AN EXAMINATION OF THE CORRELATION BETWEEN CONE CALORIMETER DATA AND FULL-SCALE FURNITURE MOCK-UP FIRES

by

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Introduction. As part of an on-going study of the factors which affect heat release rate performance of furniture in the California Technical Bulletin 133, we have focused most recently on the role played by interliners or barriers [1]. A barrier in this context is a layer of very low flammability material placed between the fabric and the polyurethane foam to minimize the participation of the latter in a fire. In CB 133 that fire is initiated on the seating area of an upholstered furniture item by an 18 kW gas burner that sprays flames on the seat, seatback and inner arm surfaces. The response of the chair is required to be at most an 80 kW peak in heat release rate. The test applies to furniture in public occupancies; it has been adopted in four states and is under consideration in several others.

A mock-up of the furniture item is permitted. The present study used a fixed mock-up geometry (seat, back, two arm cushions) with twenty seven material combinations (seven fabrics, three barriers and two polyurethane foams). These were tested in a furniture calorimeter in accord with the CB 133 protocol; they were also assessed in the Cone Calorimeter, in triplicate, mainly at the "standard" flux of 35 kW/m^2. More details of the study can be found in Ref. 1.

The focus of this paper is the relation between the full-scale peak rate of heat release and the data obtained from the Cone. In the full scale, the heat release process typically peaked initially near the end of the 80 second gas burner exposure. Some, but not all material combinations gave a later and frequently greater heat release peak as well. There were strong indications that the phenomena underlying these two peaks differed appreciably. They are examined separately here.

Correlation of First Peak With Cone Calorimeter. The rate of heat release at any time, t, from any spreading fire can be expressed as follows.

$$Q(t) = \int_0^t RHR(t-t') \left(\frac{dA_b}{dt}\right) dt' \qquad (1)$$

Here Q is in kilowatts, RHR(t-t') is the rate of heat release per unit area at time t for an area element ignited at time t' and (dA_b/dt) is the time-varying rate of increase of burning area. This integral simply sums the heat release rate contributions at a given instant from all of the successively ignited portions of the burning object. It takes into account the fact that those elements which ignited first have been burning longer than later elements and thus are at a different point in their burning histories.

Evaluation of the integral in Equation (1) requires knowledge of the time-dependent terms within it and, in general, this knowledge is not available. However, if one assumes that the two functions can be replaced by their average values, evaluated between time zero and the time, t_p, of the heat release peak, Equation (1) becomes

$$Q(t_p) \approx (dA_b/dt)_{avg} (RHR)_{avg} t_p \approx A_{BP} \ (q_{BS})_{avg} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Note that the average rate of increase of burning area multiplied by the time of the peak reduces to the burning area at the peak, A_{BP}. The second approximate equality has replaced the average rate of heat release per unit area on the full-scale chair with the (hopefully) equivalent value measured in the Cone Calorimeter, $(q_{BS})_{avg}$. This last suggests a proportionality between Cone Calorimeter data and full-scale peak data. (The burn area at the peak is also variable but in this study it varied much less than did the Cone behavior.) Such correlations with heat release rate have been published previously [2]. When a straightforward correlation is attempted here between the maximum full-scale heat release rate (over the entire test period) and the "standard" 180 second, post-ignition average of the Cone rate of heat release data, the result is essentially no correlation at all. This emphasizes the fact that the mechanism underlying the early and late heat release peaks in the mock-up tests is significantly different; it is best to focus on these peaks separately.

An attempt at a similar correlation between the Cone Calorimeter heat release data and the first heat release peak in the mock-up tests (during the burner exposure) is shown in Figure 1. Here, since the gas burner exposure is only 80 seconds long and the earliest mock-up surface ignition requires roughly 20 seconds, a sixty second averaging time has been used for the Cone data (first 60 sec after ignition). This is certainly more appropriate here than the 180 second averaging period used in Ref. 2.

Clearly there is some correlation between the two types of data in Figure 1. The correlation is quite noisy, however. The dashed lines suggest the outer limits of the data spread. Inspection of these implies an uncertainty of roughly ±50% in full scale peak heat release rate using the indicated correlation line with a given average rate of heat release in the Cone Calorimeter. Figure 1 indicates that, for the first heat release peak in a CB 133 test, averaged Cone heat release data are only a coarse guide to expected full-scale performance. It is of interest to see if some better correlations can be established between small scale flammability parameters and full-scale fire performance of these mock-ups.

Dimensional Analysis of Fire Growth on Chair. Dimensional analysis is a long-established, semi-empirical technique for obtaining useful expressions describing processes where the full governing equations are not available or are not tractable [3]. Its use here is prompted by the encouraging efforts along these lines in the study of room-corner fire tests [4, 5], an analogous though somewhat simpler problem. Our goal in applying this technique is to ascertain whether it can provide a simple but more complete guide than does average heat release rate in the Cone to the quantitative impact of varying the material combinations in a CB 133 test.

A key starting point for any dimensional analysis is knowledge of the component processes of the problem to be analyzed. Close study of video tapes of the tests indicates that the key component processes involve convective and radiative ignition, upward and lateral flame spread and, finally, heat release rate subsequent to spread. All of these processes have been studied in other contexts and modelled to varying degrees [6]. However, it should be noted at the outset that the general fire growth problem on thermoplastic materials which undergo significant movements has not been studied; the substantial tendency for the thermoplastic fabrics in this study to split open and pull back from the igniter flames is discussed in Ref. 1. The probable consequences of this will emerge below. Both types of ignition processes noted above, as well as upward flame spread, respond principally to the thermal inertia of the fuel surface, denoted as ($k\rho C$), where k is thermal conductivity, ρ is density and C is heat capacity of the fuel. A second parameter affecting these processes on a solid fuel is the ignition temperature, here denoted as ΔT, the difference between the actual ignition temperature and room temperature, where the latter is assumed constant. Finally, there is a characteristic heat flux from the flames to the solid, denoted as q_{ign}; this is taken to be a measure of that flux seen at all stages of the fire growth process, with no distinction between radiation and convection. Lateral flame spread introduces only one new parameter, a measure of the heat input at the attachment point of the spreading flame; it is denoted as Φ. The rate of heat release process of interest is that represented by the first peak in the Cone Calorimeter (principally due to the fabric). It will be characterized here by the height of the first Cone peak, Q_{max}, and the duration of the first peak, t_B. Finally, there is a characteristic length in this problem, the width of the gas burner, denoted as l_B; all other lengths, e.g., seat, arm and seatback dimensions can be expressed as multiples of this length.

All of these parameters can be quantified in bench scale tests, in principle. The heat flux, q_{ign}, could be troublesome and ultimately, it will be replaced by another parameter below. Similarly, we will seek a substitute for the thermal inertia.

Once the key parameters are identified, dimensional analysis provides a formal procedure that allows one to re-cast the problem into a functional relationship between dimensionless groups of parameters. The procedure is straightforward, based on the necessity for dimensional consistency in any functional relationship [3]. The usual assumed form of a functional relationship is a power law. Using this procedure we proceed from

$$Q(t) = f(t; \Delta T, q_{ign}, (k\rho C), \Phi, Q_{max}, t_B, l_B) \quad \ldots\ldots\ldots (3)$$

where Q(t) is the total rate of heat release as a function of time. This becomes

$$\frac{Q(t)}{Q_{max}} = \left(\frac{(k\rho C)^{1/2}\Delta T}{\sqrt{t}\,Q_{max}}\right)^{\alpha}\left(\frac{t_B}{t}\right)^{\beta}\left(\frac{q_{ign}}{Q_{max}}\right)^{\gamma}\left(\frac{\Phi}{Q_{max}^2\, l_B}\right)^{\delta} \quad \ldots\ldots\ldots (4)$$

It should be noted that a more general analysis of this specific problem would give rise to further dimensionless groups. These would involve test particulars such as the power output of the gas burner, exact placement of the burner, etc.; also there are further dimensionless groups involving the burner width to seat width, arm width, etc. Both types of groups are ignored here. The first because they are held constant by the test protocol; the second because they have not yet been varied experimentally.

The analysis does not produce values for the exponents in Equation (4); these must be determined by systematic experiments. It is worth noting that the exponents could be large or small, with the latter indicating a very weak dependence on the given dimensionless group.

Equation 4, while certainly simpler than a full-blown model of the fire growth process, is still too complex for the practical goal of guiding users in judging the impact of materials substitutions. Furthermore, its applicability to real CB 133 data has not been demonstrated. As a practical matter, if all the dimensionless groups in this equation must be determined for each new material combination, it would probably be less expensive to simply run a CB 133 test. We are thus led to seek some further simplifications.

A surrogate for the numerator in the first dimensionless group of Equation 4 (thermal inertia times ignition temperature) is ignition delay time at a fixed flux. Cone data for this at 35 kW/m^2 is typically obtained during heat release testing. A surrogate for q_{ign} in the third dimensionless group is the heat of combustion of the fabric, Q_{comb}; this is only a part of the source of heat flux variation with test materials, but it may suffice. The flame heat flux parameter, Φ, has no ready surrogate. (The equation below is dimensional; surrogates need not have the same dimensions as the parameter they replace.)

With these ideas in mind, in combination with Equation 4, we arrive at the following proportionality:

$$Q_{peak} \sim t_{ign}^{a} t_{B}^{b} Q_{max}^{c} \Phi^{d} Q_{comb}^{e} \ldots\ldots\ldots (5)$$

Once again, the exponents are to be determined by experiment. Furthermore, this can be turned into an empirical equation if an experimentally-determined constant is placed in front of the right hand side. We note that four of the five materials parameters are available from Cone tests. Since we do not have a measure of the lateral spread parameter, Φ, for the materials in this study, we will proceed as if it was sufficiently invariant to be lumped into the constant of proportionality in Equation 5.

The next step in testing the validity of the above approach is to attempt to fit Equation 5 (with a proportionality constant) to the available Cone and full-scale data. This was done here using a non-linear, least-squares fitting routine available within the Sigmaplot software package. Note that a subset of the indicated parameters in Eqn. 4 may suffice. Charring fabrics (here cotton, modacrylic-nylon, polyester-cotton) comprise the group that most closely follows the assumptions here as to controlling mechanisms in the fire growth. These fabrics largely stay in place during the flame spread processes. This yields the closest correspondence between their behavior in the Cone and that in CB 133 during the burner exposure.

Figure 2 shows the correlation between Equation 5 and full-scale data for the charring fabrics. Perfect agreement would mean that all of the experimental points lay on the dashed line. Agreement for these material sets is fairly good, in spite of the neglect of the factors Φ and Q_{comb}.

Figure 3 shows the correlation for full data set when the heat of combustion of the material combination is also factored into the statistical determination of model parameters. Compared to Figure 1 this tightens the correlation for most of the data points but it leaves two points out of line. Unfortunately, the out-of-line points fall to the high side of the correlation line meaning that the correlation prediction would underestimate the hazard of the specific material combinations these points represent.

For thermoplastic fabrics, Equation 5 is less successful for two possible reasons. The role of the parameter Φ may be more significant, in that it may vary more among these fabrics. There are no data with which to judge this issue at present. A possibly more significant reason is that fire growth on thermoplastic-covered furniture is inherently more complex. These fabrics tended to pull strongly away from the burner flame, leaving substantial fractions of the cushion surfaces devoid of fabric on a scale that is not modelled by Cone behavior; such pull back continues as the fire grows further. The burn duration then varied from very short where only barrier and foam were exposed to extra long where fabric melt accumulations occurred. It is doubtful that the full complexity of this behavior can be accurately modeled from first principles. On the other hand, the type of semi-empirical model which Equation 5 represents may capture it sufficiently if a proper measure of the fabric movement tendency can be included as a variable. Such a measure might be obtained in LIFT-like (i.e., ASTM E-1321, lateral flame spread test), heat flux gradient exposures of the fabric/barrier combination. An average value of the exposed barrier area for horizontal and vertical sample orientations could perhaps become the needed additional variable. This requires experimental exploration. A larger set of test materials is also needed to more fully assess the broadness of the applicability of the approach discussed here, but it does look reasonably promising as a basis for guidelines in the manufacture of furniture that must pass CB 133.

The second heat release peak, as noted above, is due to a different mechanism; this is discussed in Ref. 1. Only limited examination of this peak has been carried out thus far; it appears to be more difficult to correlate with Cone data. It might possibly be suppressed or prevented by relatively simple design measures in furniture assembly.

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Fig.1 Linear Fit Between Cone Avg. RHR and First Full-Scale RHR Peak

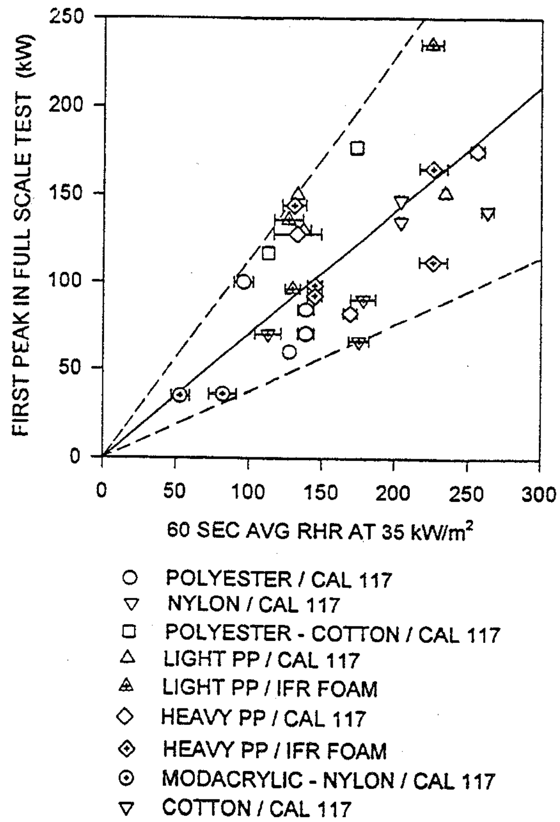

Fig.2 Correlation Based on Charring Fabrics (Cotton, Polyester-Cotton, Modacrylic-Nylon)

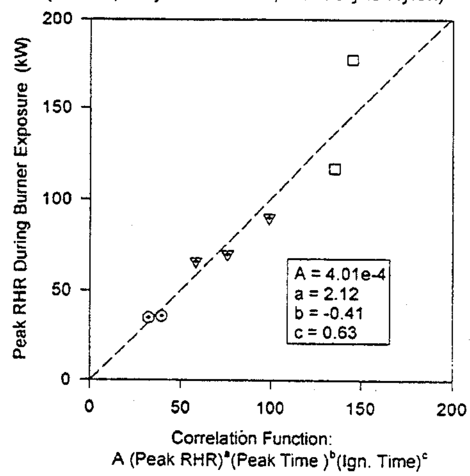

Fig. 3 Correlation Based on Four Parameters From the Cone Calorimeter