NISTIR 6030

THIRTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY, MARCH 13-20, 1996

VOLUME 2

Kellie Ann Beall, Editor

June 1997
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Gaithersburg, MD 20899

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FLAMMABILITY OF UPHOLSTERED FURNITURE

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ABSTRACT

Upholstered furniture flammability is both an ignitability and a heat release rate issue. Limited work on ignitability has been done recently. The major focus in three recent studies is the intensity of burning which follows exposure to a source strong enough to assure ignition. No adequate model of the post-ignition fire growth process exists. Examination of the attempts to correlate Cone Calorimeter data with full-scale heat release rate shows mixed results. Reasonably good correlations have been obtained but it is not clear that they have broad applicability and thus clear usefulness in designing furniture with known fire performance.

1. The Nature of the Problem

A substantial fraction of U. S. fire fatalities continues to be attributable to situations in which upholstered furniture is the first item ignited [1]. Significant reductions have occurred in this furniture-related death toll over the past twenty years, evidently as a consequence both of the widespread use of smoke detectors and of a voluntary industry standard on resistance to cigarette ignition. Cigarettes and small flames continue to constitute the bulk of the ignition sources, however, with a smattering of other sources such as electrical shorts or misused heating appliances. Once ignited to flaming by any of these means, the typical upholstered item, with its large volume of polyurethane foam, is capable of a rapidly developing fire that can exceed a megawatt in size.

2. General Approaches to the Problem.

Two broad approaches to this persistent flammability problem are possible: decrease the likelihood of ignition or decrease the impact of ignition. The ignition event itself, if it is a consequence of the most common scenario of a dropped cigarette, can be prevented by changes in the upholstery (mainly the fabric) or by changes in the cigarette. The former approach is at the heart of the voluntary program by the Upholstered Furniture Action Council. While this program has been in effect for two decades, a quantitative and objective measure of its effectiveness has been lacking for the last ten years. The Consumer Products Safety Commission is currently engaged in sampling and testing representative upholstered chairs from the residential furniture market. A recent program at NIST showed the feasibility of altering cigarettes to reduce their furniture ignition propensity and an appropriate test method for this purpose was developed [2, 3]. At present there are no regulatory requirements of this nature on cigarettes.

The Consumer Products Safety Commission is also now addressing the question of the ignition of upholstery by small, match-size flames. Their statistical studies show that dropped smoker's matches and children playing with matches are substantial parts of the problem. Thus they are studying the ignitability of upholstered items in three locations: the seat/back crevice (a worst case location for a dropped smoker's match), the bottom of the stiffened fabric skirt found around the base of many furniture designs and the dust-cover fabric that typically covers the bottom surface of a chair or sofa. The last two locations are thought to be typical areas of interest for children playing with matches.

To decrease the impact of ignition of upholstered furniture, either by a cigarette or a flaming source, one needs to sharply limit the rate of heat release from the subsequent fire. Typically this implies a need to either modify (flame retard) the polyurethane foam or protect it from direct flame impingement by the use of a barrier layer. These are relatively costly solutions, not known to work with all possible fabrics. The enormous diversity of fabrics, due to varied fiber blends and weave designs, greatly complicates the search for assured solutions. This has led to recent studies, summarized below, which seek to understand and quantify the relation between upholstery composition and its rate of heat release behavior.

3) The Rate of Heat Release from Upholstered Furniture.

Furniture manufacturers need quantitative information on the relation between the properties of their materials and the fire performance of the chairs they manufacture from them. Room fire modelers need quantitative models of the development of fires involving the room contents and the interaction with the room, particularly for upholstered furniture. Both needs should be satisfied, if possible, by inputs derived from inexpensive tests on small samples of the materials of interest, thus precluding the need to burn a sample of each new chair design. This has led to several studies that examined the relation between behavior exhibited by furniture composites in the Cone Calorimeter and that shown by full-scale mock-ups or chairs.

Most of the recent interest in this area has been driven by regulatory issues. In the US, several states have adopted a stringent requirement on furniture to be placed in public occupancies (hotels, hospitals, etc.). In this test, known as California Technical Bulletin 133, an item of upholstered furniture (or a closely modeled mock-up of it) is subjected to an 18 kW gas burner playing flames on its seat area for 80 seconds. The resulting fire must not exceed 80 kW (including the igniter). NIST as well as a textile industry group have recently completed studies of materials effects in this test [4]. In Europe, the EC recently sponsored a large furniture flammability study, known as the CBUF study, aimed at harmonizing regulations across member countries [5]. Various chairs and sofas were subjected to the same gas burner design, but it was run at 30 kW for 120 seconds. In all of the above studies, the upholstery material combinations were also tested in the Cone Calorimeter, typically at 35 kW/m^2.

Ideally, one would be able to plug the Cone Calorimeter measurements into a well-developed predictive model of fire growth and calculate the heat release rate as a function of time for the full-scale furniture item. Unfortunately, the fire behavior of upholstered furniture items can be among the most non-ideal imaginable due to the strong role played by material movement in response to heat. Thermoplastic materials flow under the influence of gravity, moving fuel and heat to new, ill-defined locations. No model is able to handle these kinds of complications at present. A significant conclusion from the CBUF study was that, of the several dozen chair and material combinations studied, only a small proportion, perhaps one third or less, behaved in a manner consistent with a "simple" physical model in which material movements could be ignored prior to the peak in heat release rate. Thus it appears that the majority of real upholstered furniture will not be describable by a model that ignores the complexities of thermoplastic behavior. This has led to other, much more simplified approaches to relating Cone and full-scale behavior.

In the recent NIST study, the focus was on fabric and barrier effects in mock-ups tested according to the CB-133 protocol. A barrier is a nominally incombustible fiber layer placed between the fabric and polyurethane foam to minimize the participation of the latter in the burning process. The fire behavior during the gas burner exposure and afterward was sufficiently different as to suggest the controlling mechanisms are not the same for the two situations; the former involves mainly the fabric and the latter mainly the foam. It is worth noting that if the barrier layer were fully successful, there would be no significant heat release rate after the burner exposure but this was frequently not the case. Thus the behaviors during and after the burner exposure were assessed separately.

The fire growth problem during the gas burner exposure is dominated by lateral and upward flame spread processes on the fabric. The fundamentals of these processes are essentially similar to those in a room corner test, <u>if</u> thermoplastic material effects are minimal. Thus a dimensional analysis analogous to that performed by Thomas, *et al.* [6, 7] was made for this problem. The result, for a fixed chair geometry and igniter, is as follows:

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

Here Q(t) is the rate of heat release behavior of interest, i. e., the growth toward a peak, Q_{max} is the height of the first heat release peak seen in the Cone Calorimeter at a flux of 35 kW/m^2 for a mock-up of the chair materials (fabric, barrier, foam), (kρC) is the effective thermal inertia of the mock-up during ignition, ΔT is the temperature increase of the mock-up surface at ignition, t_B is the duration of the first heat release peak in the Cone test, q_{ign} is the heat flux from the spreading flames to the unignited chair surfaces during fire growth, Φ is the lateral flame spread parameter normally measured in a LIFT apparatus (ASTM E-1321), l_B is a reference length, taken here as the width of the gas burner. The exponents on these dimensionless groups, α, β, etc., are determined, in principle, by matching this expression to experimental data.

It is highly desirable to simplify this, if possible, by using surrogate parameters that may be more readily available. A surrogate is a parameter that is in large measure proportional to the original. A surrogate for the numerator in the first group is the ignition delay time in the Cone test. A partial surrogate for q_{ign} is the heat of combustion which influences flame temperature. We also confine our interest to the value of the full-scale peak in heat release rate. Then the above becomes a dimensional proportionality:

$$Q_{peak} \sim t_{ign}^{a} t_{B}^{b} Q_{max}^{c} \Phi^{d} H_{comb}^{e} \ldots\ldots\ldots (2)$$

All of these parameters are available from the Cone Calorimeter except for Φ, the LIFT heat flux parameter. Since this parameter value was not available for the materials in this study, the fitting process between the full scale results and Equation (2) omitted this; if reasonable fits are still found without it, this implies that the role of this parameter is minor.

Since simplicity is clearly desirable and not all of the above parameters will necessarily have a substantial role to play in correlating full-scale data, one starts with a limited subset. The non-linear, least squares curve-fitting routine in the SigmaPlot* software package was used to evaluate the exponents and the proportionality constant in the above that makes it into a predictive equation. One seeks to minimize the norm which is the square root of the sum of the squared residuals (difference between a predicted and an actual point). This is a purely mathematical process. The exponent values which are generated tend to be closely coupled to each other and sensitive to noise in the data. Thus no physical significance should be assigned to the particular values which emerge.

When this approach is applied to the full data set obtained in the recent NIST study [4], the result is mixed; see Figure 1. All but two of the twenty-eight data points fall fairly close to the 45° line which indicates equality between predicted and measured full-scale heat release rate peak (during burner exposure). However, there is no evident reason to dismiss the two outlying points and they are non-conservative (the actual heat release peak is greater than that predicted).

If the correlation is limited to charring fabrics, clustering along the 45° line is much tighter suggesting that omission of ill-behaved thermoplastic fabrics could be beneficial to this form of correlation [4]. However, the number of charring fabrics in this data set was quite limited (seven points).

The recent textile industry study included twenty-two charring fabrics. Figure 2 shows the result of the best fit obtained with this data set; note that an additional surrogate parameter (from the Cone Calorimeter) is included here, the test average smoke extinction area. The estimated 95% (i.e., $\pm 2\sigma$) confidence limits are included on a typical data point on this graph to make it clear that there is significant inherent noise in both the correlation function and the measured full-scale peak heat release rate. Thus, one should not expect the points to fall much closer to the 45° line than they do in Fig. 2. This would thus seem to be a very good correlation. However, there is a worrisome element. The smoke extinction area was included in the correlation as a surrogate for the flame flux (instead of heat of combustion which gives a somewhat lesser degree of clustering on the 45° line) with the thought that soot concentration may be a controlling factor for a predominantly radiative heat flux. The exponent for this parameter is negative. Thus the implied role for soot is one of radiation attenuation, not enhancement. It is not possible to discern if this is a real effect or a peculiarity of the limited data available.

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*Certain commercial products are mentioned for clarity and completeness; this does not imply any endorsement by NIST nor does it imply that they are the best for this purpose.

Before looking at the correlation efforts made in the European Community furniture flammability study, it is of interest to look briefly at the heat release peak that often occurs after the gas burner exposure. When a barrier is present, as it was in the NIST and textile industry studies, this peak occurs after a lull of a few minutes or more. The NIST study found this peak to be a result of the ultimate failure of the barrier to protect the foam [4]. Failure occurred when a fire became established on the base of one or more cushions and transferred enough heat through the intact barrier to melt the foam out through the base of the cushion, thus assuring a continuing flow of fuel to the fire. No attempt was made to correlate the strength of the resulting heat release peak because the controlling parameters cannot yet be quantified. Some suggestions as to how to prevent such fires were made [4].

The furniture used in the EC CBUF program [5] was largely residential in character and thus most of it did not include a barrier between the fabric and the foam. The study involved open market and specially-constructed furniture, not mock-ups, as in the two studies above. In the absence of a barrier, furniture tends to give a single heat release peak occurring at times intermediate between the two peaks seen in furniture with a barrier. This single peak is typically much higher, often exceeding one megawatt.
Two types of effort were made in the EC study to relate Cone Calorimeter data to the observed full-scale fire data [5]. The first was a largely heuristic statistical correlation study. Two parameters were defined as follows:

$$x_1 = (m_{soft})^{1.25}\ (Style\ Factor)\ (Q_{max} + \overline{Q_{300}})^{0.7}\ (15 + t_{ign})^{-0.7} \ldots\ldots (3)$$

and

$$x_2 = 880 + 500\ (m_{soft})^{0.7}\ (Style\ Factor)\ (H_{comb}/q_{tot})^{1.4} \ldots\ldots (4)$$

Here m_{soft} is the readily flammable mass of the furniture item (essentially the fabric and foam mass); "Style Factor" is an empirical coefficient accounting for such things as the differences in mode of burning between a chair and a sofa made of the same materials; Q_{max} is the peak heat release rate in the Cone, at 35 kW/m^2 (as in Eqn.2 above); t_{ign} is the ignition delay time in the Cone at this same flux; H_{comb} is the test average effective heat of combustion in the Cone and q_{tot} is the total heat release from the sample in the Cone at 35 kW/m^2. Clearly, there are some parameters in common between the dimensional analysis approach used above and this heuristic approach. The predicted full-scale peak heat release rate from an item of furniture is a somewhat complex, conditional function of these two parameters [5].

The comparison of predicted and actual data from the CBUF study is shown in Fig.3. Note that the range goes from zero to 2 megawatts. The prediction is good to about ±200 kW for most test items in this series; it is conservative when outside this range. Such a correlation clearly is useful as a general guideline but it poses something of a problem for manufacturers trying to be assured of staying below some regulatory limit such as 400 kW. To be sure of success, they

must actually design the furniture so that this correlation predicts its behavior to be 200 kW less than the limit. This uncertainty could force the manufacturer to use more expensive materials (e.g., a barrier layer) when it is not really necessary.
Given that the CBUF correlation is based largely on furniture that did not include barriers, it is of interest to see if it predicts the behavior seen in the NIST study where barriers were used. Fig. 4 shows such a comparison where here, as in the CBUF study, the absolute peak is used for a given test, regardless of whether it occurred during or after the burner exposure. All points shown satisfy the CBUF criterion for "propagating fires" [5] though the open circles had very weak spread after the gas burner exposure. The comparison is marginal, at best, with the average real behavior being a significantly less intense fire than predicted.

This last result, coupled with the discussion above of worrisome aspects of the dimensional analysis approach, raises the question of whether these correlations are truly valid beyond the data set for which they were derived. This is an unresolved issue.

Finally, it is of interest to briefly describe a second approach to heat release prediction that arose from the CBUF study. The heat release rate from any spreading fire can be calculated, in principle, from the following integral.

$$q_{FS}(t) = \int_0^t (dA_B/dt')\, Q(t-t')\, \dot{m}(t-t')\, dt' \qquad (5)$$

Here the first term under the integral is the rate of growth of fire area. The product of the next two terms is the local heat release rate per unit area. The integral thus sums the heat release contributions from successively ignited areas up to the time of interest. To correctly use this expression, one needs to know the history of fire growth and the feedback flux from point-to-point in order to calculate the local heat release rate. In other words, one really needs a complete model of the fire growth process, then one can apply Eqn. (5) as a definition of the total heat release rate that the model predicts. In the absence of the necessary model, a more empirical approach was employed in the CBUF study. The heat release history from the Cone for a flux of 35 kW/m^2 was inserted into the right hand side of Eqn. (5) and the measured full-scale history was inserted on the left (for a series of times). The *effective* fire area as a function of time was thus inferred for a series of chairs of differing materials and constructions by a de-convolution process. For a given chair geometry, an average normalized effective area versus time function was deduced by averaging over results for several materials of construction. There are 100% deviations from the inferred average at some points in time. In spite of this and the fact that most of the real physical complications of the burning process are buried in the effective area function, the results work moderately well when used in a predictive mode. One plugs the area function back into Eqn. (5) along with the Cone data (at 35 kW/m^2) for a new combination of interest to predict the entire heat release history for a chair made from these materials. The predictions shown in Ref. 5 range from excellent agreement with actual measurements to mediocre agreement. Unfortunately, it is not entirely clear what causes this variability in the results though the behavior of the floor fire appears to be an element of it. It is worth noting that this approach is a hybrid of bench-scale and full-scale based prediction, requiring up to ten full-scale tests to characterize the area function for a given furniture style.

4. Conclusions

There have been significant advances in the quantification of the flammability of furniture, particularly its rate of heat release behavior. However, the ultimate goal of predicting full-scale heat release rate based on bench-scale measurements remains elusive. Modeling of fire growth from first principals appears impractical for the majority of furniture until the role of thermoplastic fabric and foam behavior is better quantified. The use of correlations to relate Cone Calorimeter and full scale data is moderately successful inasmuch as one can deduce such correlations by various approaches from a given data set. However, there have not been sufficient tests of these correlations against new data from other laboratories. There are hints that the correlations may not be very broadly useful. It seems probable that this approach has to be more narrowly limited in its scope. Thus, a correlation for charring fabrics over barriers in one limited set of chair geometries may work across laboratories but removal of the barrier would point to the need for a new empirical correlation for charring fabrics in this geometry. Excessive fragmentation of correlations for various situations could become unwieldy, of course, particularly if construction dimensions and details cannot be unified in some manner. Further study of the available data, especially that from the large CBUF program, is needed to clarify this situation.

5. References

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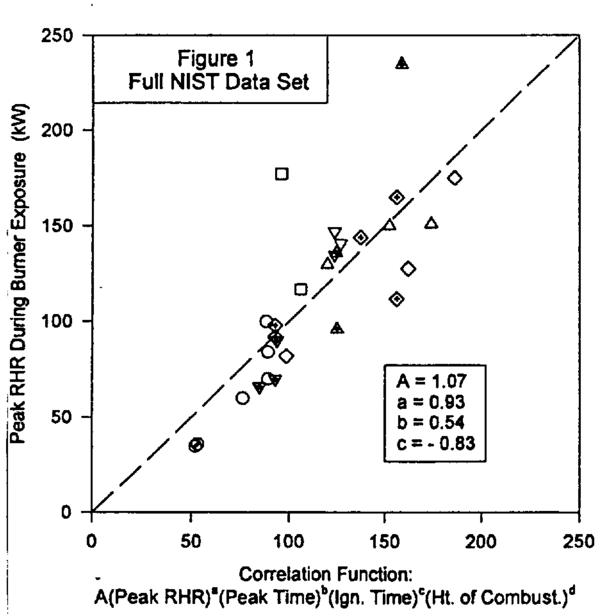
Figure 1
Full NIST Data Set
Peak RHR During Burner Exposure (kW)
Correlation Function:
A(Peak RHR)^a(Peak Time)^b(Ign. Time)^c(Ht. of Combust.)^d
A = 1.07
a = 0.93
b = 0.54
c = - 0.83

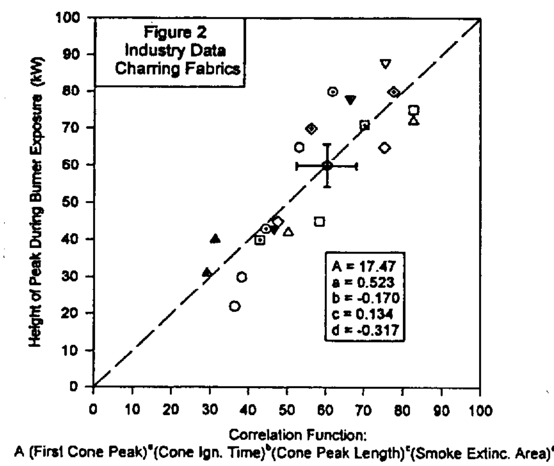
Figure 2
Industry Data
Charring Fabrics
Height of Peak During Burner Exposure (kW)
Correlation Function:
A (First Cone Peak)^a(Cone Ign. Time)^b(Cone Peak Length)^c(Smoke Extinc. Area)^d
A = 17.47
a = 0.523
b = -0.170
c = 0.134
d = -0.317

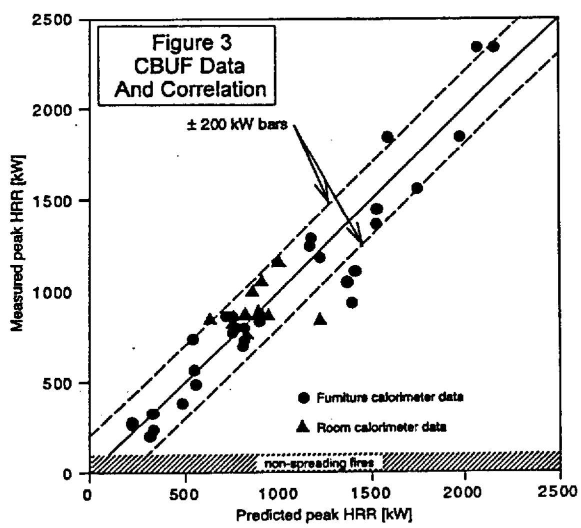
Figure 3
CBUF Data
And Correlation
± 200 kW bars
Measured peak HRR [kW]
Predicted peak HRR [kW]
Furniture calorimeter data
Room calorimeter data
non-spreading fires

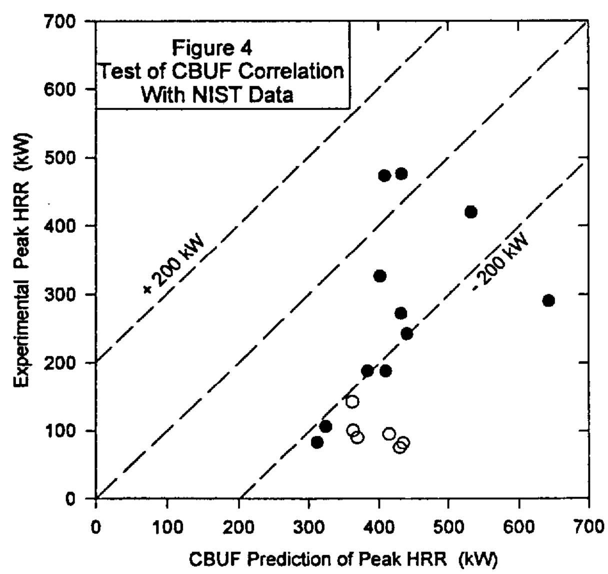
Figure 4
Test of CBUF Correlation
With NIST Data
+ 200 kW
- 200 kW
Experimental Peak HRR (kW)
CBUF Prediction of Peak HRR (kW)

Discussion

Yuji Hasemi: When we decided to move our institute from the city, there was an abundance of chairs left over, and we used those. If you just ignite a chair itself, it does not burn too much. However, if you add some heat to the chairs before ignition, then they burn very vigorously. Of course how to evaluate the flammability of chairs depends on the fire area. I think there are two different situations. One is ignition of the chairs so that the fire actually starts with the chair; another scenario is when a chair gets exposed to flames from other furniture in other parts of the room. I think they burn quite differently. It's quite natural to think about the first scenario where the chair itself ignites, but not consider the second situation.

Thomas Ohlemiller: First of all, there have a couple of studies done here with chairs igniting themselves, looking at the extent to which the heat release behavior depends on how the chair was ignited. They both showed that the heat release was essentially independent of how they were ignited, but the time at which the peak occurred shifted very much. So I would expect the chair behavior in the 133 test probably would be valid for reaction to fire types of concern.

Eiji Yanai: In Japan there are some chairs which have a fire treatment on them, and if there is no radiation, then they will not burn.

Thomas Ohlemiller: That is very dependent on how intense a fire there is. The chairs that I have been discussing do not need radiation to burn.