0.52\sqrt{\alpha_2/\alpha_1}$ *cm*	$l_2'=0.32\sqrt{\alpha_2/\alpha_1}$ *cm*
Calcium silicate	0.635	0.00194	0.489	0.476
Gypsum board	.698	.00155	.437	.428
Asbestos millboard	1.27	.00135	.408	.398
Asbestos cement	0.474	.00473	.760	.745
Granite	2.54	.0122	1.23	1.20
Stainless steel	0.061–0.670	.0646	2.82	2.76
Aluminum alloy	.051–2.54	.816	10.0	9.78

It is interesting to note that asbestos millboard ($\alpha=0.00135$) which is used as the backing material in the standard flame-spread test has a critical thickness of 1.95 cm at a time of 900 sec corresponding to the maximum duration of test exposure. Although the backing used is only 1.27 cm thick, it does provide a common heat sink for all materials and may be considered semi-infinite for the important early portion of every test.

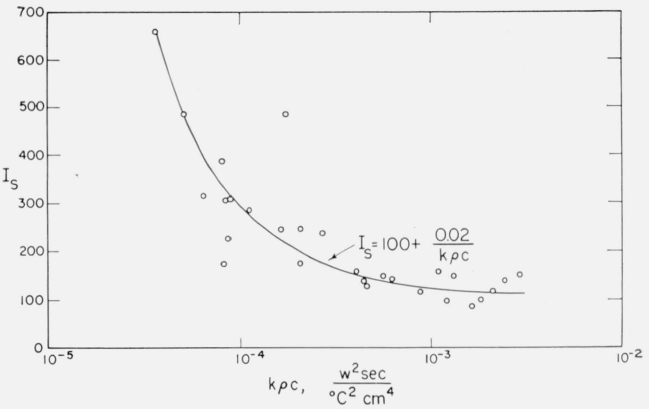


FIGURE 9. *Effect of thermal inertia on flame-spread index for thick cellulosic materials.*

While surface propagation of flame in the flame-spread test is related predominantly to the ignition sensitivity of the material (here expressed as the flame-spread factor F_s), fire spread in actual situations also depends upon the rate of heat release by the burning surfaces. The magnitude of the rate of heat release depends mainly upon the thickness involved in the flaming and the material density. Study of the Q values for the hardboard veneers shows a steady increase for thicknesses from 0.08 cm to 0.32 cm with little further increase for the 0.64-cm thickness. The combination of a decreasing flame-spread factor and an increasing heat evolution factor with thickness tends to yield a flame-spread index for which the variation with thickness is moderate. The effect of thickness upon I_s is shown in table 1. Examination of the influence of substrate properties for composite assemblies was made with the same thickness of balsa and hardboard veneers, and therefore the I_s values in table 2 follow very closely the trend of F_s. Because of the effect of density upon Q and since the thickness involved in flaming varies for different materials, a plot of I_s versus $k\rho c$ for all the thick cellulosic materials tested (see fig. 9) shows considerably more scatter than that shown for F_s in figure 5. The data may be represented approximately by the relation

$$I_s=100+\frac{0.02}{k\rho c}. \qquad (16)$$

5. Summary

Surface flame propagation measurements using the radiant panel test method have shown that the ignition sensitivity (flame-spread factor F_s) for thin balsa and hardboard veneers was an inverse function of both thickness and density. The data were analyzed in terms of the approximate relationship

suggested by Simms for the transient surface temperature rise for an irradiated thin slab, for which the time required for a characteristic temperature to be achieved is proportional to the ρcl product.

Similarly, for thick materials, the data assembled on a variety of cellulosic materials showed that the ignition sensitivity was an inverse function of $k\rho c$, the "thermal inertia for surface heating." The data were closely represented by the relation $F_s=5+\frac{0.003}{k\rho c}$. It is estimated from the data that the dividing region between thin and thick materials is approximately 0.6 cm for balsa and 0.4 cm for hardboard.

The good correlations achieved for both thin and thick materials support a simple concept for the spread of flame on the surfaces of cellulosic materials exposed to thermal radiation, namely that flame propagation consists of progressive ignition of the solid when a characteristic temperature is reached.

For a composite assembly consisting of a thin veneer over a semi-infinite substrate, the flame-spread factor was shown to be a function of the ratio of the thermal inertia of substrate to veneer. This is in accordance with the functional relationship for the transient surface temperature rise for composite assemblies. For veneers less than a critical thickness ($\sim\sqrt{\pi\alpha_1 t}$), the specific temperature rise at any given time will be greater or less than the semi-infinite value according as the thermal inertia ratio is less than or greater than 1. The substrate has the most effect upon the surface temperature with the thinnest veneer and with the greatest change in $k\rho c$ value from that of the veneer. For thin veneers over highly conductive substrates such as metals, estimates have been made which indicate that the equivalent critical substrate thickness may be several times that tested. This provides an explanation for the observed wide variation in flame-spread factor with metal substrate thickness.

Since fire spread depends on the rate of heat release as well as the ignition sensitivity, the combined effect was also evaluated, and for thick cellulosic materials the data were represented by the relation,

$$I_s=100+\frac{0.02}{k\rho c}.$$

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(Paper 67C3–136)