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The Effect of "Blistering" on the Ignition and Flammability of Painted Gypsum Wallboard

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Notice

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The Effect of “Blistering” on the Ignition and Flammability of Painted Gypsum Wallboard

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ABSTRACT

More than 300 gypsum wallboard samples coated with 0 to 8 layers of paint have been subjected to flammability testing in the Cone Calorimeter. Testing has been conducted with samples coated with either latex-based or oil-based interior paints and subjected to imposed heat fluxes ranging from 25 to 75 kW/m². During some of the tests, “blistering” of the painted surface has been observed. This blistering phenomenon is most pronounced in samples coated with multiple layers of oil-based paint. As the number of coats of paint increases, blistering is observed at lower imposed heat fluxes. When blistering does occur, the time to ignition decreases significantly, typically by a factor of 3 to 4, when compared with samples that do not blister, while the burning duration remains approximately the same. The potential for upward flame spread on painted gypsum wallboard is addressed in terms of a modified version of the Quintiere flame spread model. The concept of a critical heat flux for upward flame spread is developed as a means to account for the race between ignition and burnout.

Keywords: Cone Calorimeter, fire model, flame spread, gypsum wallboard, painted surfaces

INTRODUCTION

Painted gypsum wallboard (GWB) is one of the most widely used interior wall and ceiling finishes in the United States and perhaps throughout the world. Consisting of a core of gypsum (calcium sulfate dihydrate) sandwiched between two paper facers, GWB is available in a range of standard sizes and thicknesses. Because of its low cost, ease of installation and desirable finish characteristics, the use of GWB has largely replaced the use of traditional lath and plaster in both residential and commercial applications.

In many fire scenarios involving painted GWB finishes, the exposed painted surface and paper facer have been observed to burn out locally when subjected to fire heat fluxes. Fire investigators frequently use such damage patterns to draw conclusions regarding the development of a fire [1]. In other scenarios, the painted surface and paper facer have been observed to propagate a fire. The objective of this study is to evaluate the potential for flame spread on painted GWB and to determine the exposure conditions under which flame propagation is expected to occur. Cone calorimetry has been used in conjunction with a modified form of the flame spread model developed by Quintiere and coworkers [2,3,4] to perform this evaluation.

GWB samples painted with 1 to 8 coats of alkyd/oil-based interior paint over 1 coat of oil-based primer are subjected, along with unpainted samples, to heat fluxes of 35, 50 and 75 kW/m² in the

Cone Calorimeter for periods of 5, 10 and 15 minutes. Three replicate tests are conducted for each coating-heat flux-duration combination. Since all burning is essentially completed within the first 5 minutes of each test, for practical purposes there are **9** replicate tests for each coating-heat **flux** combination. The different test durations were used to evaluate the dehydration of the **GWB**; results of the dehydration study will be reported elsewhere. During these tests, the phenomenon of “blistering” was observed. This paper focuses on the effect of blistering on the ignition and flame spread potential **of** painted **GWB**.

BACKGROUND

The potential fire hazards associated with multiple layers **of** surface coatings have been recognized and addressed to some extent, particularly in the United Kingdom [5, 6]. As far back as 1954, Pickard [5] reported on the potential effects, both positive and negative, that paints and other surface coatings can have on the ignition and flame spread of combustible surfaces. More recently, Murrell and Rawlins [6] addressed the fire hazard of surfaces coated with multiple layers of paint following a number of fires, including the Kings Cross Underground fire in London and a number of stairway fires in New **York** tenements, where this factor was perceived to be significant. They conducted tests with samples coated **with** 14 layers of paint, using a variety of “aged” and “unaged” oil-based and water-based finishes. For these samples, they observed that flame spread was supported only for imposed heat fluxes over 15 kW/m^2 . They noted that poor adhesion and “blistering” affects performance. They concluded that all existing paint films should be perceived as potentially flammable and that the end-use hazards of existing paint films should be appropriately ascertained and addressed.

In a previous study by McGraw and Mower [7, 8], **GWB** samples were painted with 2 to 8 coats of a latex-based interior paint plus one coat of a latex-based primer, then subjected to heat fluxes **of** 25, 50 or 75 kW/m^2 in the Cone Calorimeter for periods of 5, 10 or 15 minutes. Unpainted samples were similarly evaluated. Blistering was only observed for samples coated with 8 layers of latex paint plus one layer of primer that were subjected to an imposed heat **flux** of 75 kW/m^2 . The authors did not recognize the implications of blistering at the time of this previous study.

SAMPLE PREPARATION

For the present study, **GWB** samples were prepared by first cutting 162 specimens, each 10 cm square, from sheets of 15.9 mm (5/8 in.) thick type **X** **GWB** obtained at a local home improvement center. The samples were all weighed and the masses of the unpainted samples were recorded. 27 of the **162** samples were set aside to serve as the unpainted samples. The remaining 135 samples were coated with a single layer of oil-based interior primer and a single layer **of** alkyd/oil semi-gloss enamel using a paint roller. These samples were allowed to dry in a conditioned laboratory at a temperature of approximately 20°C **and** a relative humidity of approximately 50%, then they were weighed and their masses were recorded. 27 of these 135 samples were set aside to serve as the 1-coat samples. The remaining samples were then coated with a second layer of oil-based interior paint using a paint roller. After drying, these samples were weighed and their masses were recorded. 27 of these samples were set aside to serve as the 2-coat samples. This process was continued until all samples were prepared with up to **8** coats of paint plus one coat of primer.

On average, each coating of paint or primer added approximately 0.7 g of mass to a **GWB** sample, although this value ranged from approximately 0.4 to 1.0 g depending on the coating and set numbers. For the 0.1 m square **GWB** samples, this yields an application rate of $70 \pm 30 \text{ g/m}^2$. This application rate was compared with product literature on recommended application rates for the paint

used in this project. In US units, a gallon (3.785 l) of the alkyd/oil semi-gloss enamel weighs approximately 11 pounds (5 kg) and has a recommended coverage of 400 square feet (37.2 m²) per gallon on smooth surfaces, such as GWB. This yields a wet application rate of 134.5 g/m². The percent of solids by weight in this oil-based paint is approximately 72 percent. Assuming this is the fraction of the weight remaining on the coated surface once the paint has dried, with the remaining fraction evaporated during the drying process, the recommended dry application rate would be 96.9 g/m². This would suggest that the average application rate during sample preparation was approximately 72 percent of the recommended application rate for this paint.

CONE CALORIMETER TESTS

Testing of the painted and unpainted GWB samples was performed in the Cone Calorimeter located in the Potomac Laboratory of the Department of Fire Protection Engineering at the University of Maryland. The Cone Calorimeter was calibrated and operated in general accordance with the procedures for Cone Calorimeter testing described in various standards [9, 10].

Heat release rates and mass loss rates were calculated in accordance with NFPA 271 [9] based on measured test data, including sample mass, exhaust mass flow rates and oxygen concentrations. Data were typically acquired every 2 seconds. The oxygen analyzer data was time-shifted to account for transport lag in the gas sampling line, but adjustments are not made for instrument response lags [113]. Figures 1(a-c) show exemplar heat release rate curves for samples with different coatings of paint subjected to imposed heat fluxes of 35, 50 and 75 kW/m², respectively. Ignition times based on stopwatch data are plotted for all samples in Figures 2(a-c) for these same imposed heat fluxes. Samples that did not ignite or for which data are not available are indicated by the absence of a time to ignition.

Blistering was observed during some of the Cone Calorimeter tests, as evident in Figures 1(a-c) and 2(a-c). When blistering occurred, the paint film would delaminate from the GWB substrate and form one or more pressurized bubbles above the GWB surface. Eventually, cracks would form in these bubbles, vapors would be ejected from these cracks under pressure, then ignition of the vapors would occur. Blistering was accompanied by a marked decrease in the time to ignition, typically by a factor of 3 to 4 when compared with samples that did not blister. This is illustrated in Figures 2(a-c), which also show that the potential for blistering is a function of both the imposed heat flux and the number of coats of paint. At 35 kW/m², blistering was only observed for samples with 8 coats of paint, except that one of the nine samples with 6 coats of paint also blistered. At 50 kW/m², blistering occurred for all samples with 4 or more coats of paint, but not for any samples with 2 coats of paint or less. At 75 kW/m², blistering occurred for all samples with 2 or more coats of paint, but not for any samples with 1 coat of paint or less.

ANALYSIS

The potential for upward or concurrent flow flame spread on painted GWB is evaluated based on the model developed by Quintiere and coworkers [2, 3, 4]. This model considers the potential for flame spread in terms of the ignition and burnout of surface elements as they are subjected to heat fluxes imposed by the flame and external sources. The details of the model and its simplifying assumptions are described elsewhere [2]. What is significant for the present discussion is that this flame spread model produces a dimensionless "flammability parameter," defined as:

$$b = k_f \dot{Q}'' - (t_{ig}/t_b) - 1 \quad (1)$$

According to the Quintiere model, acceleratory upward flame spread is indicated when the value of the flammability parameter is positive, while decay to extinction is expected if its value is negative. Steady fire propagation is expected if the flammability parameter evaluates exactly as zero.

Evaluation of the flammability parameter requires evaluation of the respective parameters used to calculate it. Dillon, et al. [12] discuss a number of ways to interpret Cone Calorimeter data for use with the Quintiere model. Mower and Williamson [13] describe a technique for **using** Cone Calorimeter data directly to evaluate these characteristic parameters and the associated flammability parameter for thin finish materials adhered to noncombustible substrates. These materials tend to exhibit distinct peaks in their heat release rate histories due to their relatively short burning durations. While originally developed for textile wallcoverings adhered to GWB, this technique should also be applicable to painted GWB, so it is used here. For a given incident heat flux, the ignition time (t_{ig}), the peak unit heat release rate (\dot{Q}'') and the unit total heat release (Q'') are measured and substituted directly into Equation 1.

The flammability parameter expressed by Equation 1 was calculated for each specimen using the measured values for the ignition time, peak unit heat release rate and unit total heat release. Calculated flammability parameters for each of the three data sets are plotted in Figure 3 as a function of the number of coats of paint. Linear curve fits are also plotted in Figure 3. In theory, the point where the flammability parameter becomes positive represents the point where acceleratory flame spread would be expected instead of local burnout. Based on the linear curve fits shown in Figure 4, this would occur at approximately 10 coats of paint (plus one coat of primer) at an imposed heat flux of 35 kW/m^2 , between 5 and 6 coats of paint (plus primer) at 50 kW/m^2 and between 3 and 4 coats of paint (plus primer) at 75 kW/m^2 .

Whether a finish material will spread a flame or will burn out locally can be considered as a race between the burning duration of an element that has been ignited and the time to ignition of an adjacent element being exposed to the heat flux from the burning element. If an element burns long enough to cause ignition of an adjacent element, flame spread can be expected; if not, then localized burnout would be expected. This is the essence of the Quintiere upward flame spread model when applied to materials where burnout is important.

The burning duration of an element is a function of the amount of **fuel** available in the element and the burning rate of the element. In turn, the burning rate of an element depends on the net heat flux at its surface. This can be expressed as:

$$t_b = \frac{Q''}{\dot{Q}''} = \frac{m'' \Delta H_c}{\dot{q}_{net}'' (\Delta H_c / L)} = \frac{m'' L}{\dot{q}_{net}''} \quad (2)$$

where m'' is the combustible finish mass per unit area (kg/m^2), L is the effective heat of gasification (kJ/kg) of the finish material and \dot{q}_{net}'' is the net heat **flux** (kW/m^2) at the burning surface after ignition occurs.

The ignition time of an element depends on its thermophysical properties as well **as** on the imposed heat flux. Finish materials are typically considered as either thermally thick or as thermally thin, depending on the thickness of the finish / substrate assembly as well as on the thermal properties of the assembly. For thermally **thick** materials subjected to a constant net heat **flux** at the surface, the ignition time can be expressed as:

$$t_{ig} = \frac{\pi}{4} k \rho c \left[\frac{\Delta T_{ig}}{\dot{q}_{net}''} \right]^2 \quad (3)$$

For thermally thin materials subjected to a constant net heat flux at the surface, the ignition time can be expressed as:

$$t_{ig} = \rho c \delta \left[\frac{\Delta T_{ig}}{\dot{q}_{net}''} \right] \quad (4)$$

In general, the net heat **flux** terms in Equations 2, 3 and 4 will not be equal to each other or constant. Nonetheless, the potential for flame spread can be evaluated, at least semi-quantitatively, by assuming the net heat fluxes in Equations 2, 3 and 4 are constant and proportional to each other. With this assumption, the ratio between the burning duration, t_b , and the ignition time, t_{ig} , can be evaluated in terms of Equations 2, 3 and 4. If this ratio has a value greater than 1 (i.e., $t_b / t_{ig} > 1$), then a material would be expected to burn long enough for the adjacent element to ignite, in which case flame spread would be expected. For a thermally thick material, the ratio between the burning duration and the ignition time evaluates, using Equations 2 and 3, as:

$$\frac{t_b}{t_{ig}} = \chi_b \left(\frac{\rho \delta L}{IRP} \right) \dot{q}_{net}'' \quad (5)$$

where $\rho \delta$ is the combustible finish mass per unit **area** (kg/m^2), the IRP, defined in Equation 8, is an ignition response parameter that is similar to the square of the thermal response parameter defined by Tewarson [14] for thermally thick materials and χ_b is an appropriate proportionality constant to account for the ratio between the different net heat fluxes in Equations 2 and 3 (i.e., $\dot{q}_{net,Eq.2}'' = \chi_b \dot{q}_{net,Eq.3}''$). Consequently, for a thermally thick finish, flame spread would be indicated when:

$$\dot{q}_{net}'' > \chi_b \left(\frac{IRP}{\rho \delta L} \right) \quad (6)$$

This analysis suggests that there is a critical net heat flux for flame propagation on a thermally thick finish. At net heat fluxes **above** this critical threshold, upward flame spread would be expected, while localized burnout would be expected at lower heat fluxes. Equation 6 also shows that the critical net heat flux for flame propagation is expected to vary directly with the IRP and inversely with the coating application rate, which should be nominally proportional to the number of coatings. This inverse relationship with the number of coatings is illustrated in Figure 4, which shows the number of coats of paint required to yield a positive flammability parameter as a function of the imposed heat flux based on the curve fits developed in Figure 3. A curve fit for the inverse relationship expected between the critical net heat flux for flame propagation and the number of coatings is also shown in Figure 4. The value of 356.5 coats of paint per kW/m^2 imposed heat flux used as the proportionality factor in this curve fit was determined as the average value of the heat **flux** – coating product for the three data points illustrated in Figure 4. This specific value only applies to the data presented here.

For a thermally thin material, the ratio between the burning duration **and** the ignition time can be expressed as:

$$\frac{t_b}{t_{ig}} = \left(\frac{L}{c\Delta T_{ig} + \chi_{ig}\Delta H_v} \right) = \left(\frac{c\Delta T_{ig} + \Delta H_v}{c\Delta T_{ig} + \chi_{ig}\Delta H_v} \right) \quad (7)$$

The term χ_{ig} represents the fraction of the material that must be vaporized once the material is heated to its ignition temperature in order to form an ignitable mixture with air at the surface of the material. As long as this fraction ranges between 0 and 1, Equation 7 will evaluate to a value greater than or equal to unity. This implies that thermally thin materials will always burn long enough to ignite the adjacent fuel element based on this simple thermal model. Whether or not flame spread will occur for a thin material depends on the flame length, which in turn is a function of the unit heat release rate. Other factors not considered here, such as melting or shriveling, the application of fire retardant treatments or other chemical factors, would also have an influence on the potential for flame spread on thermally thin materials.

Specimens that do not blister are expected to behave as thermally thick materials. For thermally thick materials, the ignition response parameter is expected to remain constant. By assuming that the net heat flux is proportional to the imposed heat flux and that the proportionality constant, χ_{hf} , is independent of the magnitude of the heat **flux**, Equation 3 can be solved for an effective ignition response parameter in terms of the ignition time and the imposed heat flux as:

$$IRP_{eff} = \frac{IRP}{\chi_{hf}^2} \equiv \frac{\pi}{4} k\rho c \left[\frac{\Delta T_{ig}}{\chi_{hf}} \right]^2 = t_{ig} (\dot{q}_{ext}'')^2 = const. \quad (8)$$

The effective ignition response parameter expressed by Equation 8 is plotted as a function of the coats of paint in Figure 5 for all the specimens. Figure 5 clearly shows a difference in the effective ignition response parameter between specimens that blistered and those that did not. For the specimens that did not blister, the average value for the effective ignition response parameter was 105,374 (kW/m²)²-s, with a range of 66,518 to 158,750 (kW/m²)²-s. This compares with values of 104,977 (kW/m²)²-s for “common” GWB and 75,430 (kW/m²)²-s for “FR” GWB based on thermal properties reported by Quintiere [15] that are derived from LIFT tests [16]. For specimens that did blister, the average effective ignition response parameter was 31,065 (kW/m²)²-s, with a range of 22,050 to 42,875 (kW/m²)²-s. On average, this represents a decrease by a factor of 3.4 in comparison with the specimens that did not blister.

The occurrence of blistering might reasonably be expected to change the flammability performance of a surface from that of a thermally thick material to that of a thermally thin material. For a thermally thin material, Equation 4 suggests that the total energy required for ignition should remain constant provided the ignition temperature is constant. By again assuming that the net heat **flux** is proportional to the imposed heat flux and that the proportionality constant, χ_{hf} , is independent of the magnitude of the heat **flux**, Equation 4 is rearranged to solve for what is termed here the effective specific ignition energy (SIE_{eff}):

$$SIE_{eff} \equiv \frac{c\Delta T_{ig}}{\chi_{hf}} = \frac{t_{ig} \dot{q}_{ext}''}{\rho\delta} \quad (9)$$

The effective specific ignition energy is plotted as a function of the total mass of paint and primer in Figure 6 for the specimens that blistered. From Figure 6, it is evident that the effective specific ignition energy is not quite constant as might be expected for a thermally thin material; it decreases with increasing coats of paint as well as with increasing heat flux. It is suspected that this behavior may be related to the permeability of the paint film. As additional coats of paint are added, the permeability of the surface is expected to decrease. As moisture within the GWB evaporates and tries to escape from the surface, it is trapped by the paint film, causing a pressure increase that leads to blistering. As the imposed heat flux increases, the rate of moisture evaporation will increase, causing a larger pressure rise, and consequently blistering, earlier. The results in Figure 6 are consistent with these observations, but more work is needed to explore the effects of moisture evaporation and paint film permeability on the potential for blistering. Given that the paint film is initially adhered to the GWB substrate, then blisters before igniting, the actual performance of painted surfaces most likely falls somewhere between that expected of a thermally thick and a thermally thin material.

SUMMARY AND CONCLUSIONS

The flammability characteristics of type X gypsum wallboard coated with different layers of an alkyd/oil interior paint have been evaluated. The same paint was used for all layers except the primer coat, which was also an oil-based paint. The Cone Calorimeter was used to evaluate ignition and flammability characteristics under constant imposed heat fluxes of 35, 50 and 75 kW/m². Data derived from these Cone Calorimeter tests were used in conjunction with Quintiere's upward flame spread model to evaluate the potential for fire propagation on painted GWB surfaces.

This work suggests that there is relationship between the number of coats of paint on a surface and the potential for upward flame spread. As the number of coats of paint increases, the critical heat flux to the surface required for flame propagation decreases. Below the critical heat flux for flame propagation, local burnout is expected, while above this critical heat flux, flame propagation might be expected. Large-scale fire tests would be useful to verify this conclusion under realistic enclosure fire conditions.

During the Cone Calorimeter tests, the phenomenon of blistering was observed where the film of paint would delaminate from the GWB substrate under the imposed heat flux. Blistering did not occur for all painted samples. Rather, the likelihood of blistering was a function of both the imposed heat flux and number of coats of paint, with more coats of paint being required at lower heat fluxes. When blistering did occur, the time to ignition decreased significantly, typically by a factor of 3 to 4 when compared with samples where blistering did not occur. Since the potential for flame spread can be viewed as a race between the burnout of already ignited surfaces and the ignition of adjacent surface elements, such a reduction in the time to ignition would tend to tip the balance in favor of flame spread.

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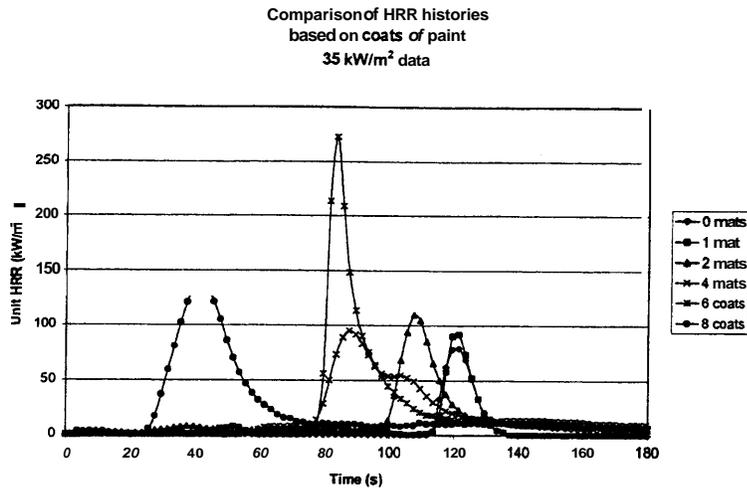


Figure 1(a). Comparison of heat release rate curves for different coatings – 35 kW/m².

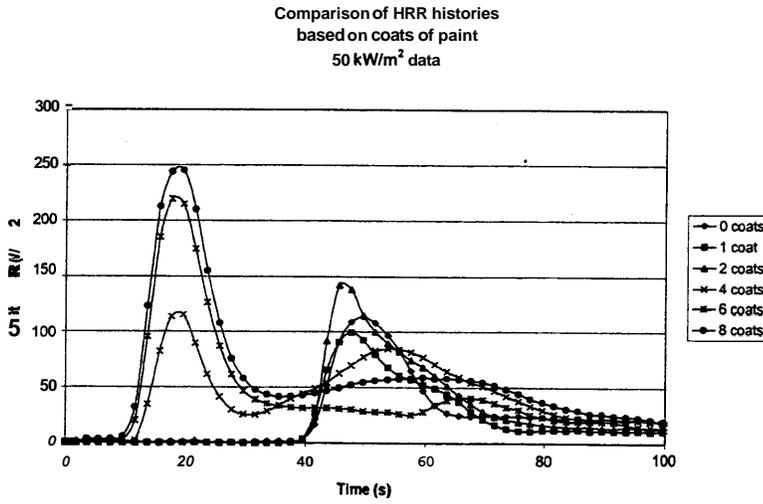


Figure 1(b). Comparison of heat release rate curves for different coatings – 50 kW/m².

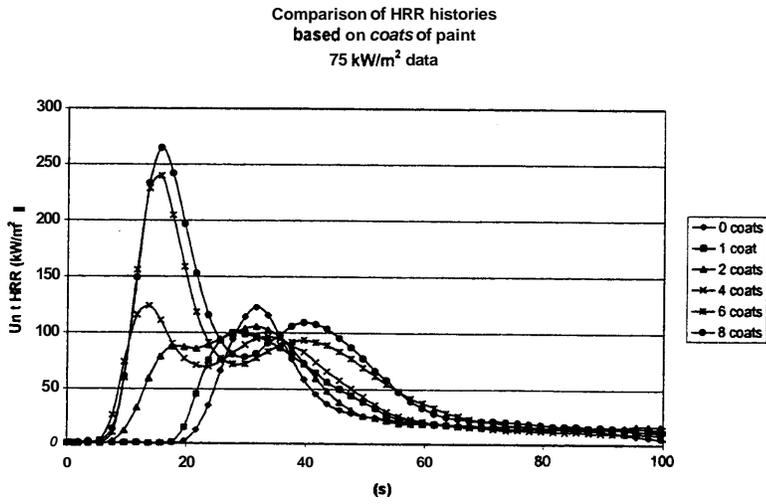


Figure 1(c). Comparison of heat release rate curves for different coatings – 75 kW/m².

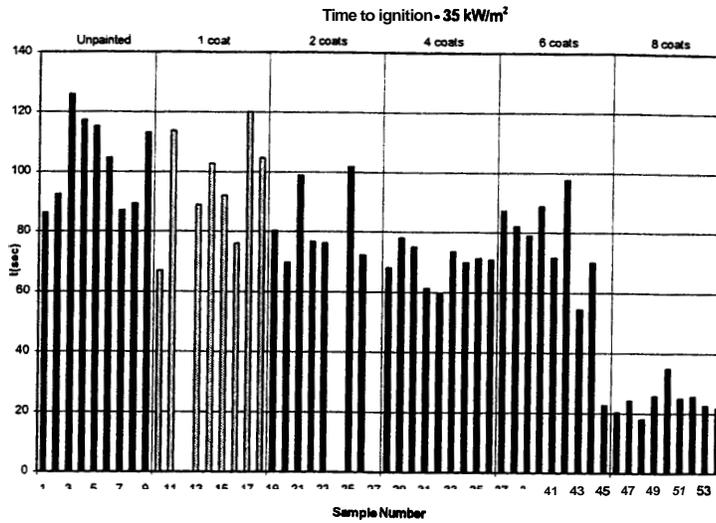


Figure 2(a). Ignition times for data set 1 – 35 kW/m² heat flux.

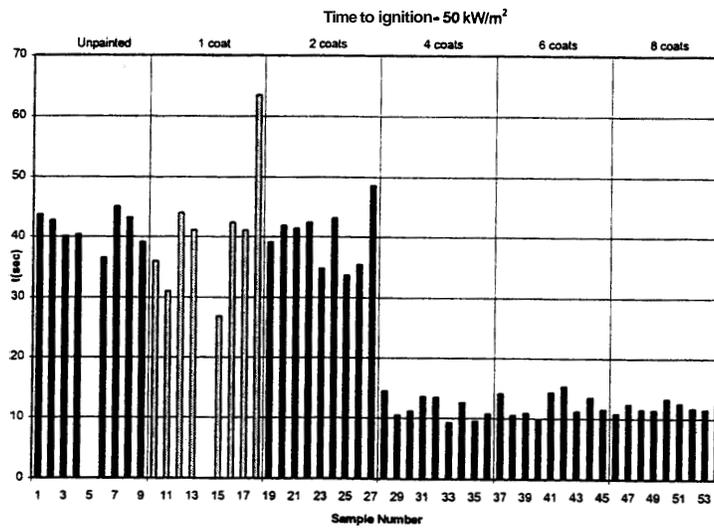


Figure 2(b). Ignition times for data set 2 – 50 kW/m² heat flux.

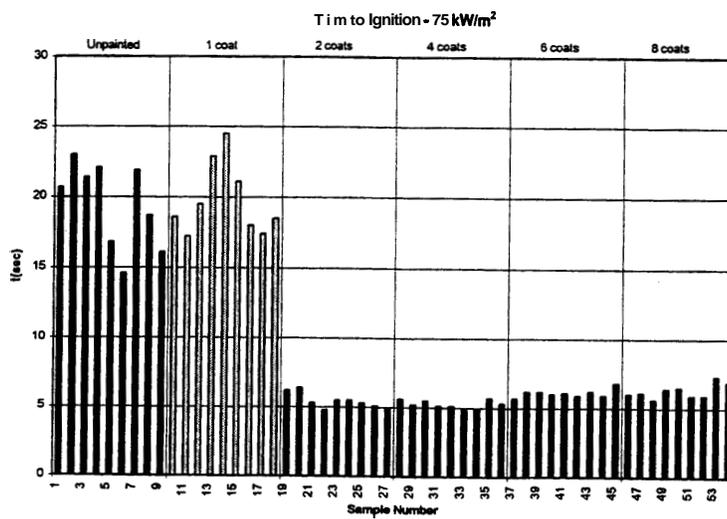


Figure 2(c). Ignition times for data set 3 – 75 kW/m² heat flux.

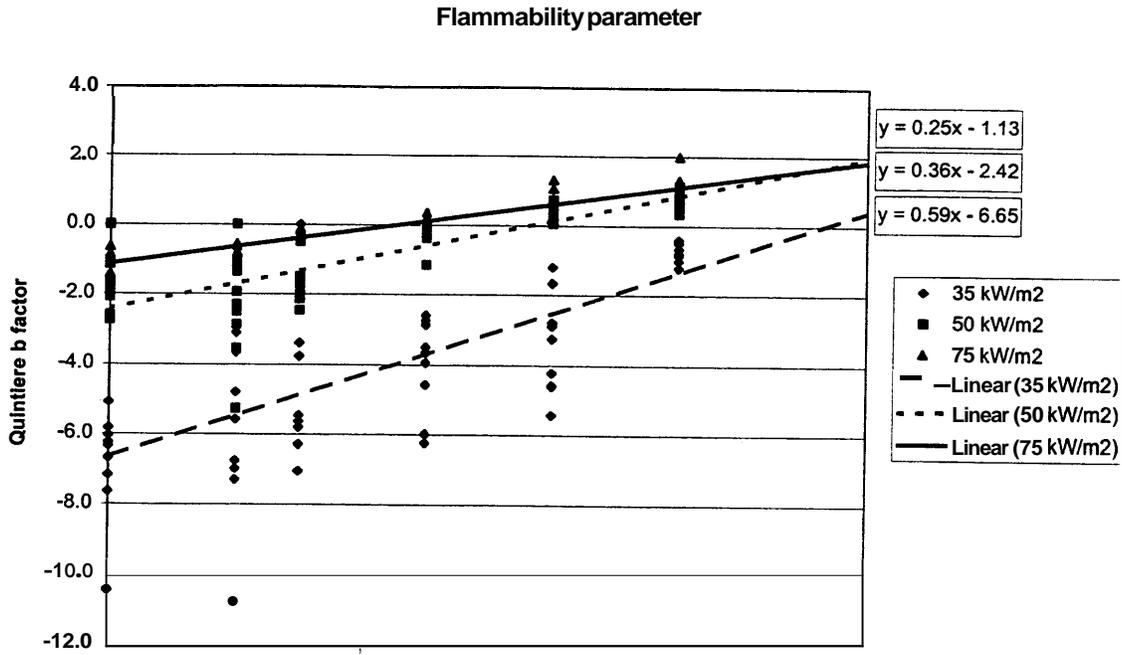


Figure 3. Calculated flammability parameter as a function of coats of paint for each data set.

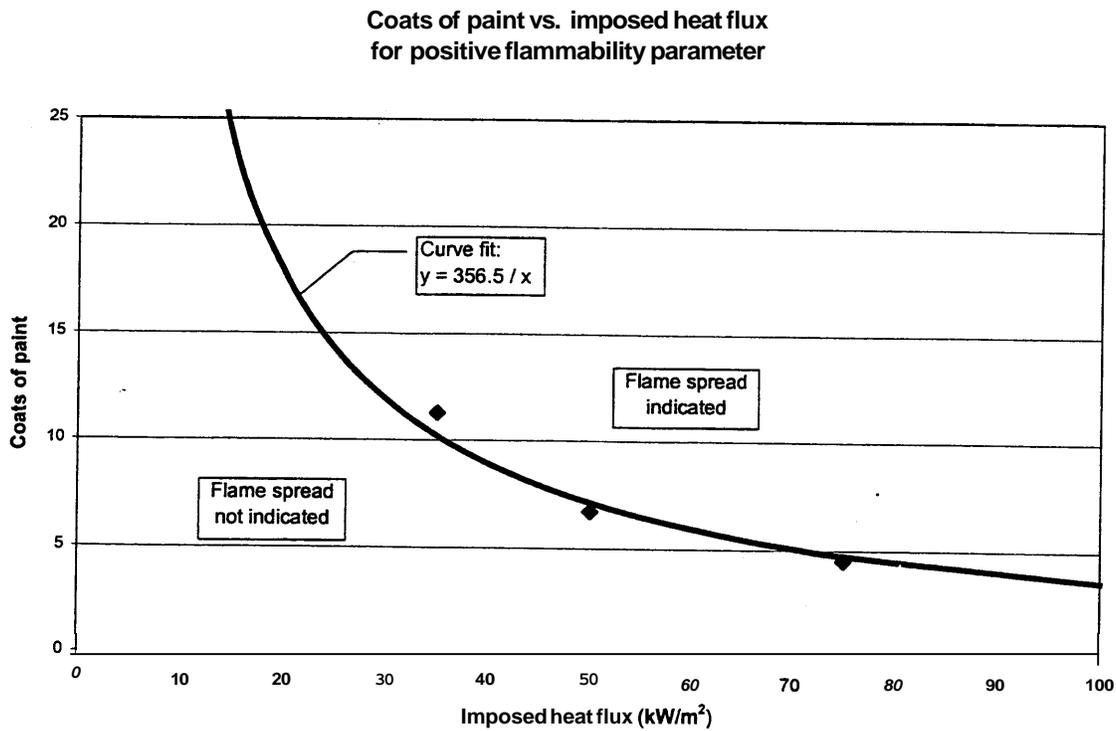


Figure 4. Number of coats of paint required to yield a positive flammability parameter.

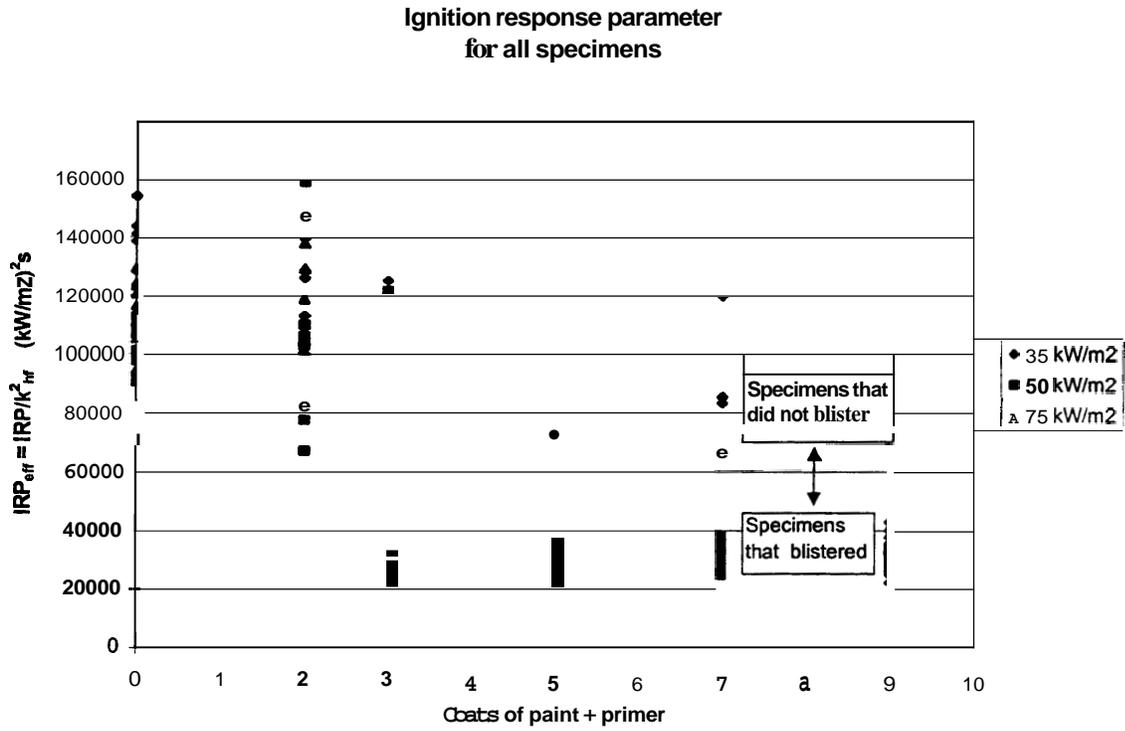


Figure 5. Effective ignition response parameter for **all** specimens.

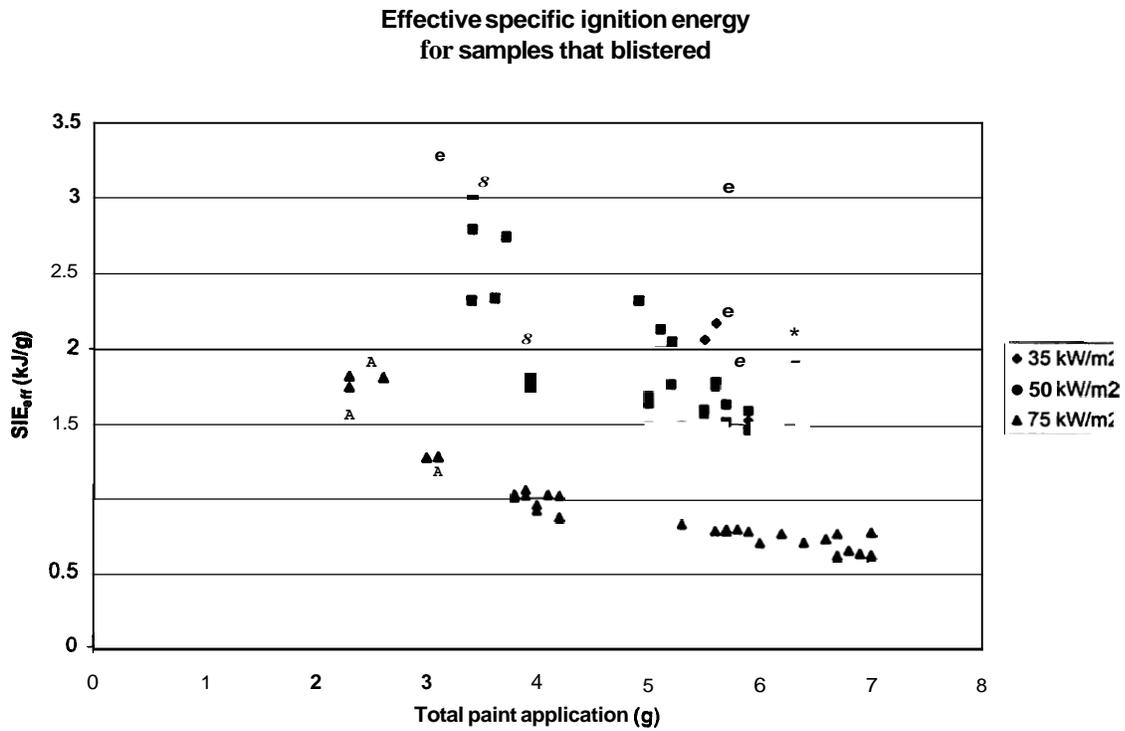


Figure 6. Effective specific ignition energy for specimens that blistered.

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More than 300 **gypsum** samples coated with 0 to 8 layers of paint have been subjected to flammability testing in the Cone Calorimeter resting **has been** conducted with samples coated with either latex-based interior paints **and** subjected to imposed heat fluxes ranging from 2 to 75 kW/m². During some of the tests, "blistering" of the painted surface **has** been observed. **This** blistering phenomenon is most pronounced in samples coated with multiple layers of oil-based paint. **As** the number of coats of paint increases, blistering is observed at lower imposed heat fluxes. When blistering **does occur**, the time to ignition decreases significantly, typically by a factor of 3 to 4, when compared with samples that do not blister, while the burning duration remains approximately the same. The potential for upward flame spread on painted **gypsum** wallboard is addressed in terms of a modified version of the Quintiere flame spread model. The concept of a critical heat flux for upward spread is developed **as** a means to account for the race between ignition and burnout.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

Cone calorimeters; fire models; flame spread; gypsum board; wallboard; paints

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