FLAME RETARDANTS AND HEAT RELEASE: REVIEW OF TRADITIONAL STUDIES ON PRODUCTS AND ON GROUPS OF POLYMERS

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SUMMARY

This is part of a project considering whether flame retardants affect polymer heat release, a critical issue to assess whether adding flame retardants decreases fire hazard. The work investigated the following. (1) Fire properties affecting fire hazard, confirming that heat release rate is the key fire property most strongly influencing fire hazard. (2) Ways to assess heat release and whether full scale fire heat release rate can be predicted from small scale test results, confirming that cone calorimeter and OSU data are adequate to predict full scale heat release. (3) Analysis of key 1988 NBS/NIST study comparing the fire hazard of flame retarded products versus non-flame retarded products for the same application. This confirmed that the study demonstrated that flame retardants lower fire hazard and that the levels of additives in the flame retarded products used were not excessive. (4) Review of studies investigating effects of flame retardants on various polymeric systems. The overall conclusion is that flame retardants do indeed improve fire safety (when used appropriately) primarily because they decrease heat release. Part 2 of the project (separately) considers the key polymers that need to be potentially flame retarded and reviews recent studies on effects of flame retardants on heat released by such polymers.

1. INTRODUCTION

Fire safety can be improved in one of two ways, or via a combination of both, as shown below. This work will address exclusively passive fire protection.

- Passive fire protection. This means using materials and products with superior fire performance so as to either minimize the probability of ignition or, if ignition does occur, minimize the damaging effects of the resulting fire.
- Active fire protection. This means relying on fire detection and suppression systems (such as smoke alarms and sprinklers). Fire detection systems alert the occupants (and/or first responders, such as fire fighters) while fire suppression systems extinguish the fire.

Flame retardants are materials that can be incorporated into combustible materials to improve their fire performance. It has been shown in many studies that flame retardants can be effective in having effects such as making materials or products less easily ignitable and/or reducing flame spread and they are extensively used to help materials and/or products meet certain fire test requirements. In view of the fact that there is no fire if ignition does not occur, a delay in ignition will improve fire

safety. However, since fire hazard assumes that ignition has occurred, it is important to also study the effects of flame retardants on fire hazard, with an emphasis on the key property of heat release, as explained below.

Fire risk is the combination of fire hazard and of the probability of fire occurring. Fire hazard is defined as "the potential for harm associated with fire". Fire risk is defined as "an estimation of expected fire loss that combines the potential for harm in various fire scenarios that can occur with the probabilities of occurrence of those scenarios". It is essential to understand that it is possible to have high fire hazard but low fire risk because the probability of such a fire is low.

Most, if not all, solid combustible materials (plastics, wood, textiles, rubbers and so on) are polymeric (meaning that they have a complex chemical structure, with repeating units). Many polymeric materials, whether natural or synthetic, have poor fire performance in the absence of added flame retardants. That is particularly important for those polymers that are in widest use, such as polyolefins (polyethylene or polypropylene), polyurethane, polystyrene, polyethylene terephthalate, nylon and cotton. When a polymer is used in applications where fire safety is an important consideration, the lack of intrinsic fire safety must be addressed for ensuring passive fire protection. The following are examples of different approaches.

- Adding flame retardants (i.e. using additive flame retardants)
- Creating new polymers with better fire performance though syntheses of variations of the polymer (i.e. using reactive flame retardants)
- Blending or otherwise compounding it with other polymers with better fire performance (i.e. creating blends or mixtures)
- Encapsulating the polymer or separating it from the potential exposure to the heat insult.

This study is looking primarily at the first aspect, namely additive flame retardants and fire hazard, mainly because more information is available on them. Information on direct comparisons of heat release between a flame retarded system with reactive flame retardants and the equivalent non-flame retarded materials is rarely published. Typical applications where fire safety can be critical are upholstered furniture, mattresses, wire and cable, interior finish, insulation, appliance and computer housings, among others.

This work presents information on a few key studies that investigated the potential effects of using flame retardants (whether additive or reactive) in order to improve the fire performance, with an emphasis on heat release, of polymeric materials. Such analyses will be primarily based on individual polymers. One portion of this study involves a new discussion of an essential study conducted at NBS (precursor of NIST) in 1988 analyzing the effects of flame retardants on the fire performance of five important consumer products: TV Cabinet housings, business machine housings, upholstered chairs, cable arrays and laminated circuit boards. This particular study has been misinterpreted recently.

A separate publication will review recent studies of heat released by individual polymers before and after the addition of flame retardants [1].

2. HEAT RELEASE RATE AND FIRE HAZARD

Until relatively recently, heat release rate measurements were seen by some people as just another piece of data to gather. In fact, the importance of heat release as a fundamental fire safety property is still not a full part of the public understanding of fire safety. However, fire scientists have now concluded that heat release is much more than a set of data. It has been shown by multiple analyses of fire hazard that heat release rate is the most important fire property and that the peak heat release rate is the numerical indicator of the intensity of a fire [2-8]. Key studies have demonstrated that heat release rate is much more critical than either ignitability (whether expressed as time to ignition or minimum heat flux for ignition) or smoke toxicity in affecting the probability of survival in a fire, as shown below in this work [2].

The key demonstration that heat release rate is much more important than other fire properties in terms of fire hazard can be seen from Table 1 [2]. In the work a simple analysis was made (using the fire hazard zone model HAZARD I) where the authors considered variations on a fire scenario in which a single upholstered chair burns in a small room with a single doorway opening. They calculated the hazard for the scenarios in terms of the predicted time to lethality. Fire properties of the burning chair in the base case were taken directly from typical such fire properties in the NIST data base. In order to assess the relative importance of several factors, the authors studied the following variations:

(1) Base case, i.e. a single burning chair in the room,
(2) The same chair with double the heat release rate,
(3) The same chair with double the smoke toxicity of the materials and
(4) The same chair with half the time to ignition for the burning chair (from 70 s to 35 s).

The authors considered the predicted temperatures and the levels of carbon dioxide in the compartment's upper layer. They chose carbon dioxide (instead of other gas species) since it has been shown that the carbon dioxide concentration is representative of the type and shape of the concentration-time curves for other gases. The results demonstrated that, as expected, changing the heat release rate has a much greater effect on fire hazard than changing the time to ignition or the smoke toxicity. The authors note that, of course, a significant improvement in time to ignition can lead to the absence of a fire; however that affects fire risk and not fire hazard, since fire hazard presupposes that ignition has occurred. The effects of the changes in the 3 variations from the base case can be seen in Table 1. The conclusions of this work is that doubling the heat release rate reduces the predicted time to lethality from greater than 600 s (the total simulation time) to about one third of that time, roughly the same time as the calculated time to incapacitation for all other scenarios. On the other hand, the effects of similar changes in time to ignition and in smoke toxicity have a negligible effect on predicted time to lethality. Note, that it is, of course, not always possible (or perhaps never possible) in practice to change one of the three variables (heat release rate, time to ignition and smoke toxic potency) completely independently, without affecting the others. However, that in no way affects the data analysis and conclusions.

In simpler terms, heat release rate is critical because, as the heat release rate becomes larger, more materials will ignite and burn and will propagate the fire. On the other hand, if heat release rate remains small, it is possible (or even likely) that the next product will not ignite and that the fire will be confined to the area (or even the object) of origin. Thus, a higher heat release rate will

promote faster flame spread. On the other hand, neither increased smoke obscuration nor increased smoke toxicity will cause a fire to become bigger.

It is essential to understand the concept that heat release rate if the most important fire safety property because a distinction needs to be made between: (a) the reason a fire becomes big and results in large losses (including fire fatalities, fire injuries and significant property loss) and (b) the actual "cause of death" for a fire fatality. The two are different.

In order to understand this it is important to review the concept of flashover, defined by the Life Safety Code as "A stage in the development of a contained fire in which all exposed surfaces reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space." In actual practice, fire statistics classify any fire that goes beyond the room of origin as a "flashover fire" [9], because typically additional details are not available and because a fire that has gone beyond the room of origin has clearly been a very large fire. Thus, it should be noted that, future descriptions in this work will talk about "flashover fires" when the fire is either known to have gone to flashover or known to have gone beyond the room of origin, without distinction. In the US the vast majority of fire fatalities occur away from the room of fire origin (i.e. have been classified as flashover fires because they extended beyond the room of origin [9]).

At the moment when fires go to flashover the concentration of combustion products (i.e. toxic gases) accelerates significantly, so that there is both a quantitative and a qualitative difference in the toxicity of the atmosphere as soon as the fire becomes a flashover fire. That is one of the key reasons why the toxicity of a fire atmosphere is much more toxic after flashover [7, 9].

On the other hand, the "cause of death" (in the US) is usually listed as "the effects of smoke inhalation". This means that the listed "cause of death" is, more often than not, the direct result of insult by smoke and toxic gases, while the actual cause of death is that the fire became large (typically a flashover fire) because the heat release rate was large. Thus, the size of the heat release rate is the best predictor of the fire hazard that caused a fire to become big. If a fire stays small (i.e. has a low heat release rate), it is unlikely to lead to significant numbers of fire fatalities. Thus, the relative toxicity of the gases emitted in fires (smoke emissions) plays a small role in fire hazard. For the reason indicated above the examples shown in this work will primarily address heat release.

In some publications it is stated that smoke toxicity is a measure of fire hazard: that is incorrect. The literature shows that the principal toxicant dominating smoke toxicity is carbon monoxide, found in all fires. In that connection, it is worth looking at toxic potency of smoke data, and Figure 1 illustrates that the toxic potency of the smoke of virtually all individual polymers is within such a narrow band (in toxicological terms) as to be almost indistinguishable [10]. In particular, this work showed that the smoke toxicity of all polymeric materials (including those releasing irritants) can be assessed together based on the lethal effective dose and that there is no need to introduce the flawed concept of fractional effective concentration (which assumes that victims are <u>instantly</u> incapacitated when a certain concentration of an irritant is reached). The latter concept is used by some toxicologists as a way to deal differently with polymeric materials containing heteroatoms, such as halogens or nitrogen. While academically potentially interesting, the technical literature and the practical reality of fires show that this is a flawed concept for predicting human survivability in fires. The work mentioned above [10] reviewed toxicity studies, including some done by exposure

of animals and people, in the late 19th century and early 20th century, to irritant gases alone or by their exposure to smoke containing them. The critical issue found was subject behavior, and whether incapacitation or lethality occurred eventually. It was found that rats and baboons were not incapacitated at huge concentrations of irritants (and in fact sometimes they died a long time after exposure, but they were able to perform the escape functions that they were taught to do, to escape from their exposure). Moreover, the volunteer humans were also neither incapacitated nor killed. This showed that irritants do not usually cause incapacitation, even at concentrations that may eventually kill the victims.

3. USE OF THE CONE CALORIMETER AS A FIRE HAZARD PREDICTIVE TOOL

The cone calorimeter is a specialized piece of fire test equipment that is used to assess heat release data, as well as ignitability, mass loss and smoke released by burning materials. There have been a large number of studies that have demonstrated that the cone calorimeter (ASTM E1354 [11]) can be successfully used for many products to predict full scale (or at least relatively large scale) fire performance of the corresponding products. The most widely studied products are wires and cables, upholstered furniture, mattresses, wall linings and aircraft panels.

The fire performance of wire and cable products is probably the one that has been investigated most extensively, usually in comparison with vertical cable tray tests, such as the UL 1685/CSA FT4 test [12-14]. One study looked at materials used in cable jackets and insulations, where a variety of different polymers were included. Tests were conducted in the cone calorimeter and in a vertical cable tray test [15]. The results showed that there is excellent correlation (Figure 2) between the cone calorimeter peak heat release rate (on the one hand) and tray cable heat release rate and tray cable char length (on the other hand). Tray cable char length was assessed because it is the typical property measured in tray cable tests. In particular, both ways (cable tray char length and cable tray heat release) of assessing the fire performance of the cables at a larger scale indicate the same trend. In fact, whichever way the data is analyzed there is a steady increase in cable tray heat release with cone calorimeter heat release at low heat release values and then a leveling off of cable tray heat release (which in the cable tray test is a result of the full consumption of the cables). Similar information was also obtained by another study [16], which focused exclusively on PVC-based cables. These two studies are part of a series of studies, summarized in subsequent work [17], that have established that the cone calorimeter is fully suitable as a predictive tool for electrical cables (see, for example, Figures 3 through 5). The figures show how predictions can be made from cone test results. This is important because it allows trends obtained in cone calorimeter tests to be indicative of trends in full scale fire tests with cables.

A similar type of prediction results from analyzing data from the cone calorimeter on tests of upholstered furniture composite tests [18]. The Association of Contract Textiles/Decorative Fabrics Association (ACT/DFA) study was intended to investigate whether the cone calorimeter could be used to predict CA TB 133/ASTM E1537 [19-20] data. They chose 26 upholstery fabrics, representative of the most widely used compositions and weights, and conducted cone calorimeter tests, at an initial test heat flux of 35 kW/m^2, with tests in the horizontal orientation. They also ran full scale ASTM E1537 tests, using the California room. The data was not analyzed directly by ACT/DFA but was analyzed later by a different author [18]. The samples were prepared as recommended by the Combustion Behaviour of Upholstered Furniture (CBUF) project of the European Union [21]. The fabrics (with a

very broad weight range) were all tested on a conventional slightly flame retarded polyurethane foam (complying with CA TB 117 [22]), weighing approximately 1.4 lb./ft^3, and an interliner, as well as on a highly flame retarded formulation containing high levels of melamine. The two interliners used were: a polyaramid weighing approximately 2 oz./yd^2 and a coated glass, weighing approximately 10 oz./yd^2. Soon after the ACT/DFA work was completed, NIST conducted a study with 27 fabric/barrier/foam systems that were tested in the cone calorimeter and in the CA TB 133/ASTM E1537 test [23]. The analysis of the ACT/DFA work [18] included consideration of the NIST results also.

The full scale testing for this furniture work was conducted using the standard mock-up cushions, constructed with thread recommended by the manufacturers of the interliners. There was no replication of full scale work. Several predictive equations and approaches to fire safety correlations were investigated, including one proposed by NIST when they compared work in two standard rooms (California and ASTM) [24]. The NIST equation [24] assumed that the key cut-off, when the full-scale construction is a standard mock-up, should be for systems with a 3 minute average cone calorimeter heat release rate of 160 kW/m^2; as shown below that value is too high. However, a system was proposed [18] that resulted in better predictions. With that system, in some cases the cone calorimeter erroneously labeled as unsafe systems (i.e. fabric/foam or fabric/barrier/foam combinations) which were found to be safe in full scale testing, but in no cases did the cone calorimeter predict satisfactory performance for systems which failed large scale tests. This was an improvement over the NIST recommendations [24]. When using the NIST suggestions, as expanded to more systems, eight systems (out of 27) were predicted to perform well (from cone calorimeter data) but actually had poor fire performance in the full scale test. Four of the eight systems incorrectly predicted contained melamine foam (which was only adequately predicted in two of six systems). In the case of one system that performed badly (although the cone data did not predict that) the repeat full-scale test performed well. The results are partially invalidated by the fact that plastic (nylon) zippers were used in several systems, a construction feature known to make systems perform badly. As a summary of this analysis, the cone calorimeter correctly predicted whether 67 of the 78 ACT-DFA systems would cause a self-propagating fire (86%), and whether 19 of the 27 NIST systems would cause a self-propagating fire (70%). If the melamine foam systems are excluded, the analysis predicted adequately 49 out of the 52 ACT-DFA systems (94%) and 16 out of the 20 NIST systems (80%). The threshold value estimated by NIST (a 3 minute average heat release rate of 160 kW/m^2) does not use the cone calorimeter as a direct predictor of full scale heat release rate, but rather as an indicator of the probability of a system to be made into a safe item of upholstered furniture. The results of this flawed "correlation" are shown in Figure 6.

Figure 7 indicates that there is a "safe zone" (based on heat release) for which furniture upholstery systems are likely to lead to safe constructions, within a reasonable probability.

The European study mentioned above (the CBUF project [21]) predicted that systems with average rate of heat release ≤ 65 kW/m^2 would not cause self-propagating fires; all 12 systems complying with that criterion in the ACT-DFA study gave good full-scale results. The conclusion from the ACT/DFA work was that the cone calorimeter could be used as a surrogate test method to assess whether systems are likely to cause a self-propagating fire, or whether they are safe. An important secondary finding was the realization that the fabric has a much greater effect in cone testing than in real-scale fires. The majority of predictive errors from the cone calorimeter are false positives, meaning materials that perform adequately in large scale tests are falsely predicted to fail by cone data; these errors do not negatively affect fire safety.

Similar work to the furniture work discussed above was also performed for mattresses [25], for a series of wall linings in Europe [26], and for a series of special wall linings, namely aircraft panels [27]. In the case of mattresses, the transition region in the cone calorimeter is still at roughly the same 3 min average value for heat release rate as for upholstered furniture: 100-200 kW/m^2 average (3 min).The corresponding equation is similar to that for upholstered furniture. However, experience has shown that bedding (such as sheets and blankets) can substantially affect heat release from mattresses, particularly when the actual mattress has fairly poor fire performance. Thus, in general, tests with mattresses and bedding are of particular interest for systems with fairly high heat release rate values. With regard to wall linings, it is interesting to note that the aircraft cabin wall lining data and actual room wall lining data (from a European project using the ISO 9705 room-corner test [28]) can both be correlated with a simple empirical equation, a first order approximation for relative time to flashover in a room-corner scenario. This information was generalized in a study that addressed several different products [29]. The predictive equation for relative time to flashover based on cone calorimeter data at an incident heat flux of 50 kW/m^2 suggests that time to flashover is proportional to the ratio of time to ignition to peak heat release rate, a ratio sometimes called the fire performance index or FPI [30]. An example using the aircraft panel and European wall lining data is shown in Figure 8 [29]. Figure 9 shows that the cone calorimeter can even be used to predict zones of flashover potential for wall and ceiling linings based on a fire model, such as the one by Karlsson [31] instead of a simple correlation like Figure 8.

It has also been shown that the computer model Conetools [32], developed at SP (in Sweden), serves as a useful means to predict ISO 9705 room-corner fire test results for wall linings from small scale fire test results in the cone calorimeter (e.g. [33]). Additionally, the work just cited and other scientific work also showed [33, 34] that the use of the cone calorimeter and Conetools can, in a preliminary fashion, help to predict results for wall linings in the European regulatory SBI test (single burning item test, EN 13823 [35]).

In conclusion, even from the limited amount of work discussed here, it is clear that the cone calorimeter can be used appropriately to assess fire performance of materials and products, and this will be done in subsequent sections.

4. OTHER SMALL SCALE HEAT RELEASE TESTS USEFUL AS PREDICTIVE TOOLS

The cone calorimeter (ASTM E1354 [11], ISO 5660 [36]) is a key tool for small scale testing of materials, composites, and products to assess heat release rate. However it is not the only such test and two other key small scale tests can be used to test materials for heat release: the Ohio State University heat release rate calorimeter (Smith [37], ASTM E906 [38], FAA Aircraft Materials Fire Test Handbook Chapter 5 [39]) and the FM Fire Propagation Apparatus (Tewarson [40],ASTM E2058 [41], FM FPA). In this study, some OSU work will be discussed here but no specific FM FPA work.

In the past, a large number of fire tests or techniques have been used, and many are still being used, to measure various individual properties associated with the fire performance of materials (and sometimes products). The measurement of single properties is inconsistent with the concept of fire hazard, since fire hazard is associated with the combination of a multitude of fire

properties, including the ignitability of a material, its flammability, the amount of heat released from it when it burns, the rate at which this heat is released, the rate at which the material is consumed, the smoke production tendency and the intrinsic toxic potency of the smoke. In 1972 Edwin Smith published detailed information on one test method (Ohio State University heat release rate apparatus; OSU) that is capable of measuring combined properties including heat release [37]. Such combined properties are thus more directly associated with fire hazard than any individual fire property. Hirschler and Smith [42] correlated data from the OSU with data from a full scale non-standard room-corner test (see Table 2), showing a reasonable degree of predictability from the test, in that materials showing high heat release in the OSU also show high heat release in the room and vice versa.

In much more extensive (and predictive) studies, the OSU was used by the Federal Aviation Administration (FAA) in order to correlate material (and composite) data with data from full aircraft burns [43]. The FAA established a four part research program to define how heat release criteria would provide appropriate safety guidance. The concept was to see whether this could then be incorporated into regulations to ensure fire safety. Using time to flashover as the primary end-point, the FAA work established a full-scale aircraft post-crash scenario to evaluate and "rank" the fire performance of the aircraft interior materials, while monitoring all major fire properties [44]. Then the FAA evaluated and "ranked" a group of five representative generic cabin interior wall panel constructions in the full scale aircraft fire test scenario [45]. Subsequently, the FAA established a series of input conditions and pass/fail criteria using the OSU test to obtain results that could be used to "rank" the five materials in the same order as they were ranked by the full scale tests [46]. Finally NIST and FM Global were commissioned to investigate whether the cone calorimeter (at NIST) and the FPA apparatus (at FM Global) would give reasonably correlated results: they gave the same type of rankings as the OSU, even if they gave different absolute numbers. The result of this work was the development of pass/fail criteria of 65 kW/m^2 peak heat release rate and 65 kW min/m^2 average total heat released after 2 minutes of test in a 5 minute test in the OSU, at an incident heat flux of 35 kW/m^2. This reliance on heat release rate has proven to be extremely effective and a July 2013 post-crash aircraft fire is an example of its effectiveness: an Asiana jet crashed in San Francisco airport with 307 people on board and no fire fatalities (although 3 passengers died of other injuries [47]).

5. NBS/NIST FULL SCALE STUDIES ON FLAME RETARDED PRODUCTS

Much of the research on flame retarded materials has focused on individual materials or on products that contain them. The potential synergy between flame retarded materials in a room-fire scenario is less well documented. In other words the question is: does individual product protection add up to a greater protection in a room containing several disparate product types? In an attempt to document and understand this, NIST (then NBS) conducted a study in 1988 [48]. This seminal study went beyond just investigating the effects of flame retardants on improved fire safety for individual materials and products, but looked at a full set of flame retarded materials, their use in products and a comparison with the corresponding non flame retarded materials.

The study involved five different product categories, which were assembled and tested in small-scale and in full-scale room fires. In one set of products, all five products were made with flame retarded materials, whereas in the other set, the same base polymers were used, but without

flame retardant additives. The products involved were (in the order in the report): (a) television housings, (b) business machine housings, (c) upholstered chairs, (d) electric cable arrays, and (e) laminated electronic circuit boards. These products were studied thoroughly in full-scale fires, in bench-scale fire tests, and by computer modeling.

The objective of this study was to investigate the fire hazard of a wide array of flame retardant containing products (FR) relative to non-flame retarded (NFR) but otherwise substantially identical products. The question to be answered was whether the fire hazard is reduced. The flame retarded formulations were chosen, in accordance with the report, to represent ones which are (or were, at the time) commercially available and in common use, but which were anticipated to represent high quality performance. None of the systems was designed to provide exceptional fire performance.

In this publication it was believed essential to retain, as much as possible, the language from the original NBS/NIST publication, from 1988, demonstrating that the systems were designed to provide adequate fire performance, within the state-of-art of the time. The executive summary states as follows: "the two central issues to be explored were:
"(1) For today's most commonly used FR/polymer systems, is the overall fire hazard reduced, when compared to similar non-fire retarded (NFR) items?
"(2) Since both the commercially popular FR chemicals and the base polymer formulations can be expected to change in the future, can appropriate bench-scale test methodologies be validated which would allow future testing to be quick and simple?"

The executive summary continues with the following statement regarding approach. "To answer these questions, a wide-ranging experimental program was formulated. Five representatives of commonly-used plastic products were especially manufactured (using commercial formulations) for this program, each in an NFR and an FR version." Note that the approach addressed "commonly-used plastic products" and "commercial formulations" and that there was no intent to meet any specific regulatory requirement.

The formulations used were:

(a) TV cabinet housing: High impact polystyrene in both sets. The FR System was composed of 12% of a brominated material (decabromobiphenyl oxide) and 4% antimony oxide
(b) Business machine housing: Polyphenylene oxide in both sets. The FR System was composed of triaryl phosphate ester for 1% P
(c) Upholstered chair: Flexible polyurethane foam padding and the same nylon cover fabric (250 kg/m^2) for both sets. The non FR foam had a density of 25 kg/m^3 and the FR system contained an organic chlorinated phosphate, an organic brominated flame retardant and 35% alumina trihydrate, for a content of 4.75% Br, 2.6% Cl, 0.32% P and 10.0% Al and a density of 64 kg/m^3. The FR system was intended to perform better than foam intended for CA TB 117 use, but was probably not as good as a BS 5852 crib # 5 foam.
(d) Cable array: Each electric cable contained five conductors (copper wires, 14 AWG, 1.63 mm diameter) with insulated wire outside diameter of 3.30 mm. The outside diameter of the jacketed cable was 12.7 mm. The same wire jacket was used in both sets and it was a black chlorosulphonated polyethylene containing antimony oxide (12.2% Cl and 2% Sb). The insulation of the non FR system was cross-linked ethylene vinyl acetate copolymer (EVA) with clay (18.9 phr), antioxidant (2 phr), processing aid (1 phr) and catalyst (1.5 phr). The

FR system was cross-linked ethylene vinyl acetate copolymer (EVA) with clay (28 phr), chlorinated cycloaliphatic flame retardant (38 phr), antimony oxide (18.9 phr), antioxidant (2 phr), processing aid (1 phr) and catalyst (1.5 phr). The FR system was probably intended to represent a vertical tray cable composition. It would not have complied with riser of plenum cable requirements.

(e) Laminated circuit board: This material was intended to represent glass/polyester electric circuit boards but contained no copper or electrical components. The board was 6.4 mm thick. The polymer in both systems was polyester resin. The non FR system contained 38 wt% polyester, 44 wt% calcium carbonate and 18 wt% fiberglass reinforcement. The FR system contained 39 wt% polyester, decabromobiphenyl oxide (10 wt%), antimony oxide (3 wt%) and alumina trihydrate (30 wt%) and 18 wt% fiberglass reinforcement. It was probably intended to represent a UL 94 V0 compound.

Tables 3 and 4 contain the cone calorimeter data for the various products at 2 different incident heat fluxes. Clearly, flame retardants had a significant effect on heat release rate and effective heat of combustion. Furniture calorimeter tests (i.e. tests in which the product is placed on a load cell under a hood and the heat and smoke released are assessed) were conducted on all products. A natural gas burner with a nominal face of 180 mm x 150 mm and operating at 50 kW for 200 s was used for most tests, except for the cable products, in which case a line burner 0.36 m long with the same flow of natural gas was used. Table 5 shows the furniture calorimeter data. Once more, the improvement due to the flame retardants is very significant.

In order to analyze the data for all products together, the full set of NFR products were set in an array as shown in Figure 10, and in a room-corridor arrangement as shown in Figure 11. The small scale and furniture scale calorimeter data (Table 5) predicted that the chair would ignite with the small 50 kW burner (on for 200 s) and then spread flame to get the other items ignited. When the same data was used for the FR products, the furniture calorimeter information showed that if the same array was used as used for the NFR products, only the TV cabinet and the chair would ignite and the heat release/flame spread would originate virtually mainly from the burner and the TV, and would give very low mass loss rate and would not contribute significantly to the fire buildup. Thus, it became clear to NBS/NIST that the array used for the NFR products would not be suitable to burn the FR products and that an auxiliary burner (120 kW, on for 2100 s, starting 300 s before the ignition of the 50 kW burner) would need to be used to avoid finding no flame propagation at all. Therefore, the arrangements shown in Figures 12 and 13 were used. The summary of the key data from the two sets of burns are shown in Table 6.

With regard to smoke toxicity, the executive summary states: “The results showed that none of the test specimens produced smoke of extreme toxicity. The smoke from both the FR and NFR products was similar in potency and comparable to the potency of the smoke produced by materials commonly found in buildings.”

With regard to overall fire hazard the executive summary states: “The impact of FR materials on the survivability of the building occupants was assessed in two ways: (1) Comparing the time to untenability in the burn room; this is applicable to the occupants of the burn room. (2) Comparing the total production of heat, toxic gases, and smoke from the fire; this is applicable to occupants of the building remote from the room of fire origin”. It continues: “For the FR tests, the average

available escape time was more than 15-fold greater than for the occupants of the NFR room. With regard to the production of combustion products,

- "The amount of material consumed in the fire for the FR tests was less than half the amount lost in the NFR tests.
- "The FR tests indicated an amount of heat released from the fire which was ¼ that released by the NFR tests.
- "The total quantities of toxic gases produced in the room fire tests, expressed in 'CO equivalents,' were ⅓ for the FR products, compared to the NFR ones.
- "The production of smoke was not significantly different between the room fire tests using NFR products and those with FR products.

"Thus, in these tests, the fire retardant additives did decrease the overall hazard of their host products."

In summary, the study showed that the proper selection of flame retardants can improve fire and life safety by significantly lowering heat release, toxic product release and mass loss, while dramatically increasing time available for escape or rescue. In summary the FR products are associated with a much lower fire hazard. Moreover, the ignition sources needed to cause FR products to burn are much larger than those for non FR products, if the products have been properly flame retarded. The authors noted that it is possible to develop flame retarded products that are not effective in lowering fire hazard because they are either ineffective systems or are being added at insufficient levels.

An interesting subsequent analysis of the NBS/NIST test data [49] found that the flame retardants added (many of which were brominated materials) did not just have an "overall positive effect" from the point of view of fire hazard (over the non-flame-retarded products), something which has been demonstrated statistically, but that there is no evidence that the flame retardants adversely affected *any aspect* of fire hazard.

The NBS/NIST work was also analyzed soon after its completion by two of the authors [2] for the identification of the most important physical variable in the tests which is a predictor of the resulting fire hazard. They found that a key conclusion of the work was that the heat release rate was that variable and that it was much more predictive than time to ignition and toxicity of the difference in hazard. This brings this present work full circle, to the analysis shown at the beginning of the paper.

6. EFFECTS ON SMOKE RELEASE

This subject will be addressed very briefly. A study was made looking at five series of studies of room-corner tests in which heat and smoke release was assessed [8]. The analysis of these five series of full scale room-corner tests in which heat and smoke release was measured showed that, in most cases, when heat release is low (as represented in Table 7 by the "materials with adequate heat and low smoke") the material or product will generate low heat and low smoke. On the opposite end of the scale, there are materials reaching early flashover and they will often release very high smoke. In between those two cases can be found some 10% of materials or products that release adequate (or low) heat but high smoke. This is the basis for data analyses that developed properties known as "smoke parameter" or "smoke factor" that combine heat release rate data and smoke obscuration data so as to give a better understanding of the type of smoke obscuration to be

expected in real fires or in large scale tests) as opposed to the (often misleading) data obtained from small scale tests. The consequence of this is that smoke release needs to be considered to identify those few cases where high smoke is associated with low heat. In general, however, as flame retardants tend to lower heat release (as shown above) they will either have minimal effect on full scale smoke release or decrease such smoke release. This is important for the present analysis to highlight the positive effect of flame retardants.

7. MAJOR CONE CALORIMETER STUDIES OF INDIVIDUAL AND GROUPS OF FLAME RETARDED MATERIALS

In one study, 35 materials were investigated with the cone calorimeter at 3 incident heat fluxes (20, 40 and 70 kW/m^2) [4]. In that study, several of the materials tested represented flame retarded and non-flame retarded versions of the same polymers for similar types of applications. In some cases there is more than one flame retarded version. In Table 8 is shown the peak heat release rate of a flame retarded and a non-flame retarded version and the ratio between the two. In each case the peak heat release rate is significantly decreased by the flame retardant system, in some cases by an order of magnitude. Some information on the materials tested is shown in the notes to the table. In Table 9 are shown some other materials (for which less detailed information is available) [50, 51], tested either in the cone calorimeter or in the Ohio State University calorimeter (ASTM E906 [52]). Some additional materials, also tested in the cone calorimeter, were also added [53]. The conclusions are similar to those for the results in Table 8. Another comprehensive study looked at a large number of different polymers and at the effects of flame retardants on all of them [54]; there is too much information in the study to summarize it here, other than to indicate that flame retardants lowered heat release for all polymers studied.

When investigating flexible polyurethane foam, which is widely used for upholstered furniture, one study [5] looked at the effects of incorporating flame retardants into polyurethane foam on the cone calorimeter, and some results are shown in Table 10. The effectiveness (to some extent) of adding flame retardants to achieve compliance with the traditional open flame test in CA TB 117 [22] is weak but clear. However, much better improvements can be found with additional levels of flame retardants. The importance of choosing the right level of flame retardant additives is exemplified by a recent unpublished cone calorimetric study of two foams [55] with a small amount of flame retardant added, in order to comply with the widely criticized FMVSS 302 [56] test used for foams (and other plastics) inside automobiles. The study showed that the foams treated purely to meet FMVSS 302 and the untreated foams exhibited virtually no difference in heat release (Figure 14). The effect of adding enough flame retardants to polyurethane foam simply to meet CA TB 117 has some effect, albeit not very large, on heat release. However, results from a US National Institute of Justice (NIJ) research study on estimations of the burning rates of upholstered furniture [57], show something that had not been identified earlier. When polyurethane foam is treated with flame retardants to achieve CA TB 117 level and the foam is used in conjunction with a flame retarded fabric (the study used a cotton fabric that met the requirements of NFPA 701 [58]), the effect on heat release is very significant, while it is much less significant when used with a very flammable fabric (compare Figures 15 and 16, both showing cone calorimeter data) [59]. The same work also expanded the work by conducting full scale tests. Figure 17 shows the effect of using CA TB 117 foam as compared to non FR foam with an FR cotton fabric on a one seat sofa ignited in the seat by

the ASTM E1537 square burner [60]. The figure shows that the system with the flame retarded foam and the flame retarded fabric has such a significant effect on heat release that there is virtually no fire from the sofa after ignition. For comparison, Figure 18 shows that, if neither the foam nor the fabric is flame retarded, the sofa releases abundant heat and results in a significant fire and flashover, while a sofa with non FR cotton and CA TB 117 foam gave off much less (but still too much) heat. Note that this particular study was done using two seat sofas in a very large room. The effect on heat release of adding flame retardants to the foam is clearly noticeable but is less pronounced than it is in the presence of a flame retarded fabric.

Another study investigated polyurethane foam in the cone calorimeter (at an incident heat flux of 25 kW/m^2) and in the British Standard BS 5852 [61], using various wood cribs, ranging from # 4 (smallest, 8.5 g), through # 5 (17.0 g) up to # 7 (largest, 126 g) [62]. It showed that well flame retarded polyurethane foam (using, in this case, melamine flame retardants) could resist very severe ignition sources and, even if ignited, would generate low heat release and perform very well in mock-up furniture tests. The study used 2 foams (one without flame retardants and one that met BS 5852 crib # 5). Some cone calorimeter results, together with the pass/fail results according to BS 5852, are shown in Table 11. It was of interest that one of the fabrics (polyolefin) was so poor that it would fail the BS 5852 test with both foams while one of the fabrics was so good that even the non-flame retarded foam passed the BS 5852 test with the largest wood crib.

One type of materials needs to be considered separately: those are foam plastic insulation materials. It is often difficult to conduct a proper fire test with these materials, especially those that are melting materials, such as polystyrene foam. In the US, these materials are usually assessed for code use by means of the Steiner tunnel (ASTM E84 [63]), while in the European Union they are being assessed primarily by means of the Euroclass testing system, via the SBI (single burning item) test (EN 13823 [35]) or by the ignition test (ISO 11925-1 [64]). With both systems, the flame retarded polystyrene foam significantly outperforms the foam that is not flame retarded. In the ASTM E84 test, flame retarded foam typically exhibits a flame spread index (FSI) in the range of 20-70 and a smoke developed index (SDI) of less than 450 (code requirements are for an FSI less of than 75 and an SDI of less than 450). On the other hand, if the foam is not flame retarded it inevitably fails the requirements. In the EU, flame retarded extruded or expanded polystyrene will normally result in a Euroclass ranging from B (rarely) to E (depending on the level of flame retardants added), while a non flame retarded foam will almost always result in a fail (i.e. Euroclass F) [65].

A comprehensive study of the flammability characteristics of foam plastics at NIST [66] was designed to try to obtain a test method for foam plastics that is a suitable alternative to the Steiner Tunnel Test as a measure of flammability for foamed plastic. The work investigated test apparatuses such as the cone calorimeter and the lateral ignition and flame spread test apparatus (LIFT, ASTM E1321, [67]) and the authors were attempting to more completely characterize foamed plastic flammability. Key flammability properties were obtained from these apparatuses to describe ignitability, flame spread rate, heat release rate, and smoke obscuration. An extensive data set of these flammability properties for 10 selected foamed plastics was generated. The tested materials included melting foams (polystyrene foams) and charring foams (polyurethanes, polyisocyanurate and phenolic foams). The problems due to the effects of melting and dripping were limited by testing the materials in the horizontal orientation. In addition, an integrated approach to material

flammability characterization was presented that uses these parameters to predict fire growth potential. The results were somewhat disappointing in that no test apparatus was identified that would assess the materials appropriately. The authors developed variations of both the cone calorimeter and the LIFT but they were still unsatisfactory and they recommended that modeling work be used. However, this does not affect the conclusions from the actual tests conducted, namely that flame retarded foam plastics outperform non-flame retarded ones.

Important work on television sets, which are emblematic of other appliances, was primarily conducted by Jürgen Troitzsch [68-69], who was able to shown that non-flame retarded television sets, such as those commonly used in Europe, can quickly take a room to flashover. The main full scale fire test was carried out with a TV set purchased in Germany, with a 20 x 20 mm hole cut in the lateral right front side of the back plate adjacent to the housing, where flame originating from a solid fuel pellet (0.15 g, 40-55 W, 5-10 mm flame) was applied. After ignition, the solid fuel pellet flame impinged on the back plate on top of it and later on the edge of the housing, simulating an external and internal low intensity ignition source. After just 24 s following pellet ignition the TV back plate began to burn and after 4.5 min a pre-flashover situation developed in the room, with full flashover at 7 min, when all the furniture started burning, with big flames and high temperatures. The fire safety requirements for the cabinet of that TV set was no more than the horizontal (HB) version of the UL 94 test [70]. In contrast, TV sets purchased in the US and in Japan, where the cabinets had to be flame retarded in order to meet the vertical requirements of the UL 94 test (Class UL 94 V2, V1, V0 or 5V), either did not ignite or extinguished quickly when exposed to ignition sources as high as 200 mL of isopropanol or cloth soaked in isopropanol (representing up to 40 kW insults).

A separate study by Margaret Simonson on TV sets showed the vital benefit (for fire safety and environmental issues) found in life cycle analyses of flame retarded products versus non flame retarded products conducted at SP in Sweden [71]. Similar studies followed later also on upholstered furniture [72] and on cables [73], also at SP.

8. DISCUSSION AND CONCLUSIONS

A recent study found, based on much of the same data reviewed here, that the addition of flame retardants improves fire safety in a variety of ways, but with particular emphasis on the fact that it increases time available for escape and rescue [74]. A 1999 publication [45] looked specifically at the NBS/NIST work discussed in depth in the first part of this study, and concluded that the addition of flame retardants had a positive effect on not just the overall time available for escape but also on the smoke toxicity of the fire atmospheres. The author stated: “there is no evidence that [the flame retardants] adversely affect any aspect of fire hazard. Because they reduce ignitability they reduce flame spread, because they reduce flame spread they reduce the fire's burning rate; because they reduce the burning rate they reduce the quantity of smoke the fire produces.”

Another study investigated the safety, health and environmental aspects of flame retardants [75] and concluded that “this survey shows that the appropriate use of flame retardants, as a class, effectively provides improved fire safety via lowering the probability of ignition, the heat released and the amounts of smoke, combustion products and dangerous environmental

toxicants. In consequence the use of flame retardants increases the available time for escape from a fire." Much of the work in this specific study was based on earlier work [76] that received insufficient analysis.

In this work, the investigation of the importance of heat release rate in fire hazard, the investigation of the use of small scale heat release tests for predictions of real scale heat release information and the in-depth analysis of the NBS/NIST work are all based on the best fire safety science.

In summary, this work demonstrates the following:

1. Heat release (and particularly heat release rate) is the most important property associated with fire hazard and fire safety.
2. The NBS/NIST work of 1988 demonstrated that flame retardants (as used in 5 products) decreased heat release and significantly increased time available for escape and rescue from a fire and fire safety.
3. Cone calorimeter (and OSU calorimeter) data on small scale samples can be used to measure heat release rate and to predict the results of fires in full scale with many materials and products.
4. Flame retardants, when added as appropriately researched systems, will decrease heat release rate by well beyond statistical deviations for the polymeric materials studied, which represent most of those where fire safety is a potential concern.

In conclusion, this work demonstrates that the correct use of flame retardants (by using efficient systems, designed for the substrate, at sufficient levels) will decrease heat release rate and thus have a very positive effect on fire safety.

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Table 1 – Effect of Individual Variables on Fire Hazard – Example of Chair [2]	
Scenario	Predicted time to lethality
Base case	Greater than 600 s
Double heat release rate	180 s
Double material smoke toxicity	Greater than 600 s
Halve time to ignition	Greater than 600 s

Table 2 – Comparison of Heat Release in OSU and Room Corner Test [42]				
	Pk HRR OSU	THR OSU @ 10 min	OSU Heat Flux	THR Full
	kW/m^2	MJ/m^2	kW/m^2	MJ
Natural wood oak panel	74	24.8	30	90
Natural wood oak panel	121	30.2	41	90
FR ABS	112	13.6	30	70
FR ABS	264	29.9	41	70
Polycarbonate	211	31.2	30	134
Polycarbonate	434	102.2	41	134
FR Acrylic	37	9.2	30	37
FR Acrylic	52	17.9	41	37
Generic PVC	96	21.4	30	30
Generic PVC	109	24.8	45	30
Low smoke PVC	23	6.9	30	30
Low smoke PVC	70	29.3	45	30
CPVC	20	6.3	30	28
CPVC	20	6.3	41	28
Full scale ignition source				*33*

Notes: Pk HRR OSU: peak heat release rate from Ohio State University (ASTM E906) heat release test; THR OSU: total heat released during Ohio State University heat release test; THR Full: total heat released during full scale room corner test.

Table 3 – Cone calorimeter data of NBS/NIST Products (30 kW/m^2 Heat Flux) [48]			
Material	FR or NFR	Pk HRR (kW/m^2)	Effective Heat Combustion (MJ/kg)
TV Cabinet	NFR	970	30
TV Cabinet	FR	340	12
Bus. Machine	NFR	650	30
Bus. Machine	FR	280	21
Chair (fabric/foam)	NFR	470	27
Chair (fabric/foam)	FR	290	18
Chair (foam only)	NFR	540	27
Chair (foam only)	FR	180	15
Cable (jacket/insulation)	NFR	360	28
Cable (jacket/insulation)	FR	380	23
Cable (jacket)		270	23
Cable (jacket)		280	23
Cable (insulation)	NFR	740	39
Cable (insulation)	FR	260	23
Circuit Board	NFR	250	21
Circuit Board	FR	100	13

Notes: Pk HRR: peak heat release rate from cone calorimeter heat release test; NFR: non-flame retarded product; FR: flame retarded product.

Table 4 – Cone calorimeter data of NBS/NIST Products (100 kW/m^2 Heat Flux) [48]			
Material	FR or NFR	Pk HRR (kW/m^2)	Effective Heat Combustion (MJ/kg)
TV Cabinet	NFR	1400	29
TV Cabinet	FR	480	10
Bus. Machine	NFR	1100	29
Bus. Machine	FR	570	20
Chair (fabric/foam)	NFR	1460	28
Chair (fabric/foam)	FR	760	18
Chair (foam only)	NFR	1580	29
Chair (foam only)	FR	310	14
Cable (jacket/insulation)	NFR	550	26
Cable (jacket/insulation)	FR	380	21
Cable (insulation)	NFR	1280	38
Cable (insulation)	FR	490	21
Circuit Board	NFR	250	18
Circuit Board	FR	147	14

Notes: Pk HRR: peak heat release rate from cone calorimeter heat release test; NFR: non-flame retarded product; FR: flame retarded product.

Table 5 – Furniture calorimeter data of NBS/NIST Products [48]			
Material	FR or NFR	Pk HRR (kW)	Effective Heat Combustion (MJ/kg)
TV Cabinet	NFR	515	23
TV Cabinet	FR	180	20
TV Cabinet	FR	175	20
Bus. Machine	NFR	560	24
Bus. Machine	FR	380	28
Chair (fabric/foam)	NFR	1160	26
Chair (fabric/foam)	NFR	1205	27
Chair (fabric/foam)	FR	50	No data (too low)
Cable (vertical)	NFR	400	41
Cable (vertical)	FR	75	No data (too low)
Cable (jacket, vertical)		140	34
Cable (Z configuration)	NFR	245	35
Cable (Z configuration)	FR	130	34
Circuit Board	NFR	205	18
Circuit Board	FR	100	No data (too low)

Notes: Pk HRR: peak heat release rate from furniture calorimeter full scale heat release test; NFR: non-flame retarded product; FR: flame retarded product.

Table 6 – Summary of Full Scale Results in NBS/NIST Tests [48]			
	NFR Array	**FR Array**	**Comparison**
Available escape time	113 s	1789 s	15.8 fold longer time to escape from FR
Total heat released	750 MJ	200 MJ	3.5-4.0 fold heat released by NFR
Smoke released	(overall)		No significant difference between systems
Toxic gas production	(as CO equivalent)		3 fold less toxicity from FR
Mass Loss	(based on initial mass)		Less than half the amount lost from FR
Auxiliary burner	Did not affect NFR Products		No Burning of FR Products Without It
Predicted Heat Release	1,640 kW	345 kW	4-5 fold higher heat release rate for NRF

Notes: NFR array: array of non-flame retarded products; FR array: array of flame retarded products.

Table 7 – Full Scale Room Corner Tests Measuring Heat and Smoke [8]				
Room-Corner Test Series	**Materials Reaching Early Flashover**	**Materials With Adequate Heat and Low Smoke**	**Materials With Adequate Heat and High Smoke**	**# Materials Tested**
SwRI	1	8	1	10
EUREFIC	14	12	2	28
SBI	12	15	3	30
Coast Guard	3	5	1	9
BFGoodrich	1	5	1	7
Overall	31	45	8	84

Table 8 – Effect of Flame Retardants on Cone Calorimeter Peak Heat Release Rate [4]				
Material	**Heat Flux**	**Pk HRR Non FR**	**Pk HRR FR**	**Ratio of HRR**
	kW/m^2	kW/m^2	kW/m^2	-
ABS (+ FR1)	20	614	224	2.7
ABS (+ FR1)	40	944	402	2.3
ABS (+ FR1)	70	1311	409	3.2
ABS (+ FR2)	20	614	224	2.7
ABS (+ FR2)	40	944	291	3.2
ABS (+ FR2)	70	1311	419	3.1
PE	20	913	88	10.3
PE	40	1408	192	7.3
PE	70	2735	268	10.2
PVC Rigid	20	102	25	4
PVC Rigid	40	183	84	2.2
PVC Rigid	70	190	93	2.1
PVC Wire & Cable	20	116	9	12.8
PVC Wire & Cable	40	167	64	2.6
PVC Wire & Cable	70	232	100	2.3
PVC Wire & Cable # 2	20	116	72	1.6
PVC Wire & Cable # 2	40	167	92	1.8
PVC Wire & Cable # 2	70	232	134	1.7
Polystyrene	20	723	277	2.6
Polystyrene	40	1101	334	3.3
Polystyrene	70	1555	445	3.5

Notes: ABS non FR: Cycolac CTB acrylonitrile butadiene styrene terpolymer (Borg Warner), ABS/FR1: Cycolac KJT acrylonitrile butadiene styrene terpolymer flame retarded with bromine compounds (Borg Warner), ABS/FR2: Polymeric system containing ABS and some PVC as additive; LDPE: Polyethylene (Marlex HXM 50100), LDPE/FR Black non-halogen flame retardant, irradiation cross-linkable, polyethylene copolymer cable jacket compound (DEQD-1388, Union Carbide); PVC rigid: Poly(vinyl chloride) rigid weatherable extrusion compound with minimal additives (BFGoodrich); PVC rigid FR: Chlorinated PVC sheet compound (BFGoodrich); PVC wire & cable: Flexible wire and cable PVC compound (non-flame retarded) (BFGoodrich), PVC wire & cable/FR 1: Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of a family of VTE alloys (BFGoodrich); PVC wire & Cable/FR 2: Flexible wire and cable poly(vinyl chloride) compound (containing flame retardants) (BFGoodrich); Polystyrene crystal, Huntsman 333 (Huntsman); FR: Flame retarded polystyrene crystal, Huntsman 351 (Huntsman). Pk HRR Non FR: peak heat release rate in cone calorimeter test for non-flame retarded materials; Pk HRR FR: peak heat release rate in cone calorimeter test for flame retarded materials; Ratio of HRR: ratio between Pk HRR Non FR and Pk HRR FR.

Table 9 – Effect of Flame Retardants on Cone Calorimeter or Ohio State University Calorimeter Peak Heat Release Rate [50, 51, 53]				
Material	**Heat Flux**	**Pk HRR Non FR**	**Pk HRR FR**	**Ratio of HRR**
	kW/m^2	kW/m^2	kW/m^2	-
EVA (Cross-linked)	30	463	110	4.2
EVA (Thermoplastic)	30	574	83	6.9
HDPE	30	1803	114	15.8
HDPE # 2	50	1167	476	2.5
Polypropylene	30	1555	174	8.9
PVC Rigid # 2	30	98	42	2.3
PVC Rigid # 3	30	118	56	2.1
Plywood	25	114	43	2.7
Plywood	50	150	75	2.0
Particle Board *	25	151	66	2.3
Particle Board B (+ FR1)	25	160	70	2.3
Particle Board B (+FR1)	50	227	141	1.6
Particle Board B (+FR2)	50	227	52	4.4
Polyethylene Wire & Cable (+ Cl FR1)	50	800	165	4.8
Polyethylene Wire & Cable (+ Cl FR2)	50	800	517	1.5
Polyethylene Wire & Cable (+ Mineral FR3)	50	800	126	6.3
Polyethylene Wire & Cable (+ ATH FR4)	50	800	271	3.0
Polyethylene Wire & Cable (+ ATH FR5)	50	800	179	4.5
Lumber (+ FR to FSI < 25)	75	226	83	2.7

Notes: All tests in cone calorimeter except for those marked with an asterisk (*) for particle board. The tests on polyethylene wire and cable compounds originate from reference [47], lumber and FR lumber from reference [49] and all others from reference [46]. Pk HRR Non FR: peak heat release rate in cone calorimeter test for non-flame retarded materials; Pk HRR FR: peak heat release rate in cone calorimeter test for flame retarded materials; Ratio of HRR: ratio between Pk HRR Non FR and Pk HRR FR.

Table 10 – Cone Calorimeter Study of Various Polyurethane Foams [5]			
Type of Foam	Incident Heat Flux	Peak Heat Release Rate	Effective Heat of Combustion
Units	kW/m^2	kW/m^2	MJ/kg
Non FR Foam	25	420	25.6
CA TB 117 Foam	25	350	22.7
Non FR Foam	35	910	23.1
CMHR Foam	35	110	10.8

Notes: Non FR Foam: polyurethane foam without added flame retardants; CA TB 117 Foam: polyurethane foam with added flame retardants to achieve compliance with CA TB 117 test; CMHR Foam: polyurethane foam with added flame retardants to achieve compliance with an improved (unnamed) fire test.

Table 11 – Cone Calorimeter Study of Two Polyurethane Foams with and without fabrics [58]				
Type of System	**Time to Ignition**	**Pk HRR**	**Eff. Ht. Comb**	**BS 5852/Crib #**
	s	kW/m^2	MJ/kg	-
Non FR Foam	3	533	29	Fail/4
Melamine Foam	7007	97	6	Pass/7
Polyolefin/Non FR Foam	15	613	35	Fail/4
Polyolefin/Mel Foam	22	450	31	Fail/4
Nylon/Non FR Foam	515	341	20	Fail/4
Nylon/Mel Foam	3349	313	23	Pass/5
Canvas/Non FR Foam	134	355	12	
Canvas/Mel Foam	159	187	19	
Flex Vinyl/Non FR Foam	548	142	8	Pass/7
Flex Vinyl/Mel Foam	10,000	117	3	Pass/7

Notes: Non FR Foam: polyurethane foam without added flame retardants; Melamine Foam (Mel Foam): polyurethane foam with added melamine flame retardants to achieve compliance with an improved (unnamed) fire test. Pk HRR: peak heat release rate in cone calorimeter test; Eff. Ht. Comb.: effective heat of combustion in cone calorimeter test.

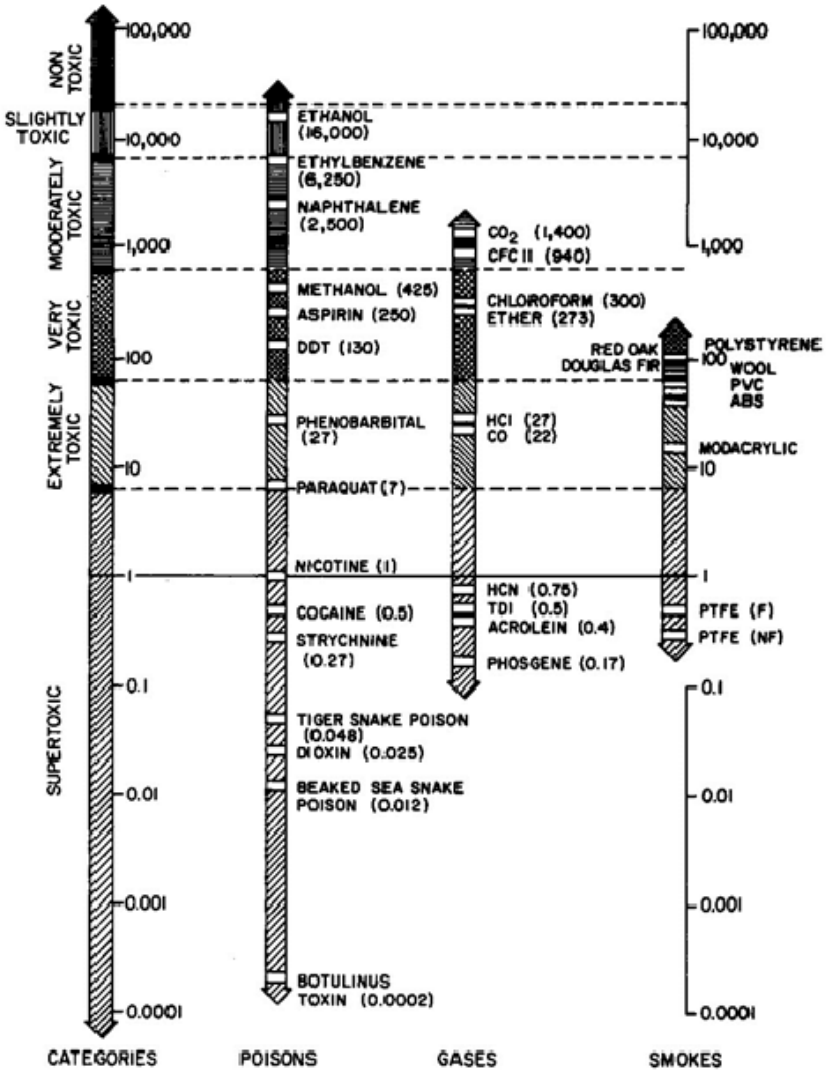

Figure 1 – Levels of smoke toxicity (in orders of magnitude) [10]

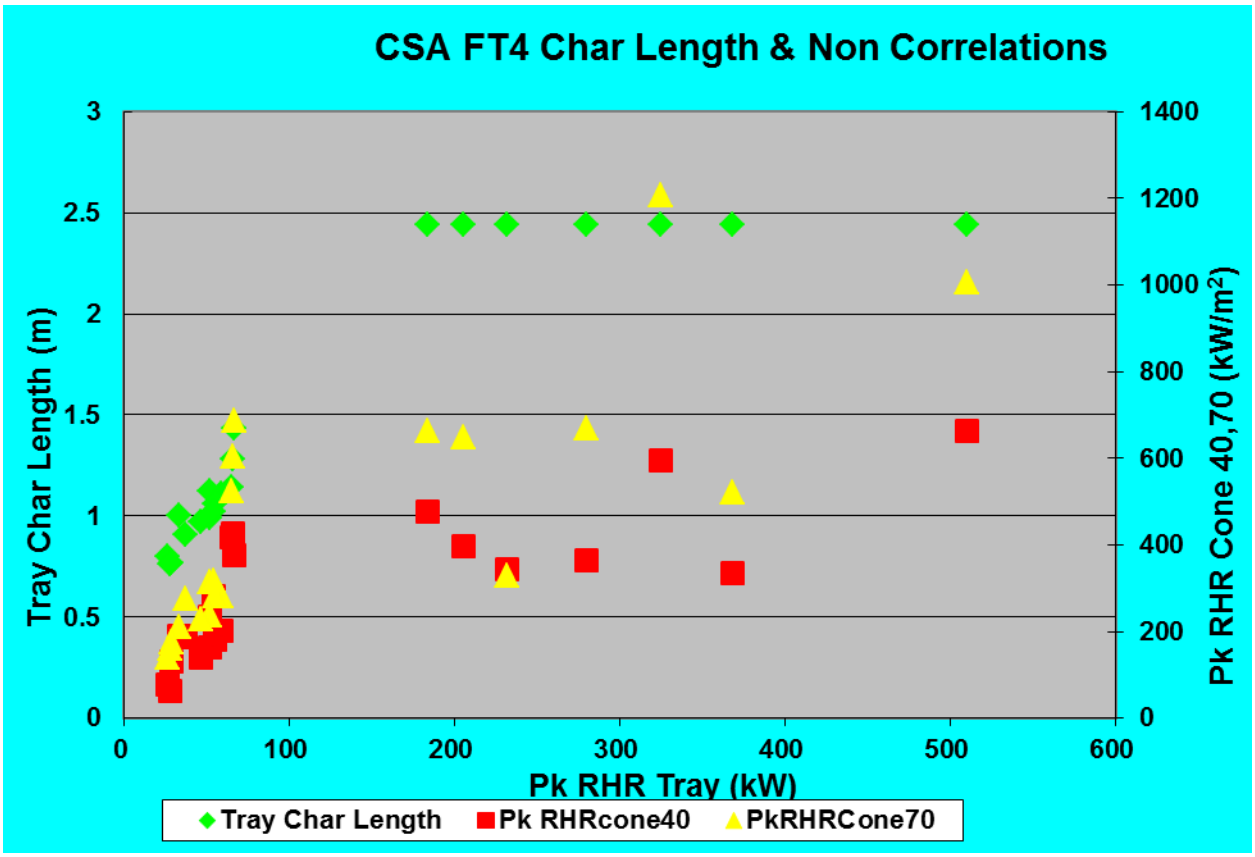

Figure 2: Char length for cables in the vertical cable tray test (UL 1685/CSA FT4) and peak heat release rate in the cone calorimeter as a function of cable tray peak heat release rate [13]

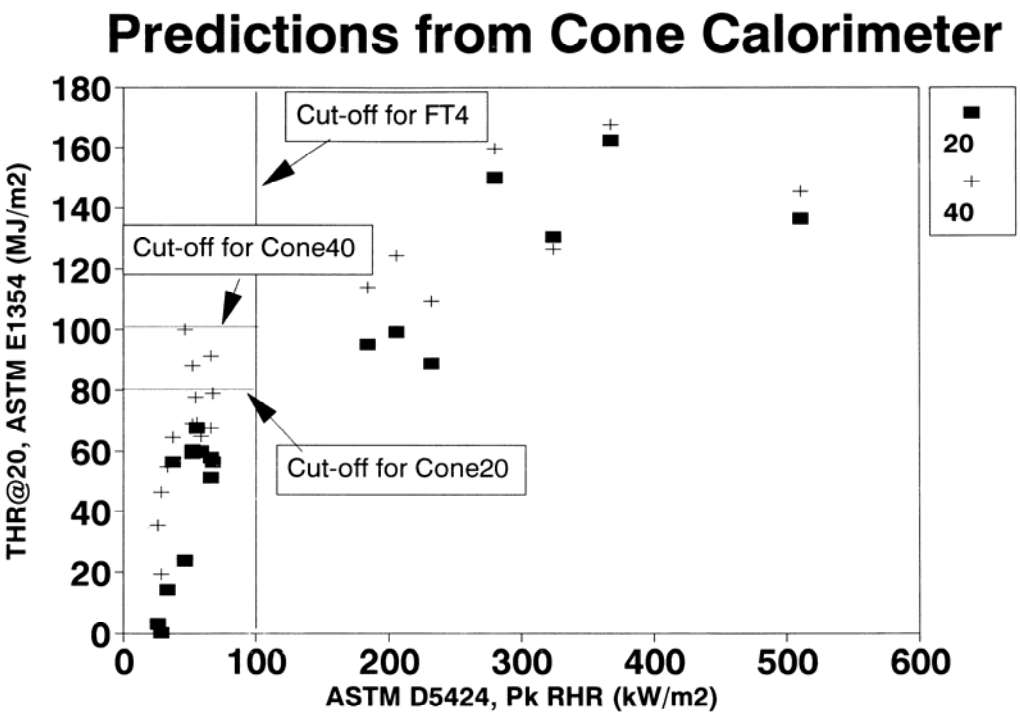

Figure 3: Comparison of Flame Spread in Tray Tests with Char Length and Heat Release Rate [17]

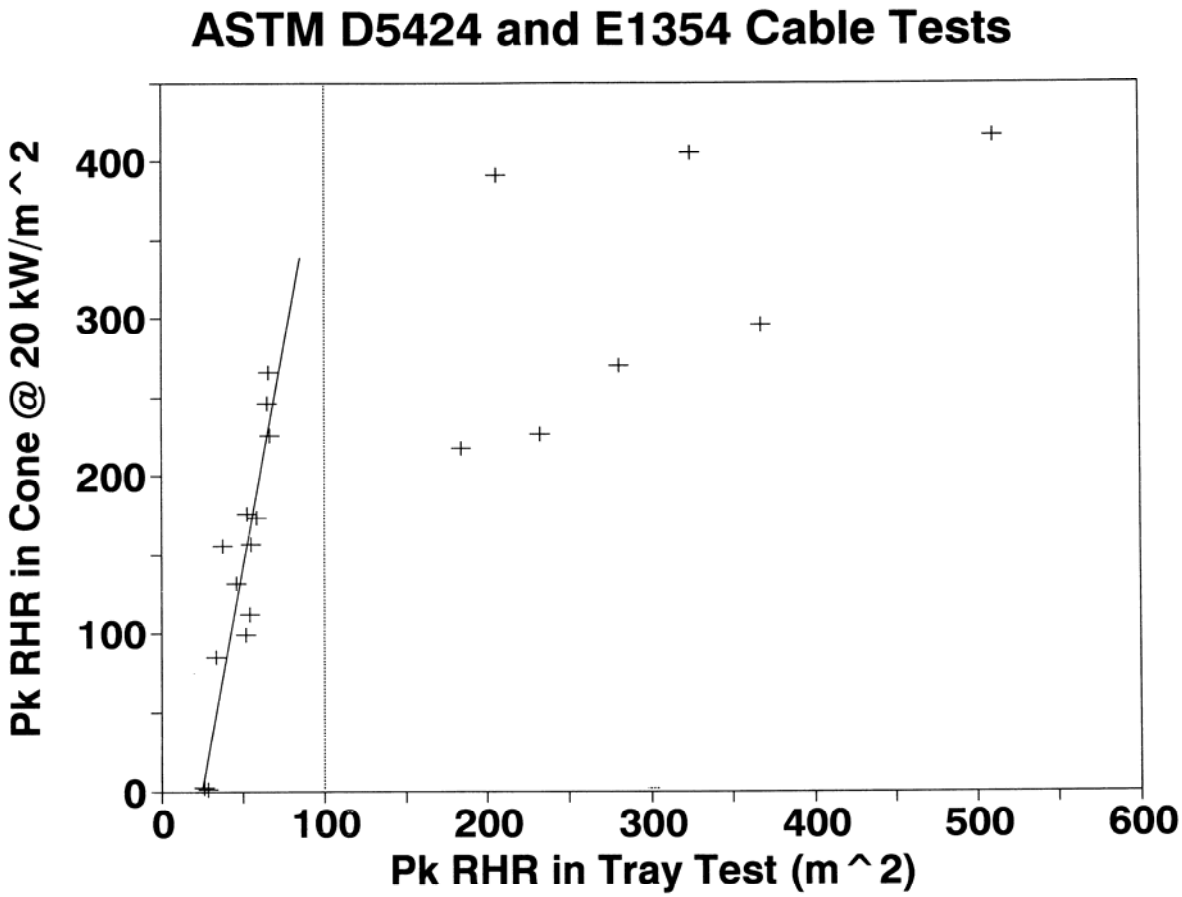

Figure 4: Comparison of Peak Heat Release Rate in Cone and Vertical Cable Tray Test [17]

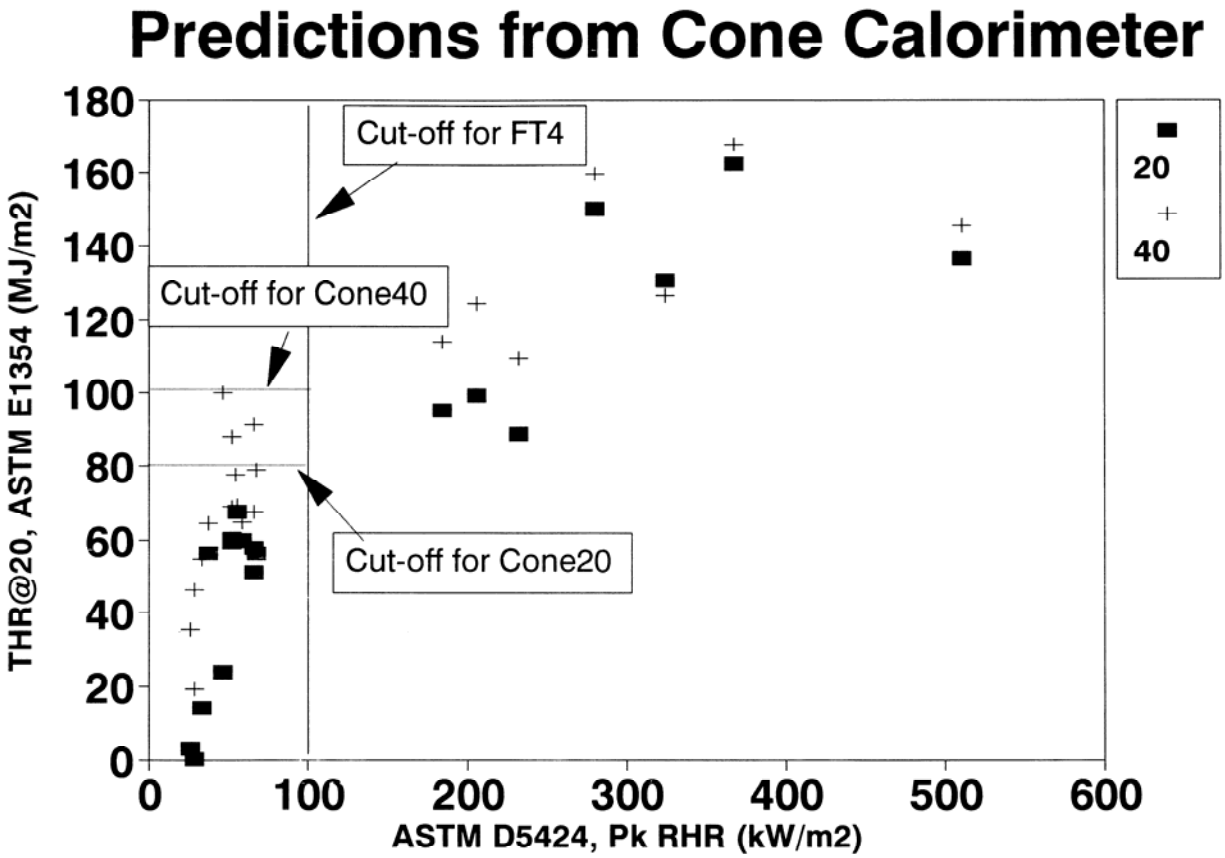

Figure 5: Indication of Vertical Cable Tray Test Results Predicted from Cone Test Results [17]

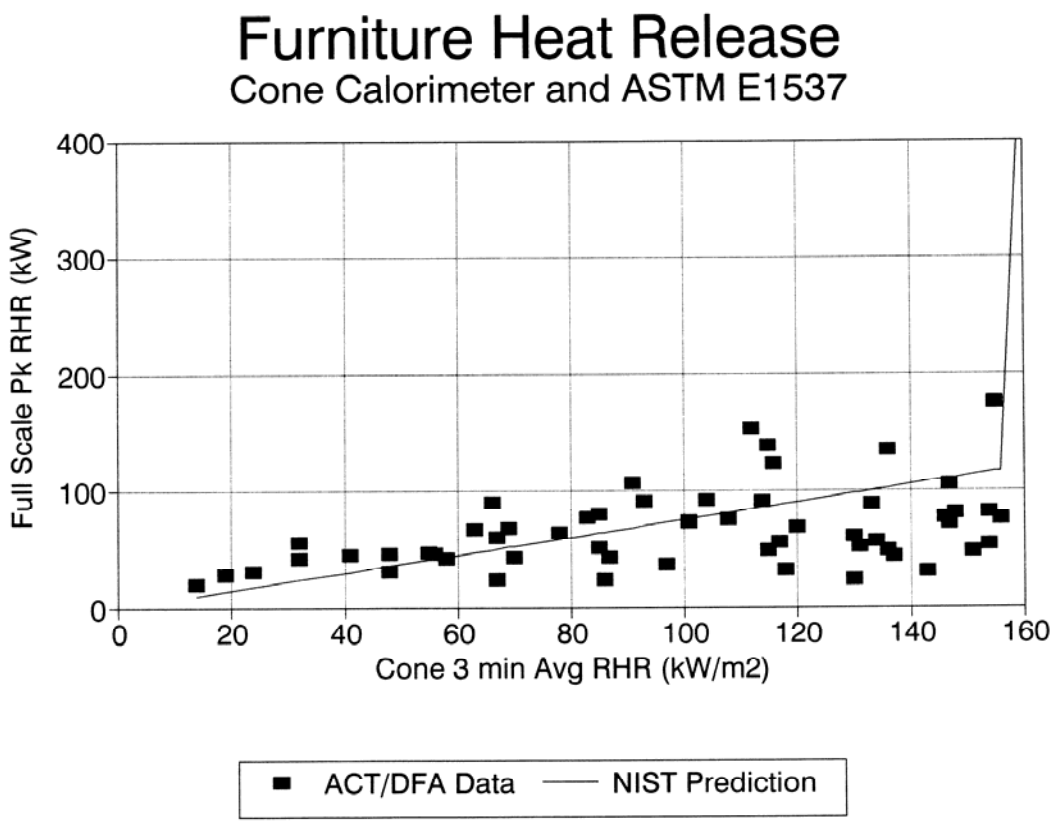

Figure 6: Prediction of CA TB 133 test results from cone calorimeter [17]

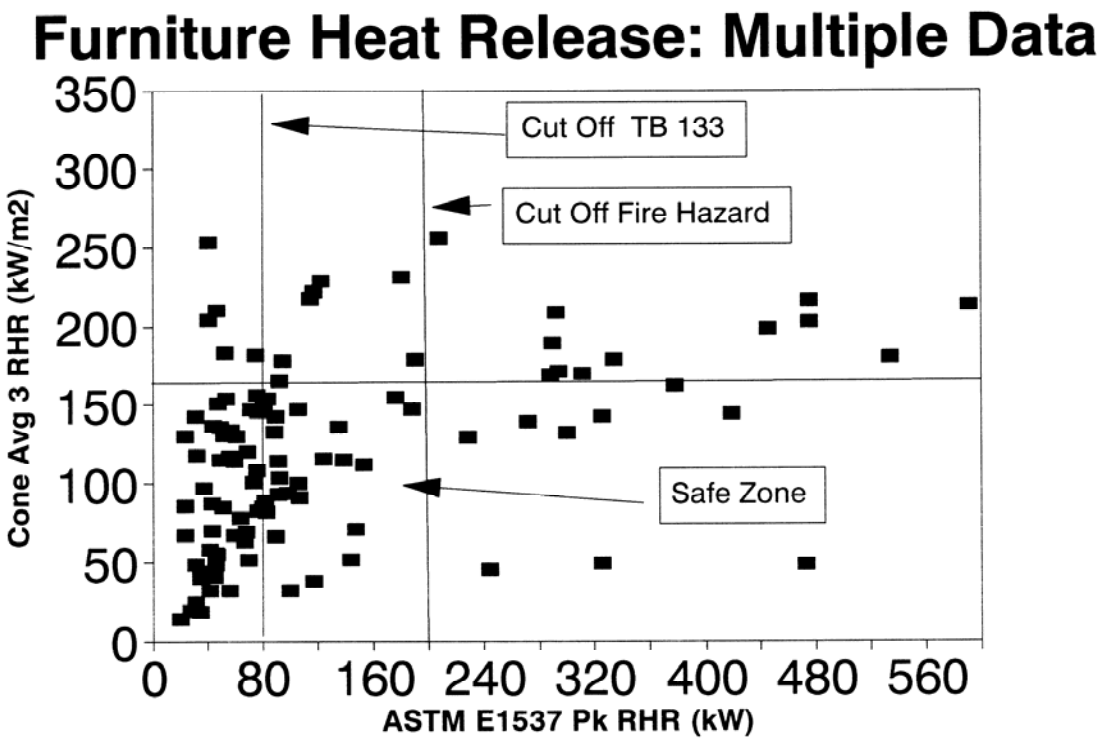

Figure 7: Predictions of Full Scale Furniture Test Data Showing Safe Zone [17]

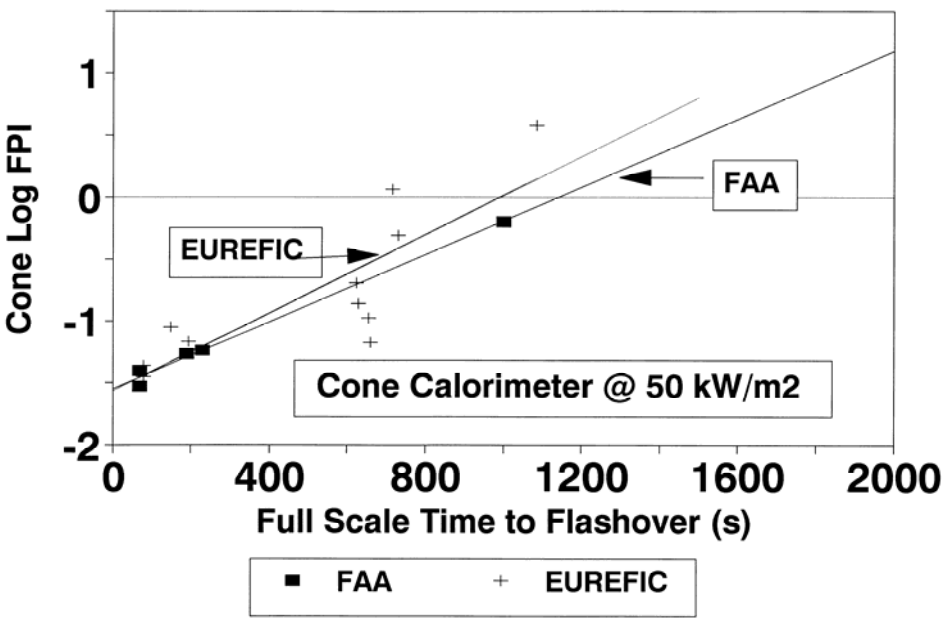

Figure 8: Comparison of Wall Linings (Eurefic) and aircraft panels (FAA) full scale test results with fire performance index predictions from cone calorimeter [28]

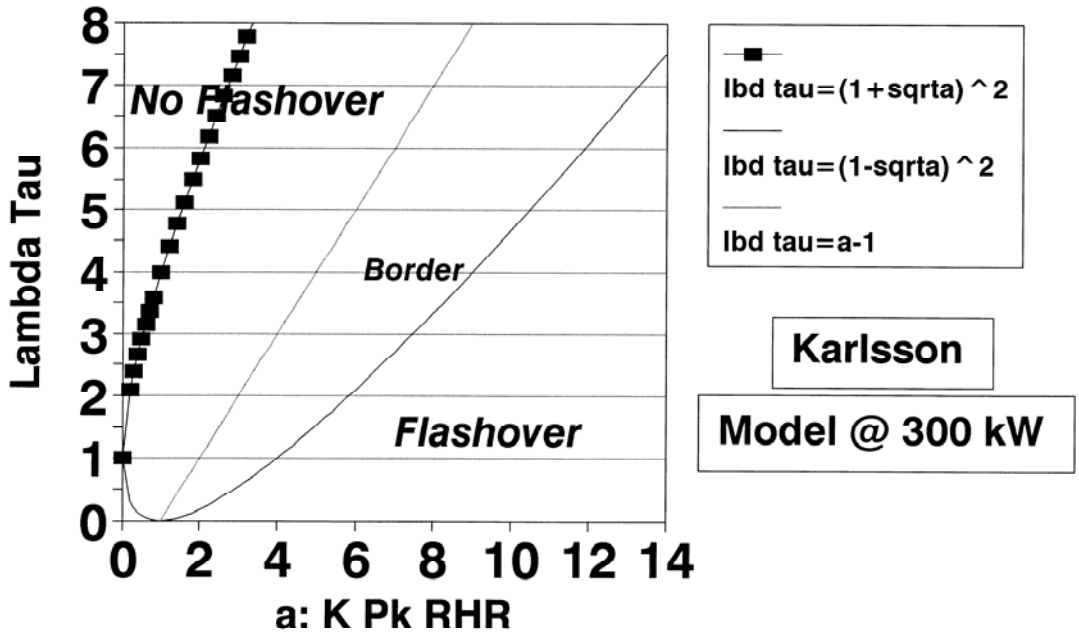

Figure 9: Safe zone predictions in wall linings based on Karlsson model and cone calorimeter data [28]

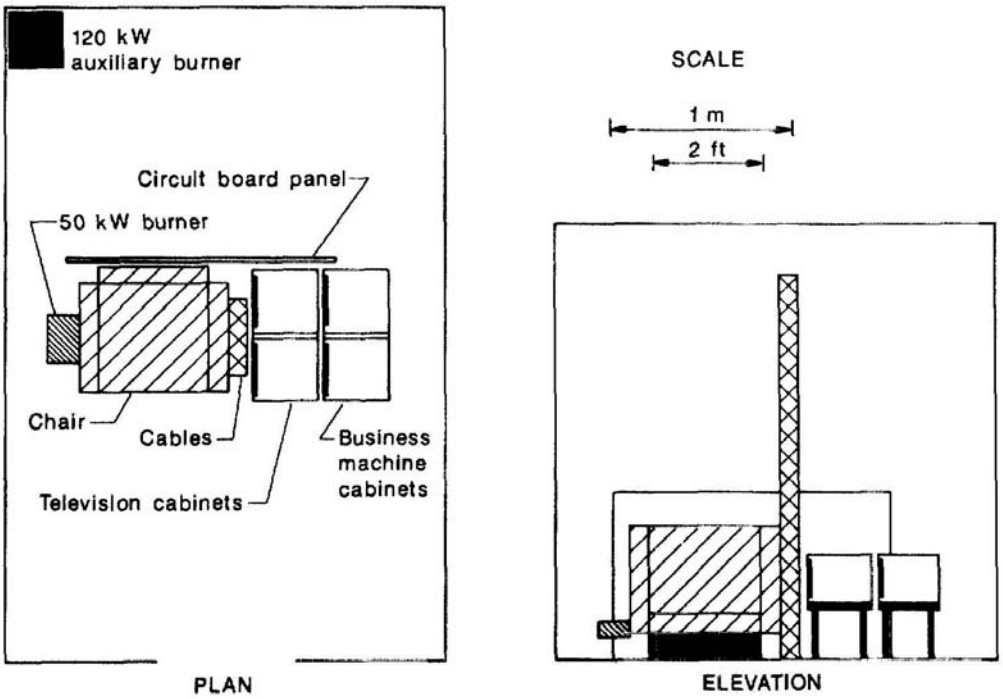

Figure 10: NBS/NIST Layout of Full Scale Product Burns for Non FR Products [48]

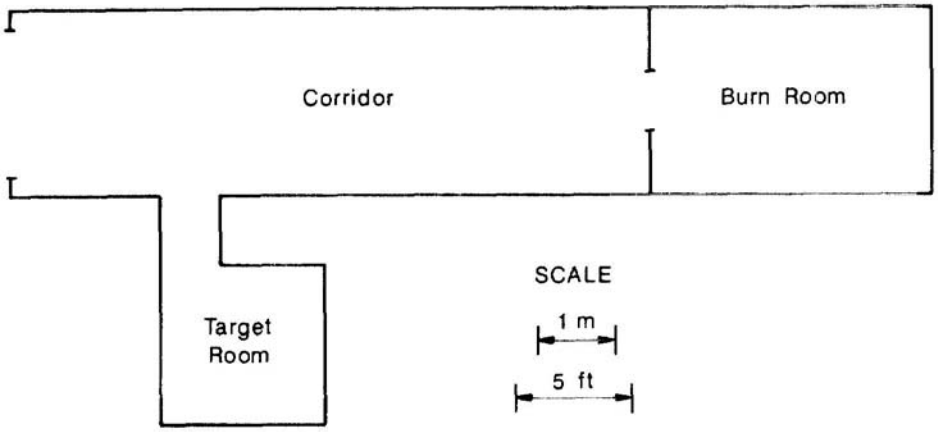

Figure 11: NBS/NIST Room Corridor Layout of Full Scale Product Burns for Non FR Products [48]

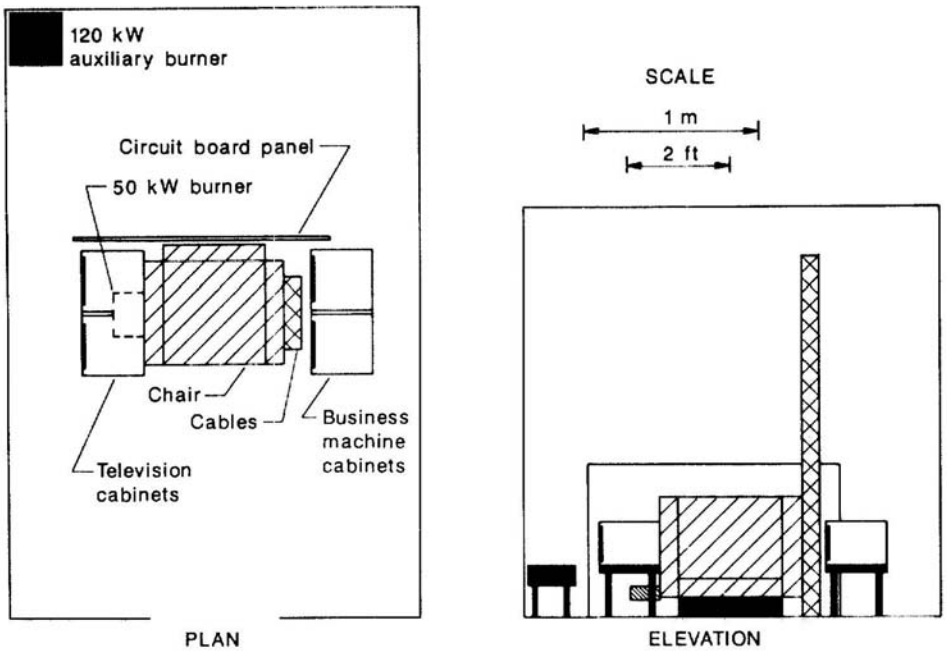

Figure 12: NBS/NIST Layout of Full Scale Product Burns for FR Products [48]

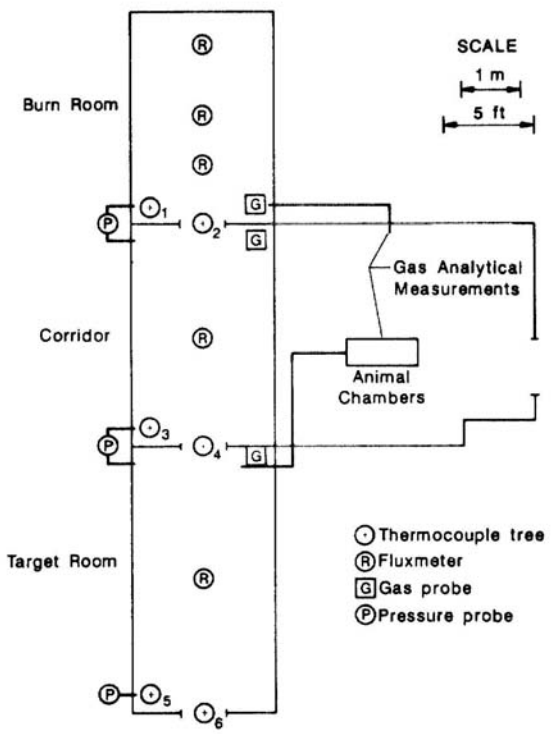

Figure 13: NBS/NIST Room Corridor Layout of Full Scale Product Burns for FR Products [48]

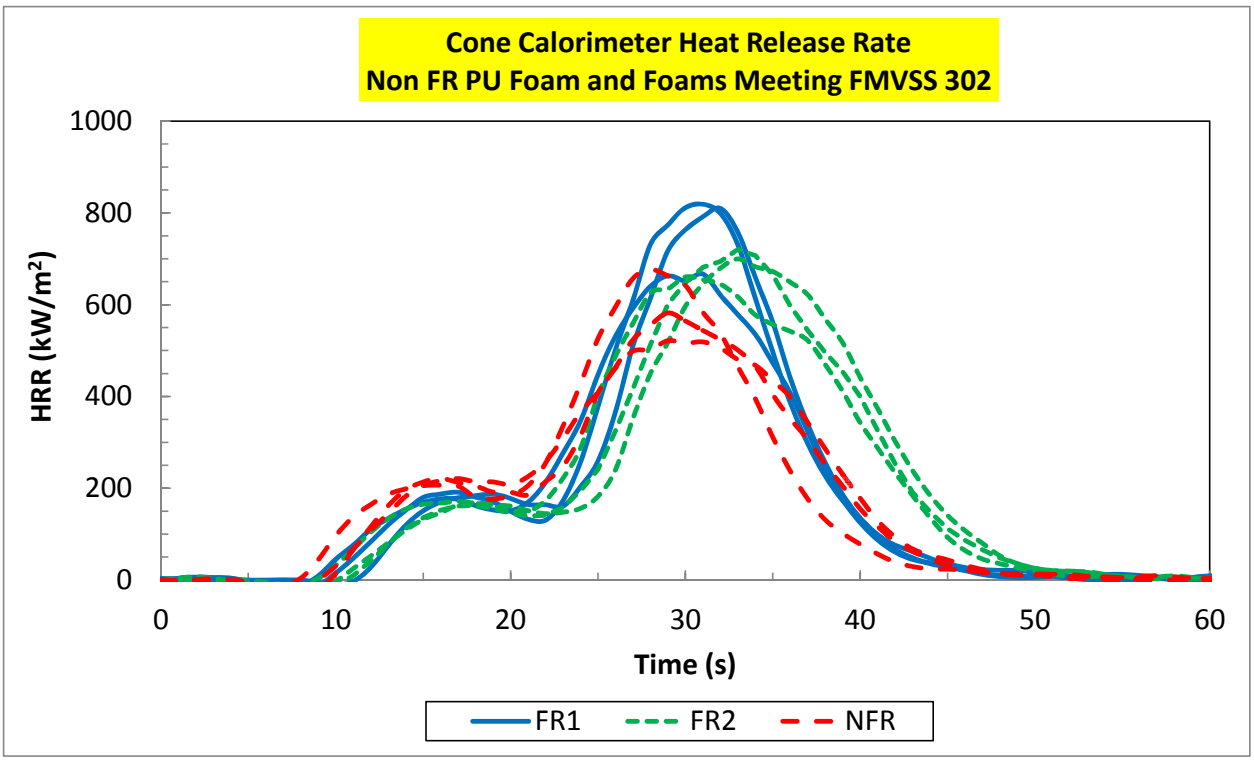

Figure 14: Alexander Morgan Cone Calorimeter: Polyurethane Foam Treated for FMVSS 302 [55]

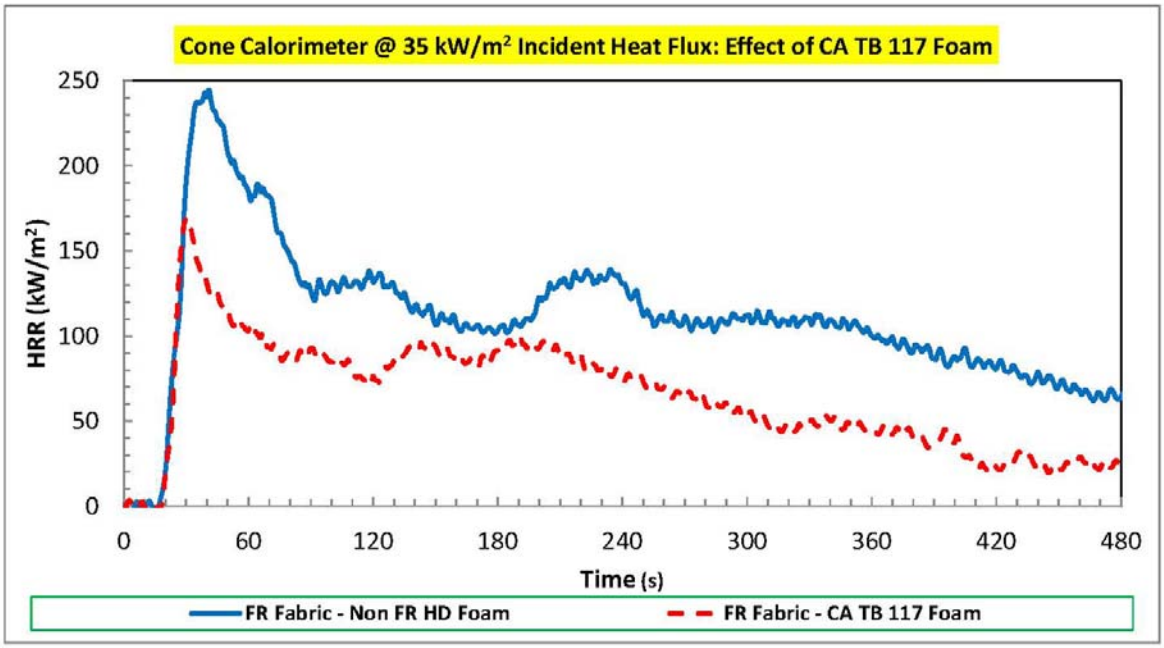

Figure 15: NIJ Cone Calorimeter Comparison of Polyurethane Foam Treated for CA TB 117 and Non FR with an FR Cotton Fabric Treated for NFPA 701 [57, 59]

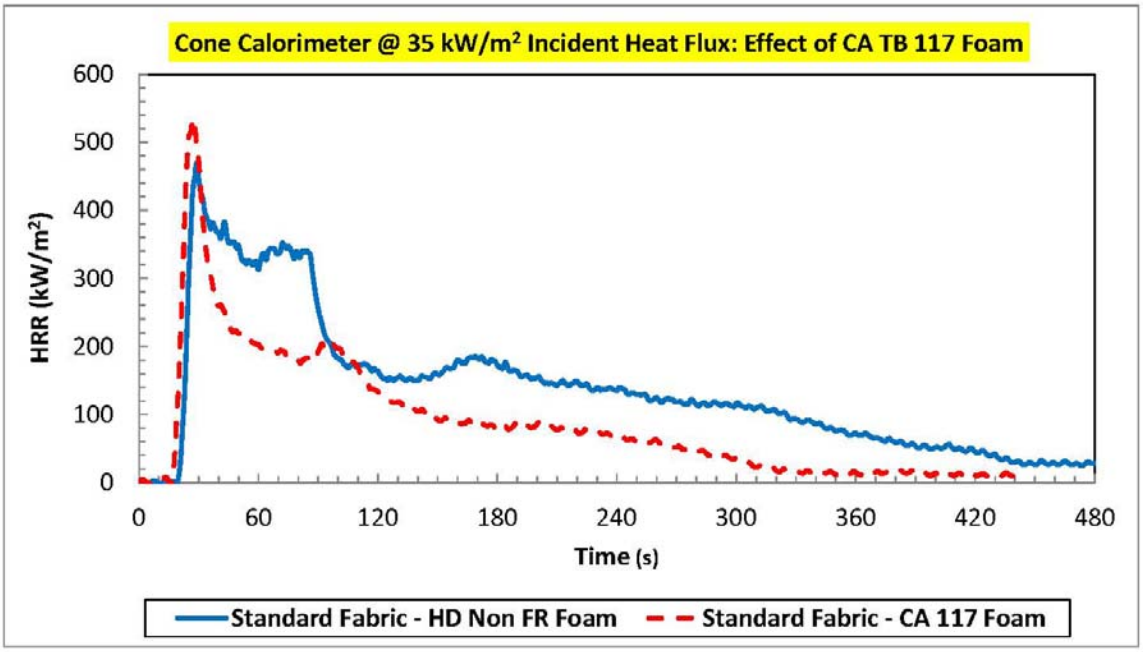

Figure 16: NIJ Cone Calorimeter Comparison of Polyurethane Foam Treated for CA TB 117 and Non FR with a Non FR Cotton Fabric [57, 59]

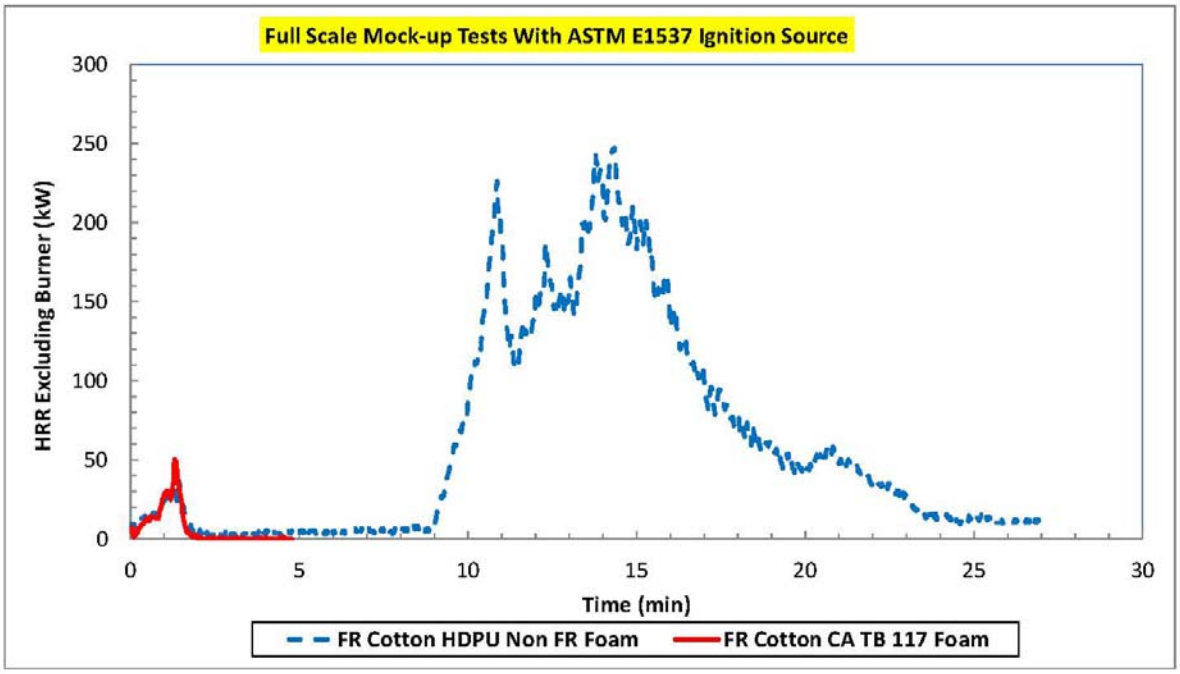

Figure 17: NIJ Full Scale (ASTM E1537, One Seat Sofa) Comparison of Polyurethane Foam Treated for CA TB 117 and Non FR with an FR Cotton Fabric Treated for NFPA 701 [57, 59]

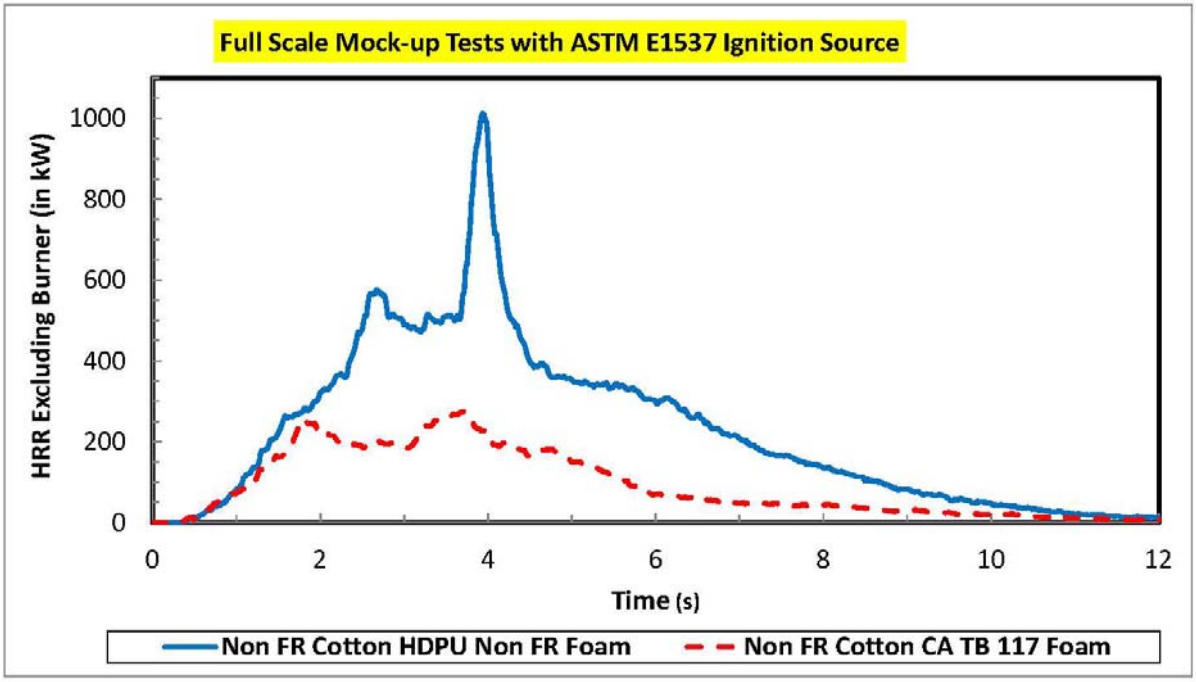

Figure 18: NIJ Full Scale (ASTM E1537, two seat sofa) Comparison of Polyurethane Foam Treated for CA TB 117 and Non FR with Non FR Cotton Fabric [57, 59]