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Thomas J. Ohlemiller
John R. Shields

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Thomas J. Ohlemiller
John R. Shields
Department of Commerce
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

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T. J. Ohlemiller and J. R. Shields

ABSTRACT

Six polyurethane foams of widely varying flame retardant levels have been tested in two modes: as four, fabric-wrapped cushions in a chair mock-up based on California Technical Bulletin 133 and in a two foam slab Vee configuration that uses multiple propane flames to simulate fabric burning. The latter test was developed as a way to: (1) use less foam to assess real world foam flammability behavior and (2) avoid the use of fabrics in this assessment since they do not have reproducible properties. For the six foams tested as chair mock-ups with a polypropylene fabric, the Vee test correlates well for peak heat release rate but not for time to that peak. In a more limited assessment of chair mock-ups having polyester fiber wrap between the fabric and foam, it was found that this material overwhelms even high levels of flame retardants and gives a serious fire regardless of the nature of the foam. One foam, which contained expandable graphite, gave very good initial fire behavior by suppressing foam melt flow entirely. However, it ultimately began to disintegrate and yielded a serious fire as a result of the dropping of burning, solid foam chunks. New non-melting foams based on carbon nano-fibers, now under development, will have to have to exhibit greater "char" coherence if they are to avoid this performance pitfall.

Introduction.

Flexible polyurethane foam is a primary component of soft furnishings including mattresses and upholstered chairs, sofas, etc. As such, it is at the heart of products that are the two single largest contributors to residential fire deaths in the United States [12]. Its flammability has long been the subject of both research and of varying degrees of regulation. The flexible foam flammability issue has often been addressed with the use of halogenated flame retardants [1-3]. However, many if not most of these halogen compounds are the subject of increasing environmental and health concerns both in the U. S. and abroad. This has prompted increasing interest in alternative flame retardant approaches for polyurethane foam. The National Institute of Standards and Technology, Building and Fire Research Laboratory (NIST/BFRL) has embarked on a research program to investigate several possible alternatives [4]. The present report covers one facet of that effort, focused not on materials but on how best to test their flammability.

The foam-based end product category of primary interest here is upholstered furniture[1]. This class of products is complex, incorporating several materials other than polyurethane foam (though its mass usually dominates over that of other soft materials); the geometry and size are also variable. The other materials of concern (cover fabric, polyester fiber wrap between cover fabric and foam) are typically not flame-retarded and can be expected to burn if ignited. Local ignition of the materials surrounding the polyurethane foam can potentially expose it to an intense and spatially growing ignition source. The upholstery cover fabric is especially variable since a wide range of polymer fibers, natural and synthetic, are combined into countless blends and weaves that change from one year to the next in response to market forces. None of these materials is standardized; fabric samples that are known to be reproducible in their fire behavior are simply not available.

One would like to know how a candidate "improved" flame-retarded foam is likely to behave in the context of a chair exposed to an ignition source – this is the context that counts in terms of the ultimate impact of an improved foam flame retardant on residential fire deaths. However, it is prohibitively expensive to build chairs to get the definitive answer about that impact. Furthermore, there is no reason to think that there is a single answer to this quest – a foam is likely to perform worse if the materials surrounding it burn more intensely because of their increased mass, more energetic polymer fiber content, etc. In addition, chair geometries (e.g., upholstered arms) that enhance radiative interchange among flaming surfaces will accentuate the flaming behavior of all of the chair components[2]. We approach this problem, therefore by thinking in terms of a severe fabric and a severe geometry so as to be near worst-case. A foam that can perform well in these sorts of circumstances should perform better in a chair design that exposes it to fewer fire

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[1]Residential mattresses are the subject of a new (July, 2007) flammability regulation issued by the Consumer Product Safety Commission. For the most part, the mattress industry has addressed this regulation by incorporation of a fibrous fire barrier layer in the outer surfaces of the product rather than use flame-retarded foam.

[2] These two features , the highly variable nature and mass of the surrounding fabrics and the possibility of substantial radiative interchange effects, make the control of the flammability of upholstered furniture a more challenging problem than that for mattresses.

enhancements. As will be seen, however, this approach has a limitation that emerges when the fire enhancements reach a very high degree.

The exact definition of "good" fire behavior for residential upholstered chairs has not been definitively specified. The measure of general choice is peak heat release rate (HRR) since life-threatening conditions in a room (hot smoke layer temperature and depth) tend to mirror it rather closely. California Technical Bulletin 133, which specifies a severe ignition test for chairs intended for public occupancies, sets a HRR limit of 80 kW. The origin of this limit is unknown. The National Fire Protection Association (NFPA) Life Safety Code specifies the same ignition source but sets the limit for various public occupancies at 250 kW. The rationale offered has to do directly with the tenability and depth of the smoke layer, though this is not spelled out in detail. The Consumer Product Safety Commission (CPSC) mattress flammability regulation (CFR 1633) sets the level at 200 kW, based again on smoke tenability and depth, but the underlying work [5] also extensively considered the issue of the likelihood of fire growth via secondary ignitions as a function of allowed mattress fire size. There has not been a similarly extensive study of secondary ignition hazards from furniture fires but, for now, we assume that a chair fire that does not exceed 250 kW is probably not an immediate life threat. Such a heat release rate is not good fire behavior but it might be regarded as acceptable in an imperfect world.

Polyurethane foam and many of the fibrous materials immediately around it in common chair designs are thermoplastic in behavior.[3] This greatly complicates both their fire behavior in the context of a chair and the challenge of independently assessing how a foam might behave in this context. In effect, the fire, as it grows, progressively destroys the relatively simple chair geometry; at the same time, it drops flaming liquids onto the floor below. The floor fire constitutes an extension of the flaming area and, in some circumstances, the hot plume from the pool fire on the floor can accelerate the fire on the remainder of the chair. This complex, dynamic behavior is all occurring at about the time a chair fire reaches its peak intensity or heat release rate.

The cone calorimeter was originally developed with the complexities of multi-component fuels, such as one finds in upholstered chairs, in mind. Ideally, one could take the layered composite of materials from a complex object like an upholstered chair, measure the heat release per unit area from this composite and use this effective overall behavior to either model or correlate the burning behavior of real chairs made from this composite. This has met with only limited success [7, 10] mainly because of the thermoplastic response of real chairs. It is not effectively captured in the cone tests with fixed area, horizontal samples.

Here the goal is somewhat different. We want to assess the effectiveness of a test of the foam alone, independent of any of the other materials to which it would be exposed in a chair, so as to avoid the morass posed by "standard" fabrics or other fibrous materials. In effect, we substitute burning propane (in a specific manner, described below) for these other materials and attempt to get the foam to behave in a manner that mirrors its behavior in a real chair (pool fire and all). The basic test geometry used here was laid out in Ref. 7;

[3] Polyurethane foam is a cross-linked rubber that cannot flow when chemically intact. Heat degrades the cross linking bonds, destroys the foamy structure and leaves a liquid that flows with relative ease [6, 7].

it consists of two polyurethane foam slabs arranged in a Vee configuration. It is applied here to a series of polyurethane foams of widely-varying flame retardancy. We assess the correlation of results from this configuration with the same foams tested in a four-cushion chair mock-up configuration when the chairs are wrapped with two differing quantities of non-flame retarded fibrous coverings.

Experimental Methods.

Chair Mock-Ups. The test frame generally followed the guidelines of California Technical Bulletin (CTB) 133[4] but there were two modifications. The first dealt with the pronounced tendency of loose chair cushions placed on this very open frame to move and fall to the floor as they begin to lose mass. Two 3 mm wide nichrome ribbons spanned the area under the two arm cushions and the seat cushion, parallel to the front edge of the frame at seat level, with one 13 cm from the front frame edge and the other 15 cm from the rear frame edge. In addition, a steel wire was wrapped around each of the two arm cushions and around the seat back cushion, all at about 2/3 up the cushion height, to help keep these cushions in place. The wires were attached to the steel frame behind each of the cushions. The second modification to the standard CTB 133 set-up was the use of a closer catch surface under the chair seat. The standard frame places the bottom of the chair seat 41 cm above the catch surface (where a pool fire can develop). A check of one of the author's residential furniture showed at least two pieces having a separation distance of only 25 cm; here the separation distance was set at 24 cm. This distance affects the likelihood of a pool fire plume interacting with materials still on the frame. By decreasing it, we have moved toward a worst-case situation.

The seat back was tilted back at a 15º angle. The seat back cushion sat on the top of the rear portion of the seat cushion (as opposed to sitting behind its rear edge)[5].

The nature of the catch surface is not specified in the CTB 133 standard. Since this can affect the ability of a pool fire to grow, it is significant. Marinite P[6] (an inert, calcium silicate material), which has a thermal inertia[7] comparable to oak, was used exclusively here[8]. The Marinite board forming the catch surface was 90 cm wide by 121 cm long by 1.3 cm thick and it was placed between the seat frame legs with the 90 cm width in the lateral direction. In some cases (i.e., with some polyurethane foams), the pool fire did

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[4] The frame was on loan from the Consumer Product Safety Commission.

[5] The choice of seat back cushion placement could be significant in the case of a small ignition source but is unlikely to make any difference here.

[6] Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

[7] Thermal inertia is the product of thermal conductivity, density and heat capacity; it has a strong influence on the amount of heat extracted from a hot material contacting the catch surface in a transient situation.

[8] This material poses its own problems. It is somewhat porous so that, before re-use, it must have any absorbed organic liquids burned out by the application of a torch. It also tends to crack when subjected to large fires. Here the cracks, typically no more than 3 mm wide, were filled with wall board joint compound which was then scraped flat and torched lightly to dry it.

reach the lateral sides of these boards over a length of the order of 15 cm to 20 cm. This weakly limited (by a few percent) the peak HRR from these pool fires. The Marinite board sat on top of a 2.5 cm thick layer of Kaowool ceramic felt insulation which, in turn, was in an aluminum pan. The pan was on top of a scale with better than 1 gram resolution, which weighed the total mass of the chair assembly and its melt pool as a unit.

The assembly was placed under the NIST 3 meter calorimeter hood, which measures heat release rate by means of oxygen consumption calorimetry. While no uncertainty analysis is yet available for this specific calorimeter, the NIST 6 meter calorimeter, which operates with the same instrumentation, has been shown to have an expanded uncertainty (95 % confidence limits) of 11 % [9]. The calorimeter was calibrated before and after the two week test series described in this report. Its performance changed less than 1% in this interval.

The mock-up was ignited with a Tee-burner (the 25 cm long side burner specified in the CFR 1633 mattress flammability regulation), placed near one rear corner (typically 2.5 cm from both the seat back and seat cushion and ca. 6 mm from the side arm); see Figure 1 (the wires holding the cushions are not present in this picture). The burner was run at the same 6.6 (± 0.05) NTP[9] L/min flow rate (CP grade propane) as is specified in the mattress standard to provide a strong ignition source that would, in its 60 (± 0.2) second duration, locally involve both the seat back, the seat cushion and the nearest side arm cushion, thereby initiating a significant radiant interchange among burning surfaces. The burner was removed at the end of the 60 s exposure to allow a clearer view of the burning cushions surfaces.

The tests were videotaped with three cameras providing two overall views from the front (about 90º apart) and one side view of the pool fire area on the Marinite and the space above, up to and including the seat area.

Chair Cushions / Polyurethane Foams. The cushions were all of the same nominal size (based on 46 cm by 46 cm by 7.5 cm slabs of polyurethane foam[10]). The use of this relatively large size in the arm cushion positions assured a near worst-case situation for the geometric aspects of radiative interchange among burning seat surfaces.

The foams used throughout this study are described in Table 1. They cover a substantial range of flame-retardancy and density. All are commercial products. None of the NIST-developed flame retardant (FR) systems were available for this study. Only six of the eight foams listed in Table 1 were included on the chair mock-up portion of this study due to time limitations. The viscoelastic foam and the Green FR foam were not included.

All chair cushions were made by a local re-upholstery firm and were of good quality. All of the foams were marked beforehand to assure that the desired foam was indeed in each

[9] Normal temperature and pressure, i.e., 21 ºC and 1.0 atmosphere pressure.
[10] Here and in the Vee tests the foams were not necessarily available in this size. It was necessary to glue pieces together using a light spray of polyurethane glue on both surfaces of a joint. This had no significant visible effect on the behavior of the foams during the fire tests.

cushion. (The cushions were closed with a zipper on one side which allowed this to be checked.)

All cushions were covered in one of two, nominally identical 373 g/m^2 (11 oz/yd^2), 100 % polypropylene fabrics. The fabrics, part of a homologous series of identical weave designs from a single manufacturer, were purchased at the same time from the same retailer and appeared to differ only in color; they were, nevertheless, separately tracked throughout this study (denoted as Fabric A and Fabric B below). A check of their basis weight found a difference of less than 3%. Both had a light back-coating that appeared to be solely for the purpose of improved wear resistance. Three of the foams (Y, P and Graphited) were also incorporated into cushions that also had a polyester fiber wrap between the outer fabric and the foam since this is common in current upholstered furniture. It is responsible for the somewhat rounded appearance of the cushions in Figure 1. The nominal basis weight of this wrap was 680 g/m^2 (20 oz/yd^2)[11]. Note that it exceeds the fabric basis weight by nearly a factor of two though the polyester fiber would be expected to have only about half the heat of combustion (per unit weight) of polypropylene. Each cushion contained 1.1 kg (± 0.05 kg) of fabric and, if present, 1.7 kg (± 0.05 kg) of fiber wrap; the mass of foam varied with the foam density since the foam volume was fixed.

All test materials were fully equilibrated to approximately 50 % relative humidity prior to testing.

Modified Vee Tests. In its original embodiment [7], the Vee test was conceived as a differential fire growth test, roughly analogous to the Lateral Ignition and Flame Spread Test (LIFT test; ASTM 1321). The two slabs of foam could interact radiatively and via merging pool fires. As the fire attempted to grow from the narrow end of the Vee, where it was initiated, to the opposite, more open and less radiatively-interactive end, foams which were less flammable would grow outward less and produce a lower peak heat release rate. To capture the enhanced fire growth potential that would be seen in a real chair as a result of burning fabric over the cushion surfaces, two additional elements were suggested (but not implemented until now) in Ref. 7: (1) a central radiator in the middle of the Vee to boost the radiation seen by the slab surfaces and (2) “pool pilots” ‘ i.e., two linear arrays of small flames beneath the foam slabs, essentially on the Marinite surface, mimicking the flame piloting effects of flaming melt derived from the flammable fabric. The key word here is “piloting”. Gas phase flame retardants (halogens and some phosphorus compounds) in a foam can prevent the flaming of that foam by slowing the net oxidation reaction rate to the point where it is slow relative to the buoyant flow time. This is a Damkohler Number effect that precludes stable burning of the foam in isolation. The effect can be largely defeated by the presence of pilot flames that assure the gas phase flame can anchor to the foam surface. Burning fabric (or fiber wrap) can provide these pilot flames, making such a foam perform much worse in cushion form than in isolation[12].

[11] We were unable to determine if the fibers had been treated with silicone oil.
[12] Sufficient retardant can begin to swing the balance back in favor of a smaller fire, even if the foam is wrapped in a flammable fabric.

This was the rationale for the form that the test takes, as sketched in Figure 2. Ultimately, as described in this report, the rationale and mode of usage had to change somewhat in light of the behavior of the high melamine foam (Foam P). However, the essential elements, as shown in Fig. 2, were unchanged.

Implementation of this concept is not without problems. In the original Vee tests of Ref. 7, the method of holding the foam slabs in place (a few cm above the Marinite P surface) worked poorly and had to be supplemented in an *ad hoc* manner with various wires that were moderately successful. Here the method of foam support in this Vee configuration was changed completely. The new sample holder design is as follows. Each foam slab (30.5 cm tall by 61 cm long by 7.5 cm thick) is mounted on a separate, open, rectangular frame that holds a series of five parallel vertical bars from which extend, at intervals, three to four thin (3 mm dia) stainless steel spikes. The spikes (a total of 13 per foam slab) have a 2.5 cm square stop welded on at a distance of 7 cm from the tip so that the foam can be reproducibly mounted onto the frame (with the spikes ending several mm below the foam surface that faces the inside of the Vee). The rectangular frame that holds the spikes is 3.8 cm behind the back of the foam slab. Each foam slab is thus completely uncovered on all sides and, in effect, suspended in space[13]. This system worked quite well in keeping the unburned foam in place as other parts melted or burned away.

The frames holding the two foam slabs are themselves held on one end by a larger box frame. On their other end, each has a foot that rests on the Marinite P catch surface (4 cm below the bottom of the foam slabs). Figure 3 is a view of the foam slabs mounted in place. The angle between the foam slabs there is 30º; this was used throughout this study though the apparatus allows it to be varied, if desired. A cut-out jig with a 30º angle was used to assure that the angle was the same for each test. Note that the two slabs do not meet at the narrow end of the Vee, rather they are spaced apart to allow the 1.3 cm diameter igniter tube to play on the local inner surface of each slab. The igniter flame jets spray outward in two vertical lines (full height of each slab) that are 45º apart.

The "pool pilots" are not visible in Fig. 3. They are provided by two tubes arrayed in a Vee under the foam slabs. The tubes are 6 mm outside diameter (OD) and 53 cm long, having 1.3 mm dia holes at 3.8 cm intervals along their length, all pointing straight down at the Marinite surface, approximately 1 cm blow the tubes. The tubes are angled in the horizontal plane so that they are below the inner surface of the foam slabs on the narrow end of the Vee but at mid-depth on their outer ends. They are mounted to the same post which holds the igniter.

The propane-fired radiator which sits on the midline of the Vee was also a challenge. No appropriate commercial device exists to serve this function, so it was necessary to design one. At heart it is simply a way to apply the heat of a propane flame to a solid body

[13] The foam slabs were pressed into place on the spikes using a piece of plywood the size of the foam slab. For the viscoelastic foam, which has a very high friction coefficient with other materials, it was necessary to wet the spikes with silicone oil first.

radiator with a high emissivity, though this is not simple in practice[14]. A side view of the assembled radiator is shown in Figure 4. The actual radiating elements are 2.5 cm wide by 10 cm long graphite plates (3 mm thick) that are coated with silicon carbide to slow oxidation[15]. There is a total of 14 such plates arranged in two parallel rows on each side of the radiator. In the center between the rows of plates are air[16] and propane injectors. Propane enters in the two lower tubes seen on the left. These tubes feed a series of seven vertical injector tubes, one behind the center of each graphite plate. Each injector tube has eight small holes spaced along its height to spray propane toward the rear center of the two graphite plates on either side of it (in front and back of it in Fig. 4). Because this propane could not be expected to burn more than partially over the 10 cm height of a graphite plate if it had only a buoyant air supply, there are eight air injector tubes alternating with the propane injector tubes. These are visible in the Figure though some are blackened with soot; they are fed by the two upper tubes on the left. The air injector tubes have twice as many holes as the propane injectors and these are pointed at an angle, also toward the center of the back of the graphite plates. The goal of these injectors is to create propane flames which impinge on the back of the graphite plates so as to boost the net heat transfer rate to them. (The radiative flux out the front face of each plate cannot exceed the total heat flux to the rear of the plate, nor even match it since the front face also has a convective loss.) All metal components of this device are made from stainless steel to accommodate the high temperature, oxidative environment.

Propane (CP grade) was fed to the radiator from the same gas bottle that supplied the foam igniter and the pool pilots. Each type of burner has its own rotameter and control valve. Atmospheric air, from a compressor, was also fed to the radiator. The air to propane flow rate ratio used here was approximately 17 to 1.

The radiator is substantially smaller than the foam slabs. The graphite plate height, as noted, is 10 cm, 1/3 the height of the foam. The radiator is placed at foam slab mid-height, to allow the foam surfaces (and/or surface flames) to exchange radiation above and below (though the radiator gas inlet tubes block some of this). The effective length of the radiator is approximately 25 cm and it is placed approximately midway along the Vee.

The radiative flux pattern cast onto the foam surfaces at their mid-height is shown in Figure 5. The total heat flux was measured with a calibrated Schmidt-Boelter flux gage, accurate to approximately ± ½ kW/m^2. The flux profile is shown in Fig. 5 for two possible Vee angles, 30º and 45º; here the distribution for 30º applies. The skewness of the flux distribution is due to the 15º angle between the foam face and the radiator. The “Inner End of the Radiator” referred to in the abscissa caption in Fig. 5 is the end toward the narrow end of the Vee. Note that the peak flux is about[17] 22 kW/m^2. This flux should largely add

[14] Electrical heating is impractical here since this device sits in the middle of a fire. Electrical heaters and their lead wires would have been destroyed.

[15] Graphite is well-suited to this application given its ease of machining, very high melting point and good thermal conductivity. However, it could be rapidly eroded by oxidation if not protected.

[16] In principle, the oxidant gas can be higher in oxygen than air. This would boost the radiator temperature and radiant flux. The cost of the substantial quantity of such gas required makes this impractical.

[17] The peak flux is approximate because there were indications, via infrared temperature readings of the graphite plates, that it was not equal from both sides of the radiator, at least near the “inner end”. The inner

to the flame heat flux when the foam surfaces are burning, yielding a total of the order of 50 kW/m^2. That total is appreciably less than the 80 kW/m^2 measured in an earlier study[18] of polypropylene-wrapped cushions in a CTB 133 mock-up [10], but it does help simulate the larger, more complex geometry of the chair mock-up. Here this flux causes a fairly rapid recession of the foam surface locally at the start of a test but is typically insufficient, by itself, to ignite the foam.

Because of the mass of the graphite plates and the metal support structure, the radiator requires ten minutes of pre-heating in order to reach its steady-state condition. This was done with the radiator well-removed from the foam Vee assembly. An insulated piece of aluminum sheeting, shaped into a Vee was in place protecting the foam slab surfaces when the hot radiator was lifted into place and positioned with the aid of a locator rod on the center of the Vee. Removal of the shield initiated a test and was followed within 10 seconds by the ignition of both the pool pilots and the vertical igniter at the narrow end of the Vee.

These tests were performed in the same calorimeter hood and atop the same catch surface and overall weighing apparatus as for the above chair tests. The values and durations for the propane flows to the various heat sources are best discussed in the context of the test results below.

The tests were videotaped from the front and from the side though the radiator (and the flames themselves) made it difficult to see details of events on some portions of the inner surfaces of the foam slabs. As with the chair tests, the order of testing was fully randomized. Figure 6 is a photo of a test of the Non-FR foam, rather early in the sequence, before it developed a pool fire. This rapid early involvement of much of the inward-facing surfaces of the foam slabs was fairly typical in this test.

Results and Discussion.

Chair Mock-Up Tests. These tests were performed first since they are the closest to the real world and help define the type of behavior that is to be emulated in the Vee tests.

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end of the radiator was typically displaced about 6 mm toward the left foam slab (left as seen from the open end of the Vee) to compensate for this unevenness. This appeared to be fairly successful, as judged by recession rates of the foam surfaces on either side of the radiator. The source of the unevenness appeared to arise both from uneven coating thickness on the graphite plates and slight asymmetries in the placement of the propane injectors relative to the graphite plates. Fine tuning could probably improve this but it did not appear to alter any conclusions here. A further problem with the radiator was seen near the end of the test series. In spite of its stainless steel construction, exposure to the hot gases (probably halogen acids from flame retardants in some foams) caused partial clogging of the some of the holes in the propane injectors. The net effect appeared to be a shifting of the balance of the flow somewhat rearward along the length of the radiator and this probably shifted the peak flux backward as well. This may have contributed to some of the noise seen in the data here.

[18] This value was the flux to a cold flux gage surface so it would have been as much as 10 kW/m^2 less to a burning surface.

Table 2 summarizes the heat release behavior[19] for the various cushion compositions. Figures 7 and 8 show examples of the transient heat release rate (HRR) behavior for opposite extremes of foam flammability, the Non-FR foam and the high melamine foam (Foam P). Note the HRR scale on both graphs is the same, but the time scales differ by more than a factor of two.

The two polypropylene cover fabrics used for all of these cushions are completely thermoplastic in nature. Being unretarded, they are also quite flammable. In a typical test, within ten seconds or so of igniter initiation, the seat back fabric near and above the igniter split open and the melting fabric receded and curled into vertically-oriented clumps, mainly to the sides of the split. The retreating clumps ignited and began to drip flaming material onto the seat; these clumps continued to recede and thereby led the flame spread process on the vertical surface. The fabric on the inside of the arms behaved similarly while the seat both accumulated flaming fabric (and foam) melt and the flame spread outward on its fabric, as well. Ultimately, the entire inner seat area had been ignited. For the Non-FR foam in Fig. 7, essentially all of this inner seat area was then burning at the same time and this, plus a small pool fire on the Marinite, gave the initial HRR peak.

The pool fire formed first (in all cases) under the left rear corner of the mock-up, beneath the area where the igniter first began the consumption of material. That consumption ultimately provided a path (evidently between the seat and arm cushion) for polymer melt to flow off the seat area and onto the Marinite "floor". For the highly retarded Foam P in Fig. 8, by the time that flames had spread over the entire seat area, much of that area (especially vertical surfaces) no longer continued to burn, presumably because of a lack of flaming fabric on these areas. The left arm and seat back cushions showed significant shape distortions by this time. Both mock-ups then showed a temporary decrease in HRR, probably because the increasing consumption, distortion, and partial dropping of the cushions was lowering the burning area and decreasing the radiative feed back among flaming surfaces. The material falling from the Non-FR chair continued to burn vigorously and without hesitation as it fell to the floor and this ultimately led to a second, higher HRR peak as this pool fire grew somewhat via "radial" melt flow (of the order of 15 cm in radius beyond its initial size) and began to lose less heat to a now heated slab of Marinite. The material falling from the Foam P chair appeared to include much flaming fabric and much non-flaming foam in a randomly-clumped mix. As the fabric flames persisted amidst the fallen material, they melted and then evidently ignited much of the foam, yielding the second HRR peak from what was by then primarily a pool fire[20]. The pool fire in the Non-FR foam case was large enough to be self-feeding before the bulk of the material came off of the chair frame. This would tend to increase its peak HRR or at least shorten the time to that peak. This effect appeared to come into play only late in the

[19] Table 2 includes both the actual peak HRR values and a ± 5 s value averaged around the peak. The difference gives some indication of how sharp (and possibly noise-affected) the peak is. The Figures here use the actual peak values, not the averaged values.

[20] Inspection of Table 2 shows that the majority of the chair mock-up tests yielded only one HRR peak, rather than two distinct peaks. In most cases this was the result of the full chair seat burning merging smoothly into chair collapse and pool fire evolution.

collapse of the Foam P chair, where the pool fire became relatively large only after the bulk of the material was off the chair frame.

The above brief description does not begin to convey the extreme disorderliness of how the flames spread and engulf two thermoplastic materials that start out in the simple, clean geometry shown in Fig. 1. The only thing that should come through clearly is that there is considerable movement of the fabric (and then of the foam) to new locations as it begins to burn. For the fabric, this movement is caused by a variety of forces from fiber shrinkage to surface tension to gravity. Similarly the foam collapses when heated as its molecular cross-links are broken and the resulting liquid moves under the influence of capillary forces and gravity. Both liquefied materials are gasifying as they flow and, during this flow, they partially mix together.

A simplified, qualitative picture of what is happening in these chair mock-up burns is useful conceptually since it relates to what is needed in the Vee tests. The various movements of the liquefied materials create, both on the chair seat and then on the floor, a sort of heterogeneous, "plum pudding" mix of fuels, one of which is totally non-flame-retarded and the other of which is (in most cases tested) significantly flame retarded. The mix is heterogeneous on a scale of centimeters in many locations. In other areas the fuels are more coarsely mixed. On even the finer scale of unmixedness, the polypropylene melt, being a very energetic material, is able to burn intensely with little interference from nearby flame retardants[21]. Instead, this intense burning serves to at least partially defeat the flame retardant in the nearby foam melt. Essentially all flame retardant mechanisms ultimately work by pushing the energetics of the flame into an imbalance where heat losses will overcome heat generation and the flame will extinguish. Added heat restores the balance and stabilizes the flame. The intermixed polypropylene flames provide this added heat, but they have a limited spatial range of effect. In areas where the unmixedness scale is larger than a few centimeters, sufficiently flame-retarded foam will not burn except on areas near where it abuts the polypropylene flames. We will return to this picture below in the context of how the pool pilot flames are to be used in the Vee tests.

Figure 9 shows the peak heat release rate for the six chair mock-up compositions that did not use a polyester fiber wrap between the outer fabric and the polyurethane foam. In accord with the discussion in the Introduction, the fires ranged from serious (1/2 MW) to relatively benign (ca. 200 kW). The ½ MW fires will not come close to causing room flashover by themselves, but they are large enough to begin a progression of second item ignitions that, combined with the chair, could do so. Furthermore, a 500 kW fire by itself can cause fatal heat conditions in the room of origin and beyond while posing very challenging escape conditions [5][22]. A fire that peaks at 200 kW will probably not pose either of these threats. The moderately flame-retarded foams Y and G give intermediate results for which both threats are somewhat alleviated but not eliminated.

[21] The two liquid fuels would probably have to be mixed on the scale of millimeters before they would burn more like a homogeneous mixture that was partially flame-retarded.
[22] The hot smoke layer, which is deadly, drops to about ½ m above the floor.

It is worth noting that these results are obtained for a very energetic fabric and one can expect that many real world fabrics, particularly those that include sufficient quantities of charring fibers[23], would give lower HRR peaks. As noted above, we are seeking to be at or near worst-case in the behavior elicited from a foam so that a foam which looks very good here is unlikely to provide unexpectedly bad behavior in real world usage.

Note that the replicate tests in Fig. 9 were all done with the two differently-colored versions of the same polypropylene cover fabric. In the Figure, the results for the darker colored version (Fabric B) are always shown as the right hand bar in each set of two tests per foam type. These two fabrics, which differed in basis weight by less than three percent, gave results differing by as much as 20 %, with the darker fabric always being higher in peak HRR. There was no obvious reason for this that one could discern from visual inspection of the fabrics[24]. This is an unexpected demonstration of the variability of fabric fire behavior and yet another[25] indication of why it is preferable to avoid "standard" materials as components of a test of a polyurethane foam.

Another caveat regarding Figure 9 is that the HRR peak values shown for the Graphited Foam are the initial peaks from Table 2; see the further description of the behavior of this sample below. We discuss the reason for using the first HRR peak here in the context of the Vee test results below.

Figure 10 shows the more limited results obtained for cushions having the polyester fiber wrap between the cover fabric and the polyurethane foam. Here, for the Graphited Foam, the comparison is the second (and highest) HRR peak for the cushions with and without the polyester (PE) fiber wrap since that is most relevant here. Inspection of the results in Fig. 10 shows that the presence of the fiber wrap essentially removes all distinctions among the foams in the cushions – the cushions based on the two best foams in Fig. 9 and on one of the intermediate foams all look bad. In effect, the PE fiber wrap (coupled with the PP cover fabric) dominates the fire behavior of the chair mock-up[26]. Given the popularity of this fiber wrap in current furniture, this is a disturbing result – it suggests that, if this material is used, there is little to be gained by improving the flammability of the foam. Fortunately, as a result of pending flammability regulations on other products (bed clothes, mattresses) less flammable materials are becoming available that can fill this fiber wrap role and remove the threat it poses.

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[23] The charring fibers in a fiber blend will probably be most effective if included in both warp and weft directions so that the fabric resists splitting open when heated and exposing the foam (or fiber wrap) beneath it. Unpublished NIST results with 100 % cotton show that such strongly charring fabrics can also retard pool fire formation by soaking up and holding a good amount of foam melt.

[24] The darker-colored fabric was only slightly darker in visible light. One would expect that they would both be essentially black in the infrared where their radiative properties might enter in to their fire performance.

[25] The standard fabric issue has caused great difficulties in the development of flammability tests for such items as furniture.

[26] The mechanism by which this occurs is not clear. There would seem to be at least two possibilities: first, that the polyester fiber melt tends to stay somewhat preferentially on the outer surface of the "fuel mix" even as it collapses to the floor, thereby dominating the burning, and/or, second, that the exposed "fuel" area of the collapsed mock-up that is flaming is at a maximum (i.e., covering the entire outer surface of the collapsed fuel mass) when the PE melt is participating in the burning.

The Graphited Foam exhibited some unique behavioral aspects. The expandable graphite appears in the unheated foam as random black flecks that are seemingly a minor component. These flecks expand by about 100× when heated and form what is effectively a char layer that is insulating and has the added benefit, apparently, of fully absorbing all of the melt which the foam may generate. Thus, the burning of the fabric on the exterior cushion surfaces turned the cushions into somewhat fuzzy black versions of their former selves, which largely preserved the original mock-up geometry. If the fire stopped at this point the results would have been a moderate HRR peak corresponding to full involvement of the interior seat surfaces; see Figure 11. Persistent burning, especially around the seat periphery (including, surprisingly, the upper front edge of the seat cushion), coupled with flames spreading slowly on the fabric to the outer surfaces of the cushions led eventually to a slow resurgence of the seat interior fire. This began earlier than one might expect.[27] It was once again evident that radiative interchange in the seat interior was able to boost the flaming seen there. This was a relatively minor effect compared to what began at about 650 s – disintegration of the charred foam cushions. A large chunk of mildly flaming foam/char fell off the seat back initially, but this immediately flared up into an interactive floor fire because the dropped material contained substantial amounts of pre-heated fuel (incompletely degraded foam from the interior plus, perhaps, absorbed foam melt). This was soon followed by similar material falling from the bottom of the seat cushion and the resultant "pile fire" on the floor was strongly interactive with the now-exposed foam surfaces above. The result was a rapid spike in HRR to more than 350 kW. The term "pile" is aptly descriptive; there was a mound of dry, charred chunks forming the floor fire; not a liquid pool.

The preceding behavior reveals an important point: it is not sufficient for a foam additive to prevent melt flow to lower surfaces[28] unless it also keeps the foam/degraded foam mass intact until the fire dies out. The degraded foam needs to have mechanical strength. How much strength is sufficient will depend on the chair design since potentially supportive wooden frame members could be expected to remain essentially intact on the time scale shown in Fig. 11. One could perhaps estimate worst-case conditions (and thus the maximum char strength required) from the assumption that charred foam be a self-supportive beam with a span equal to the length or width of the cushion (ca. 45 cm). This would probably translate into a minimum tensile strength for the degraded foam/char since the "beam" would be in tension on the bottom.[29]

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[27] Simple thermal diffusion with a typical organic material's diffusivity of about 0.002 cm^2/s would imply a thermal wave depth in the foam of only about 1 cm at 400 s when the HRR in Fig. 10 begins to move upward after a dip. The foam was 7-1/2 cm thick. Even with heating from both outer surfaces, one would expect an appreciably longer delay before thermally-thin behavior began to kick in. Two possible reasons for this sooner than expected resurgence are (1) the expanded graphite char has an appreciably higher thermal diffusivity than the foam (2) foam melt was moving inward by capillary flow, carrying heat with it.

[28] Here this lack of melt flow did still buy several minutes of time and this can be an important factor in escape from a fire.

[29] Another additive system which has been shown to form a melt-absorbing char-like residue is carbon nano-fibers [4]. Since the fibers form an interlocking physical network and have much higher strength along their longitudinal axis than the very weak and flaky expanded graphite, they may give the desired tensile strength to the charred foam residue.

Table 2 also reports the time to the heat release rate peaks. Obviously, in the real world context of residential furniture, it is better to delay the heat release rate peak as long as possible to allow more time for fire discovery and suppression or escape. The initial peaks, which, as noted above, correspond to full involvement of the interior seat area, all come within about 2 min to 4 min after ignition, which is a very short time.[30] There is no simple trend in these numbers, i.e., the more flame-retarded foams do not necessarily give longer times to the first peak. In fact, the Graphited Foam gives the shortest time, perhaps because its fluffy "char" surface serves as a good re-radiator and flame-spread enhancer in the concave chair seat geometry. This foam also gives the longest time to the second (higher) HRR peak. However, as explained above, this is a result of the collapse of the foam "char" and is dependent on chair design. Foam P not only gives a lesser HRR peak but it also requires a significantly longer time (8 min to 8 ½ min) to reach it (in the absence of PE fiber wrap).

Table 3 summarizes the overall energetics of the chair mock-up tests. The estimated energy content values for the mock-up assemblies come from best estimates of the mass of each component in a cushion plus handbook values [11] of the heat of combustion of closely similar polymers. The melamine content of Foams Y and P was separately accounted for since melamine has a distinct heat of combustion. The heat evolved in each fire test comes from the integral of the HRR curve. The percent mass recovered comes from the scale under the mock-up. This last has one significant caveat: the water content of the Marinite P board was not controlled. Marinite P has a 3 % equilibrium moisture content, amounting to 0.4 kg here. Half of this may have been driven out by the larger pool fires, somewhat lowering the calculated percentage mass recoveries.

Table 3 shows that the various mock-up compositions varied by a factor of more than two in initial energy content, mainly due to the differences in polyurethane foam density. Note that the highest energy contents go with the most flame-retarded foams, again because of foam density. It should be noted that in many cases the fabric energy content (ca. 50 MJ) was greater than that of the foam. Despite its greater mass, the energy content of the PE fiber wrap (ca. 37 MJ), when present, was less than that of the fabric.

Table 3 shows that the trend of energy recovery varies inversely with mass recovery, as expected. It is perhaps surprising that the energy recovery, even for the unretarded foam is less than 90 %. The general trend of poor energy recovery reflects a large amount of material being left behind, mainly on the Marinite. Often the pool fires did not burn all the way to the pool periphery, presumably because of heat losses to the cooler Marinite surface there. With the foams having appreciable melamine content (Y and P), another factor also entered in – melamine slowly forms an intumescent char in a pool fire. With Foam P this char layer could reach 15 cm in depth. It tended to sequester flammable melt material beneath it, preventing its burning. This is probably the reason that the combination Foam P/ PE Wrap / Fabric A or B gave more residue at the end of what was a more intense fire than Foam P/ Fabric A or B.

[30] Of course, the ignition source here is large and intense. One could expect longer times and bigger differences among the foams with a match-sized ignition source, though this polypropylene fabric would probably lead to the development of comparable peak HRRs ultimately.

Modified Vee Tests. The above results, particularly those for Foam P, changed the concept of what was demanded from the Vee tests if they were to correlate with the chair mock-ups. In previous work [7], Foam P responded in an essentially passive manner, melting, not burning, in the original Vee test exposure (without the central radiator or pool pilots). In preliminary tests here with the added radiator but with the pool pilots set at a level that was strictly a small, local pilot flame (ca 2 cm high flames), the results were again essentially the same; Foam P simply melted with minimal to no heat release. This is not, of course, how it responded in the mock-up tests above, where, though it was the best foam of those examined, it certainly contributed significant heat to the fires.[31]

Recall the simplified picture of the chair mock-up behavior posed above. A heterogeneous blend of melting, burning polypropylene fabric and foam interact both on the chair seat and on the Marinite floor. The pool pilots of the Vee test offer a chance to mimic this, but only if the propane supply to them is made comparable to the rate of consumption of the polypropylene fabric. Of course, since the fabric is melting, contracting and flowing to new locations as it burns we have no accurate way to pin down its burning rate locally as a function of time. We simply assume that the fabric on one face of a cushion burns in a time of the order of 200 s and that a comparable fabric burn rate continues when the cushions collapse to the floor and other portions of the fabric are exposed. This led to an estimate that the propane flow to the pool pilot tubes should be increased substantially (total flow of approximately 23 L/min). In addition, the pool pilot tubes were shifted somewhat upward above the Marinite (to about 2 cm) so that intumescing foam melt from foams with melamine could still flow below them. At this higher propane flowrate, the pool pilot flames become tall enough[32] to not only act locally in the pool fire but also to sweep upward on the interior face of the foam slabs, possibly anchoring flames there as well.

Figure 12 is a photo of the apparatus with the radiator and pool pilots operating in the absence of a sample so that one can get some sense of the size of the pool pilot flames. Though the flames there look disorganized, when the sample was in place, the plume flow induced by the radiator caused the pool pilot flames to come inward to the interior of the Vee and move up along the inner face of the two foam slabs being tested.[33] Flame contact was maintained, even as the foam faces contracted, because the pool pilot tubes were oriented diagonally under the sample slabs. Note that the original concept of a differential flame spread process on the inner faces of the Vee is largely submerged in this version of the test though there is still fire spread on the interior Vee surfaces out beyond the end of the radiator that varies in rate with foam composition (and can leave a small amount of a heavily retarded foam, like Foam P, unburned).

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[31] Consider the case of Foam P/ Fabric A or B in Table 3. For this combination, the PP fabric accounts for a maximum of 41 % of the available energy, whereas the total recovery of potentially available heat was 62 to 67 %.

[32] These flame jets point down at the Marinite but then rise up vertically, driven by buoyancy.

[33] There was one improperly oriented hole on the outer end of the left pilot tube that caused flames to tend to partially go up the outside face of the sample in that location.

The following sample exposure regimen was used throughout the Vee test series. With the sample in place and shielded, the pre-heated radiator was inserted into the middle of the Vee. The shield was withdrawn and, within 10 s the vertical igniter (narrow end of Vee) and the pool pilots were lit. The vertical igniter was turned off after 60 s. The radiator was left in place for 6 min then removed. The pool pilots were shut off after 10 min. Typically (except for the Graphited Foam), the sample was completely melted before the time that the radiator was removed. Also, for several foams, sample combustion had largely ceased by the time that the pool pilots were turned off. The total propane heat release rates at each stage of sample exposure were as follows.

Time	Sources	Heat Release Rate (kW)
1st 60 seconds	Radiator + Vertical Igniter + Pool Pilots	51
1 min to 6 min	Radiator + Pool Pilots	44
6 min to 10 min	Pool Pilots	32

The response of the foams (again, except the Graphited Foam) was qualitatively similar. The radiator quickly initiated surface recession and this accelerated as soon as the pool pilots came on. However, it typically took a few tens of seconds before melt could be seen accumulating on the Marinite surface below the sample faces and more time before one could see that flames were attached on this pool. The most intense pool burning took place on the surface below the interior of the Vee since there was radiation there from the pool pilot flames, from flames on the sample face and from the radiator. Any melt flowing inward thus tended to be consumed. Melt flowing outward was escaping to a much less heated area, however, since it saw all radiant sources at an increasing distance. Heavily retarded melt, like that from Foam P, would typically not burn much beyond 2 cm to 3 cm outside the pool pilot tube lines. A closer representation of the conceptual picture given above of the heterogeneous fuel mix in the chair tests would have required that the there be more than the two pool pilot tubes so that a larger fraction of the pool area was forced to burn by further propane flames.

The calorimeter measured the total heat release rate from both the propane flames and the sample. Thus it was necessary to do a baseline run[34] without a sample to get the time-varying contribution from the propane flames alone, which could then be subtracted out. Figure 13 is an example of the HRR data from a test before and after this subtraction.

[34] The flow system used here relied on one bottle of propane for all of the burners and the radiator. As each separate burner was turned off, this tended to cause the propane flow to step upward slightly and so the flows had to be adjusted. Since this distracted from observing the sample behavior, it was done at variable times during the tests. The small influence of these flow shifts was assessed during the baseline run and then accounted for in averaging the baseline value to be subtracted from each segment of the exposure regimen. Use of three separate bottles of propane would have obviated this issue.

Table 4 summarizes the results from the modified Vee tests. Only two of the foams gave two HRR peaks, the Visco Foam and the Graphited Foam. For the former, the second peak merged into the first and appeared to be due to simple growth of the pool fire by outward flow and as a result of in-depth heating of the Marinite. For the Graphited Foam, the second peak was mostly the same onset of thermally-thin behavior plus burning on the back side as was seen in the early part of the chair mock-up tests with this foam. However, the major cause of the second peak in the chair mock-up, disintegration of the charred sample followed immediately by an interactive "pile fire", was not seen here. The charred sample was too solidly held on the 13 spikes per slab for it to disintegrate appreciably (a small chunk feel away from the back of the sample to a non-interactive location). For this reason, when we compare the chair mock-ups with the Vee test results below, we use the first peak for the Graphited Foam rather than the second peak since the first had a much closer physical correspondence between the two types of test (full seat interior involvement in the chair and full Vee inner surface involvement in the Vee test).

For all of the other foams the peak HRR came as the full or near-full involvement of the inner surfaces of the Vee, accompanied by a strong pool fire below the Vee, gave way to a dominant pool fire when the foam slabs essentially completed their collapse onto the Marinite. This dynamic process corresponds fairly closely to the processes occurring near and at the peak in the chair mock-ups. Note that these single peaks occurred in the first 30 s to 90 s of the test when the "assaults" on the foam by the three external heat sources were occurring. That time range seems to have more to do with foam density than anything else so there is no predictive value in the time-to-peak obtained from the Vee test; see Figure 14. This is probably a consequence of loading all of the thermal insult on the foam immediately in the Vee test to get directly to the state corresponding to the full interior surface involvement of the chair. This state takes a varying amount of time in the chair mock-up due to differing flame spread and radiative feedback conditions with different foams.

The predictive value of the Vee test for peak heat release rate from a chair-like configuration is much better, as Figure 15 shows. The R^2 correlation coefficient here is 0.88 which, as the 95 % confidence limit lines show, is good enough to be useful. One can clearly distinguish and predict from the results of the Vee tests whether a foam will give a moderate or large fire in the form of a four cushion chair mock-up and one can make a semi-quantitative prediction of the peak heat release rate of that fire. This should provide a satisfactory basis for discriminating the real world flammability behavior of new polyurethane foam compositions. The approximate correspondence in physical circumstances and physical behavior at the heat release rate peak, noted above, between the two types of test is probably a key aspect of this correlation since the peak has much more to do with the dynamics of how the fire engulfs the melting, collapsing foam than it has to do with such things as the energy content of the foam.

The ability to correlate peak heat release rate is more important than the ability to correlate time-to-peak. First and foremost, one seeks to lower peak heat release rate, especially since, in all cases here, it occurs within a few minutes of ignition. If the peak HRR can be reliably reduced to a level where it does not pose a direct life threat or a second-item-ignition threat, then the time to the peak is not of great importance.

It must be noted that the correlation shown in Fig. 15 is highly specific to the conditions under which it was obtained. Thus, the particular correlation line shown there applies only to the use of the particular polypropylene fabric used here and to the specific propane flame and radiator exposure regimen used in the Vee tests. It is reasonable to expect that other correlations (not this same correlation) will exist more broadly for other fabrics and for other (not too excessive) variants of the heat exposure regimen. Because of the design of the Vee test and the energetic fabric is has been correlated with, we expect the Vee test results to be predictive of near worst-case behavior in a fabric/foam upholstered chair.[35] In this sense the Vee test appears able to give a meaningful assessment of likely real world performance of new flame-retarded foam formulations.

One caveat is significant here. As noted elsewhere in this report, one new foam additive class of interest is carbon nano-fibers [4]. Their interest derives from their evident ability to retain any melt generated during foam degradation much as did the Graphited Foam used here. The correlation here should work for these foams <u>if</u> they give the charred foam sufficient strength to stay intact in a chair configuration[36]. If they do not do this, they will presumably yield the same kind of threatening, interactive "pile fire" seen here with the Graphited Foam in the chair mock-ups. That behavior is only a modest improvement over a weakly retarded foam.

In Ref. 4 the foams were assessed using a bench-scale test that was done in the cone calorimeter using less than a liter of foam (compared to about 28 L in the Vee test). Testing on this much-reduced scale is highly desirable for various reasons. It requires only a fraction of the foam that can be produced in a hand-made test batch. This facilitates assessment of new formulations. Furthermore, the testing in the cone calorimeter is fast and does not require access to an operationally-more-expensive furniture calorimeter. However, these small scale tests are useful only if they are truly predictive of real-scale behavior. Some correlation with the earlier Vee tests was reported in Ref. 4. Here, however, we have seen that when we attempted to look at the most flame-retarded foam (Foam P), it was necessary to subject it to much more severe heating conditions in order for it to behave as it does in the context of a burning chair. The test used in Ref. 4 would likely cause this foam to do little more than passively melt, thus the test would give an overly optimistic indication of its real world performance. It remains to be seen whether the bench-scale test can be modified so as to give a proper assessment of more heavily flame retarded foams. Certainly the cone heat flux can be raised considerably from the level used previously but it may also be necessary to more closely mimic the flame heating and pool pilot effects used in the Vee tests here, as well as enlarge the available pool area.

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[35] Increased size (love seat, sofa) and/or substantially increased mass of flammable materials could raise the real world HRR peak. Also, as noted earlier, if PE fiber wrap is used, it will overwhelm the foam flame retardants and produce a result that will not correlate with a test such as the Vee test.

[36] At present, this can only be determined by actually doing a chair mock-up test. This puts a heavy demand on preparation of new foam formulations since it calls for 64 L of foam per test and professionally-made cushions.

Foam P is a natural test case for further development of this bench-scale configuration, as it was in this study.

Summary and Conclusions.

We have carried out an experimental comparison of the fire behavior of six polyurethane foams of widely differing properties in two contexts. The first was the California Technical Bulletin 133 chair mock-up, which is an accepted analog of real upholstered chairs. Here the foams were covered with a moderately heavy, 100 % polypropylene, thermoplastic fabric, which, by itself, burns vigorously. Some cushions also included a layer of polyester fiber wrap between the cover fabric and the foam. The second test context was a newly developed Vee test configuration which was modified here to more closely mimic the thermal insult which the burning fabric imposes on a foam. The advantages of this Vee test are twofold. First it uses less than half of the volume of foam required in a chair mock-up. Second, it requires no standard fabric (which does not exist at this point). The purpose of the comparison of the two test methods was to determine if the Vee test produces results which correlate with the chair mock-up test. If so it would provide a preferred basis for assessing new foam formulations.

The chair mock-up tests were conducted first and these revealed some significant points. First, it was clear that inclusion of polyester fiber wrap into a chair produces a uniformly serious fire regardless of the level of flame retardants in the foam. We infer that real progress in reducing the flammability of upholstered furniture will require that less flammable substitutes for this material (increasingly available) be used. The second point to emerge was that even the most flame-retarded foam used here (a high melamine foam) contributed significantly to a chair mock-up fire. Since this foam was not seen as a contributor in earlier Vee test configurations, we inferred that the severity of the Vee test exposure must be increased for it to mimic reality. Finally, it was noted that a foam with expandable graphite was very successful at preventing a melt fire during a chair mock-up test. However, since the “charred” foam did not hold together as the test progressed, it still gave rise to an equivalently-severe, interactive fire between the chair and solid material that fell to the floor. We inferred that carbon nano-fibers, which have a similarly promising ability to prevent foam melt flow, will be truly useful only if they overcome this char disintegration problem.

The modified Vee tests were conducted on the same six foams (plus two others). The addition of a central radiator plus “pool pilots”, turned up to emulate the burning rate of the polypropylene fabric, gave physical behavior during the heat release rate peak that was largely similar to that seen during the peak of the chair mock-up fires. The time to peak heat release was not correlated between the two types of test but the peak heat release rate was well-correlated. The result is potentially useful in assessing the flammability of new foam formulations. It still calls for an inconveniently large (though manageable) amount of foam and prompts the search for a still smaller test configuration. It remains to be seen if an existing test, conducted on a very small sample in the context of the cone calorimeter, can be properly adjusted in light of the present study so as to evoke realistic behavior from highly-retarded polyurethane foams. For charring (i.e., non-melting) foams, it may be necessary to complement such a cone-based heat release rate test with a measure of their ability to resist physical disintegration while burning.

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Table 1. Properties of Polyurethane Foams[37]

Designation	Density (kg/m^3) (lb/ft^3)	Comment
Non-FR	23.2 (1.45)	Non-flame retarded; 30 - 36 lb Indentation Force Deflection
Visco	63.2 (3.95)	Viscoelastic foam; positive for halogens[38]; possibly contains an inorganic filler
Z0	23.2 (1.45)	6 % Br/P flame retardant
Green FR	24.3 (1.52)	6.1 % Br/P flame retardant; 2.0 % melamine
G	15.5 (0.97)	9.7 % Br/P flame retardant; 1.1 % melamine
Y	26.9 (1.68)	3.5 % Cl/P flame retardant; 11.1 % melamine
Graphited	54.4 (3.40)	Expandable graphite; positive for halogens
P	42.2 (2.64)	2.9 % Cl/P flame retardant; 28.4 % melamine

[37] For the foams with a precise FR content analysis, the data and the foams were provided by the Consumer Product Safety Commission.
[38] The applied test was a simple copper wire/ Bunsen burner flame test that gives a green color in the presence of a halogen.

Table 2. Summary of Four-Cushion Mock-Up Chair Test Results

Materials	Test #	HRR Peak 1 (kW)	Avg'd Peak 1 (kW)	Time to HRR Pk 1 (s)	HRR Peak 2 (kW)	Avg'd Peak 2 (kW)	Time to HRR Pk 2 (s)
Non-FR Foam / PP Fabric A	1	408	400	196			
"/ PP Fabric B	13	531	520	197			
Foam Z0 / Fabric A	11	451	444	183			
" / Fabric B	17	532	509	160			
Foam G / Fabric A	14	284	274	167			
" / Fabric B	8	333	326	185			
Foam Y / Fabric A	7	290	282	244			
" / Fabric B	15	387	379	201			
Graphited Foam / Fabric A	6	155	148	125	366	347	732
" / Fabric B	10	197	189	115	266	250	720
Foam P / Fabric A	3	113	107	238	183	179	491
" / Fabric B	12	See Note			210	206	509

Note: For this combination, the first peak was indistinct from the noise.

Table 2. (Cont'd) Summary Four-Cushion Mock-Up Chair Test Results
(Cushions with Polyester Fiber Wrap)

Materials	Test #	HRR Peak 1 (kW)	Avg'd Peak 1 (kW)	Time to HRR Pk 1 (s)	HRR Peak 2 (kW)	Avg'd Peak 2 (kW)	Time to HRR Pk 2 (s)
Foam Y / PE Wrap / PP Fabric A	9	449	435	171			
" / " / PP Fabric B	5	482	471	193			
Graphited Foam / PE Wrap / Fabric A	16	205	199	111	495	459	481
" / " / Fabric B	2	233	227	102	442	427	348
Foam P / PE Wrap / Fabric A	4	515	498	236			
" / " / Fabric B	18	511	497	255			

Table 3. Summary of Energy and Mass Recovery Percentages

Cushion Composition	Estimated Energy Content (MJ)	Heat Evolved in Fire (MJ)	Percentage of Energy Recovered	Percentage of Mass Recovered
Non-FR Foam: Fabric A, Fabric B	**87.5, 88.6**	**70.5, 77.6**	**81, 88**	**5.3 (Fab. A)**
Foam Z0: Fabric A, Fabric B	**89, 90**	**74.1, 73.2**	**83, 81**	**5.3 (Fab. B)**
Foam G: Fabric A, Fabric B	**76, 76**	**53.5, 62.2**	**71, 83**	**9.2, 0**
Foam Y / Fabric A, Fabric B	**94, 93**	**65.7, 71.8**	**70, 77**	**15.8, 14.1**
Graphited Foam: Fabric A, Fabric B	**142, 142**	**85.5, 95.4**	**60, 67**	**25.5 (Fab. A)**
Foam P: Fabric A, Fabric B	**122, 115**	**76.2, 77.2**	**62, 67**	**27, 32**
Foam Y+ PE Wrap: Fabric B	**90**	**78.7**	**87**	**26**
Graphited Foam + PE Wrap: Fabric B	**174**	**117**	**67**	**20**
Foam P + PE Wrap: Fabric A, Fabric B	**153, 163**	**76, 87**	**50, 54**	**42, 34**

Table 4. Summary of Modified Vee Tests of Polyurethane Foams

Polyurethane Foam	Test #	HRR Peak # 1 (kW)	Avg'd Peak 1 (kW)	Time to Peak 1 (s)	HRR Peak # 2 (kW)	Avg'd Peak 2 (kW)	Time to Peak 2 (s)	Total Heat Released (MJ)
Non-FR	3	162	156	56				15.3
"	18	176	170	55				16.6
Non-FR Visco	4	197	191	86	208	203	152	38.7
"	6	143	138	78	138	133	173	31.2
"	15	174	168	92	182	175	178	37.5
Green FR	9	168	164	50				14.9
"		172	168	65				15.7
Z0	14	221	210	61				15.4
"	17	214	206	64				15.5
G	1	84	81	29				9.3
"	8	88	86	37				9.0

Table 4. (Cont'd) Summary of Modified Vee Tests of Polyurethane Foams

Polyurethane Foam	Test #	HRR Peak # 1 (kW)	Avg'd Peak 1 (kW)	Time to Peak 1 (s)	HRR Peak # 2 (kW)	Avg'd Peak 2 (kW)	Time to Peak 2 (s)	Total Heat Released (MJ)
Y	2	103	95.5	60				9.2
"	16	105	97	60				8.0
Graphited	7	40	39.6	37	52	50.5	499	26.7
"	10	40.6	38.4	49	58.7	55.5	502	27.8
P	5	42.2	39.7	67				5.2
"	12	34	30	44				6.0
"	13	55	53	65				6.6

Figure 1. Four cushion mock-up in CTB 133 mock-up frame, showing placement of Tee burner igniter.

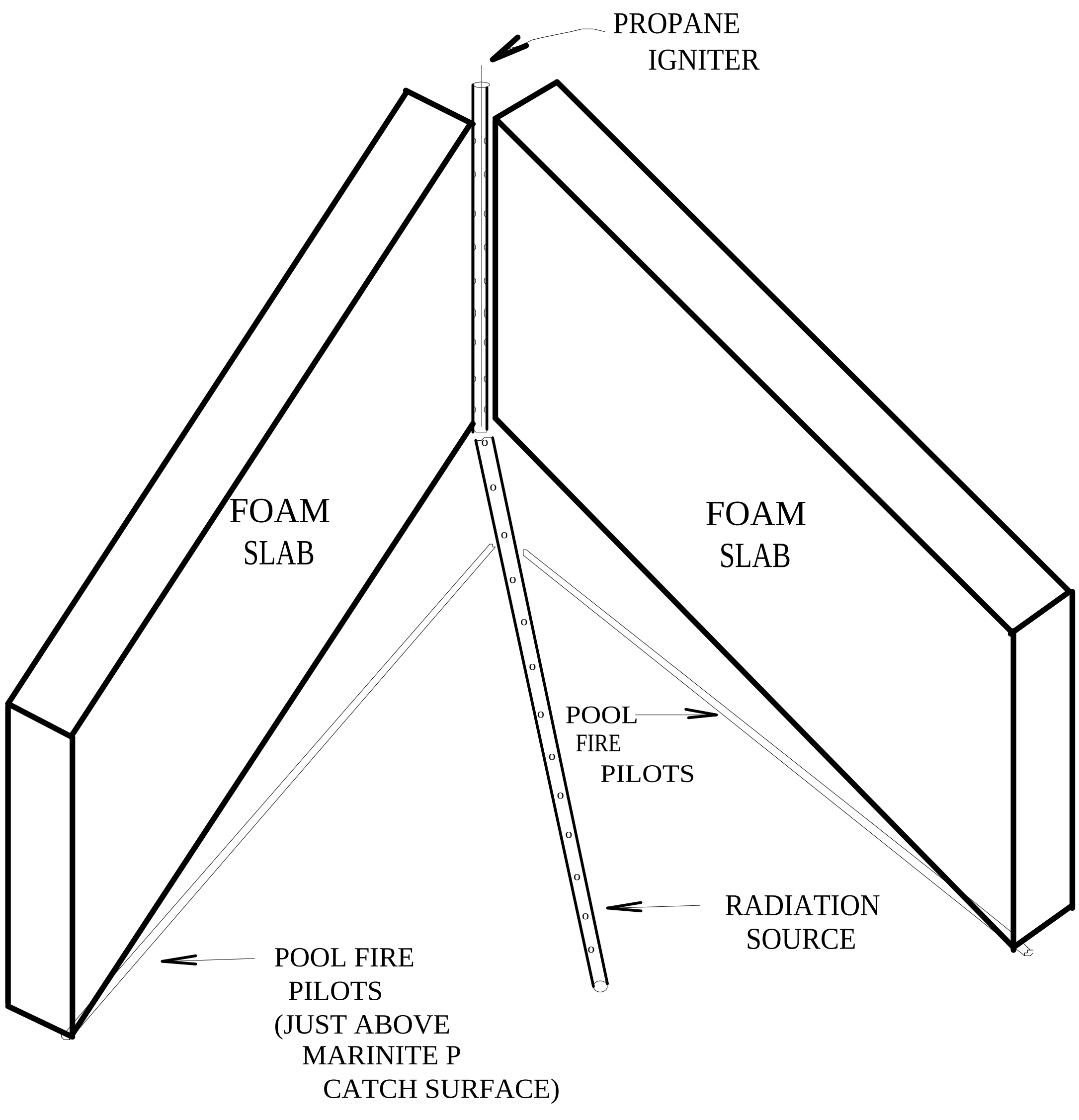

Figure 2. Sketch of the modified Vee test configuration showing the approximate placement of the central radiator and the pool pilot tubes.

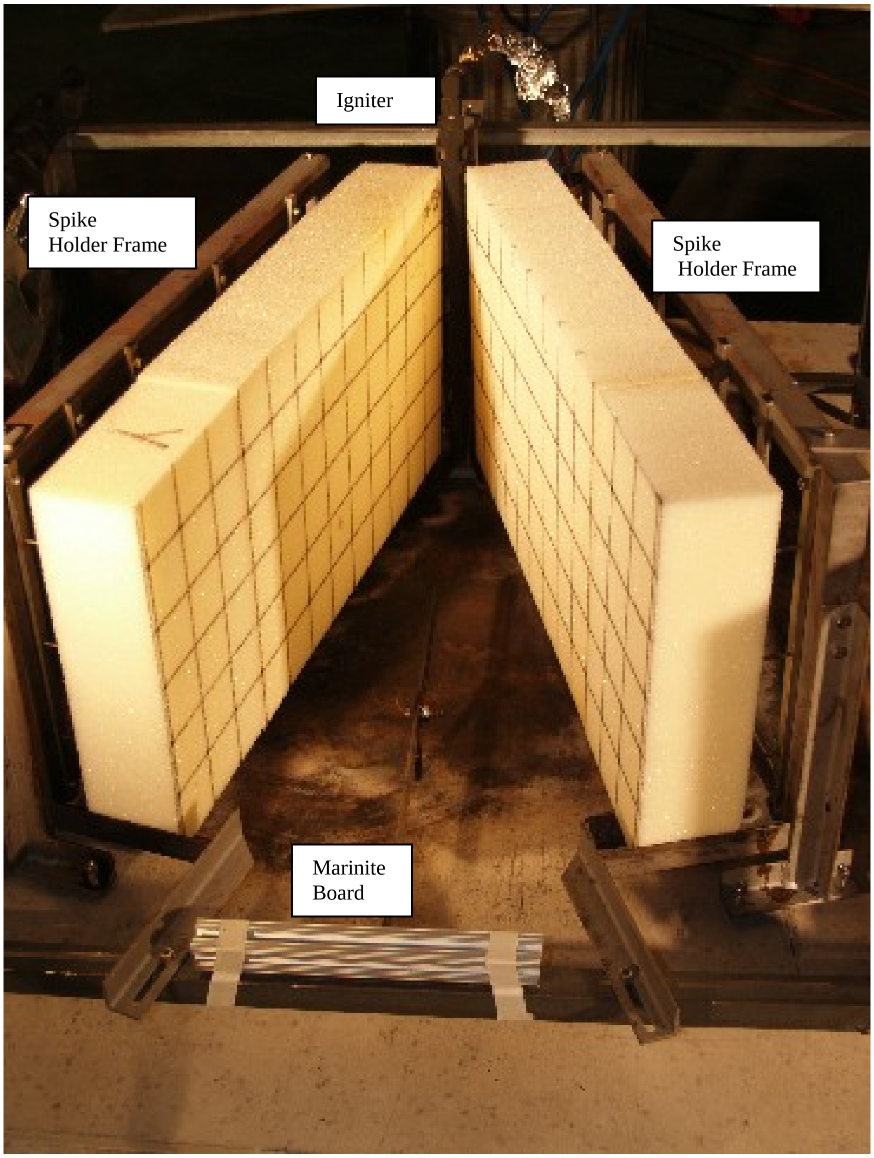

Figure 3. Photo of Vee test set-up showing foam mounted on spikes that protrude into the back surface of each slab and are held by the frames seen on the outside of each slab. The top of the vertical igniter is just visible above the narrow end of the Vee. The grid drawn on the foam slab faces is composed of 5 cm squares. The Marinite catch surface (partially discolored) is seen below the Vee assembly.

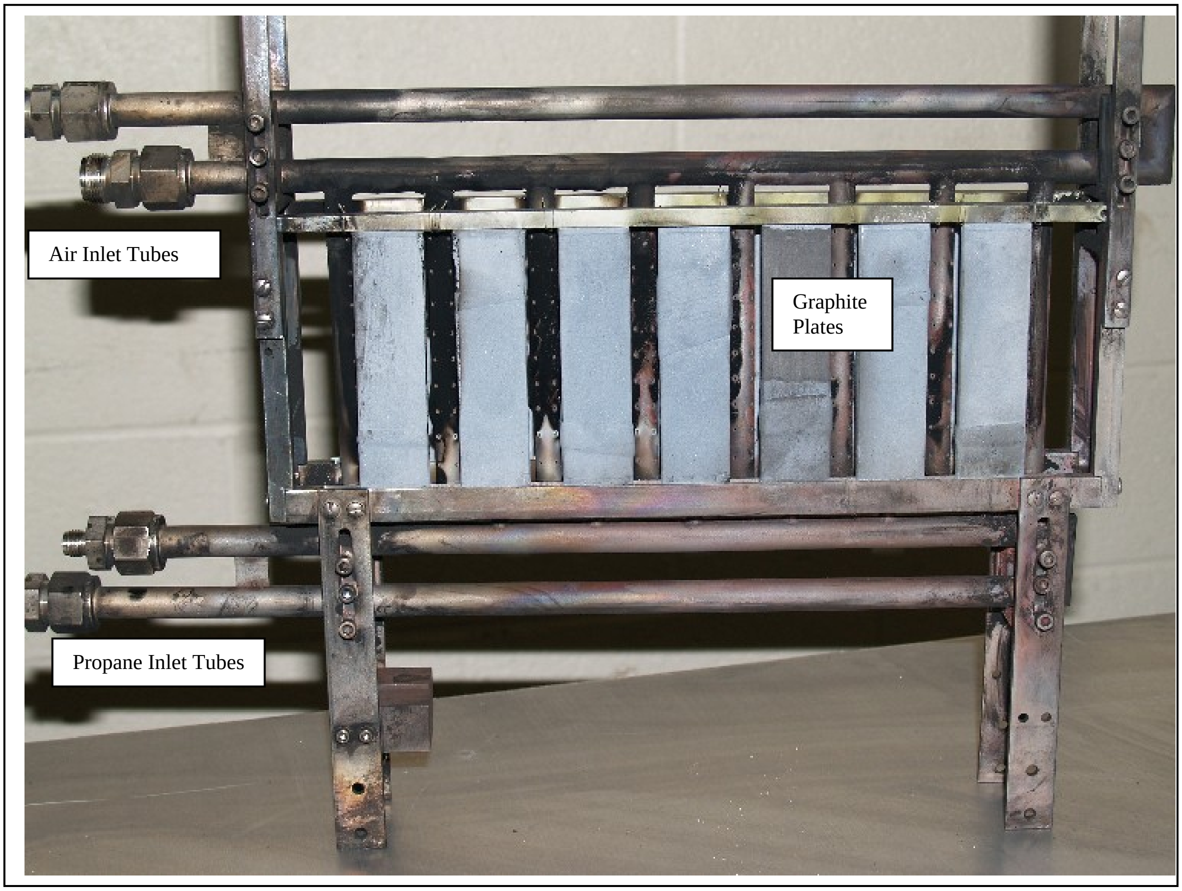

Figure 4. Side view of radiator showing one of the two rows of vertical, coated graphite plates mounted in a frame that supports propane and air injectors between the rows to heat the plates. The two lower tubes on the left introduce propane to opposite ends of the comb-like propane injector array; the two upper tubes serve the same purpose for the air injector array which is visible through the spaces between the graphite plates.

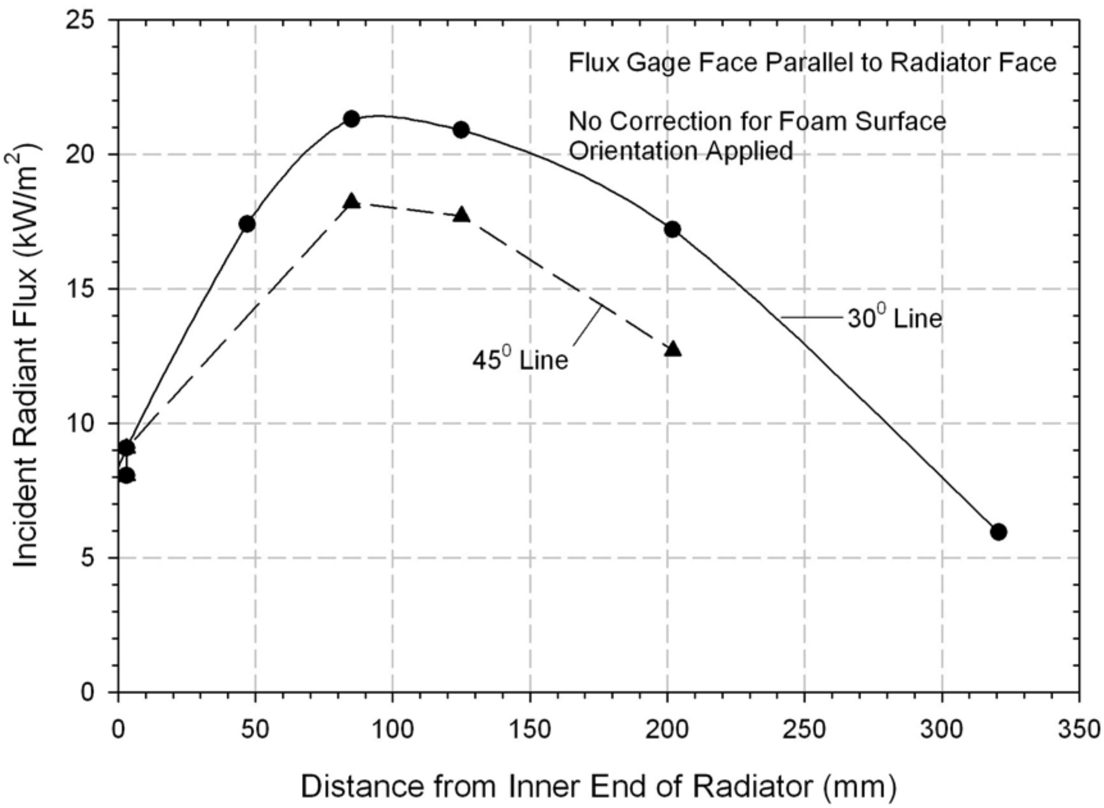

Figure 5. Measured Heat Flux Along Lines Oriented At 30^0 and at $45^{\ 0}$ to LHS of Radiator (Mid-Height on Graphite Plates)

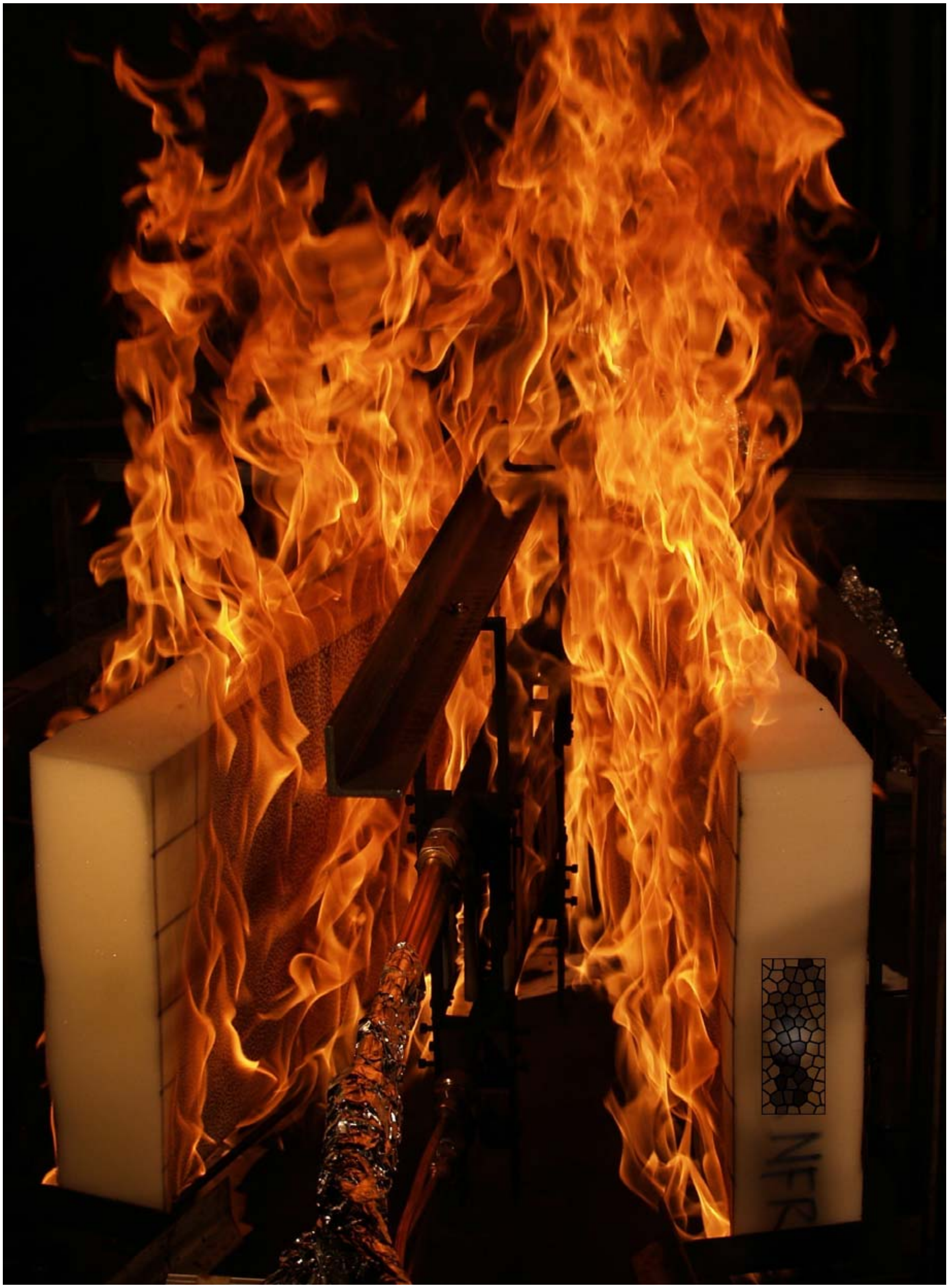

Figure 6. Early behavior of Non-FR polyurethane foam in modified Vee test.

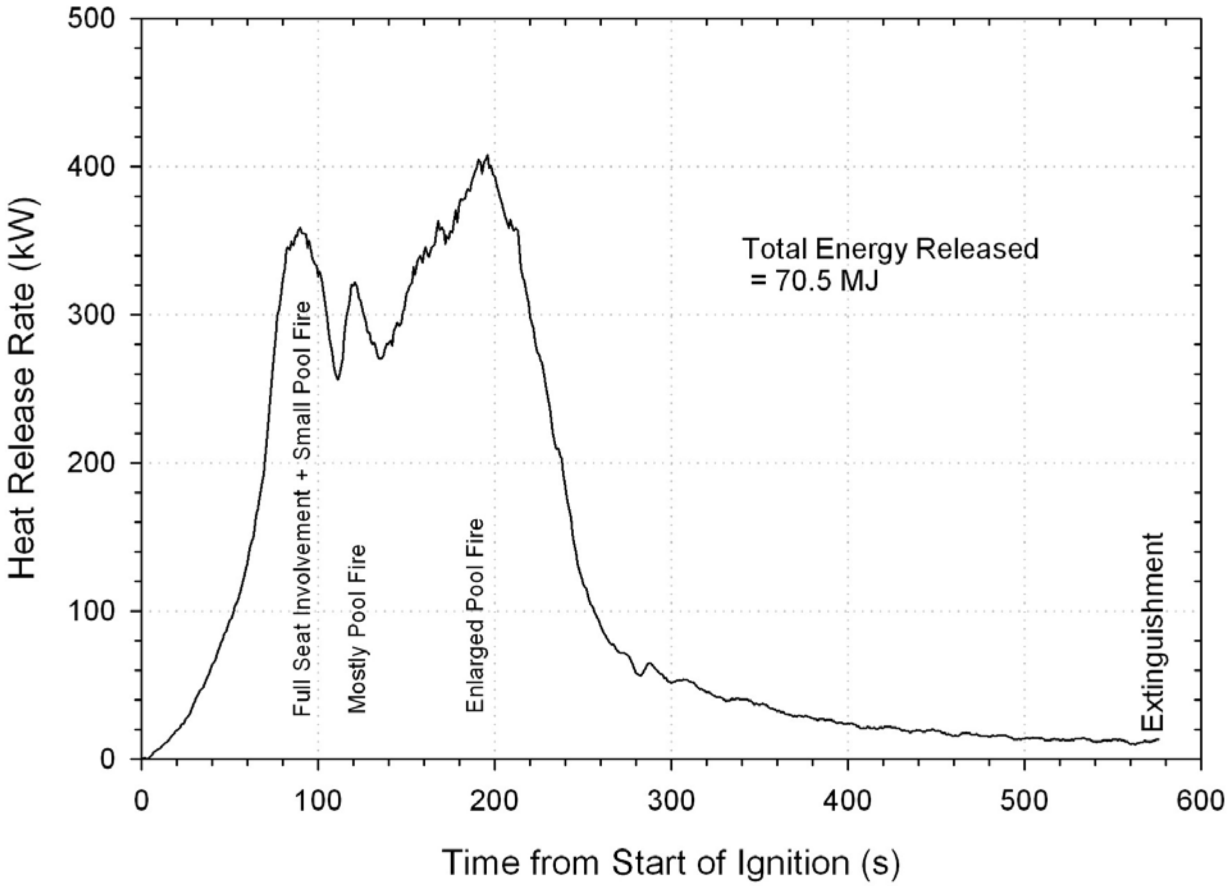

Figure 7. Four cushion mock-up heat release rate; Non-FR foam with PP fabric "A".

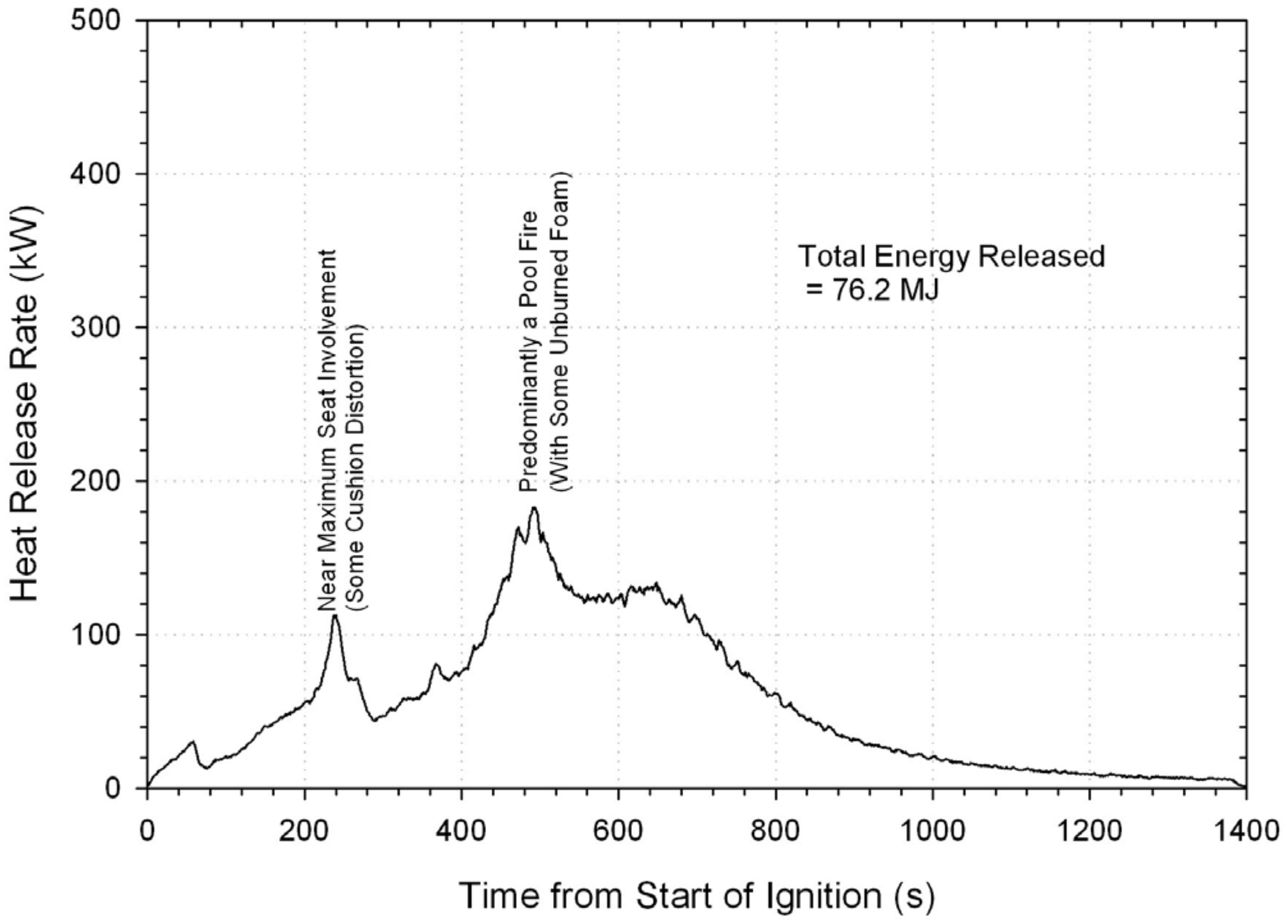

Figure 8. Four cushion mock-up heat release rate; foam P with PP fabric "A".

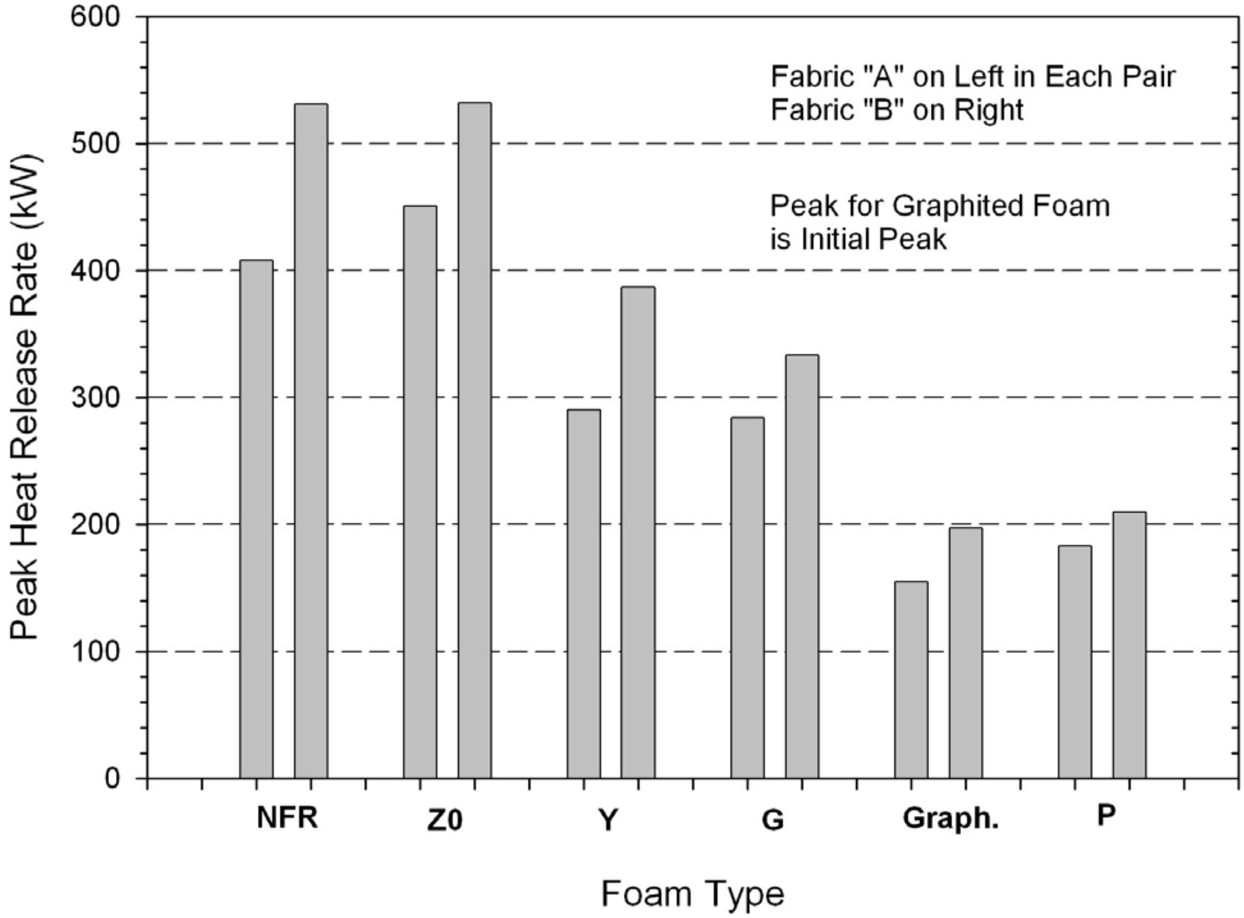

Figure 9. Peak heat release rate versus foam type (cushions with no fiber wrap).

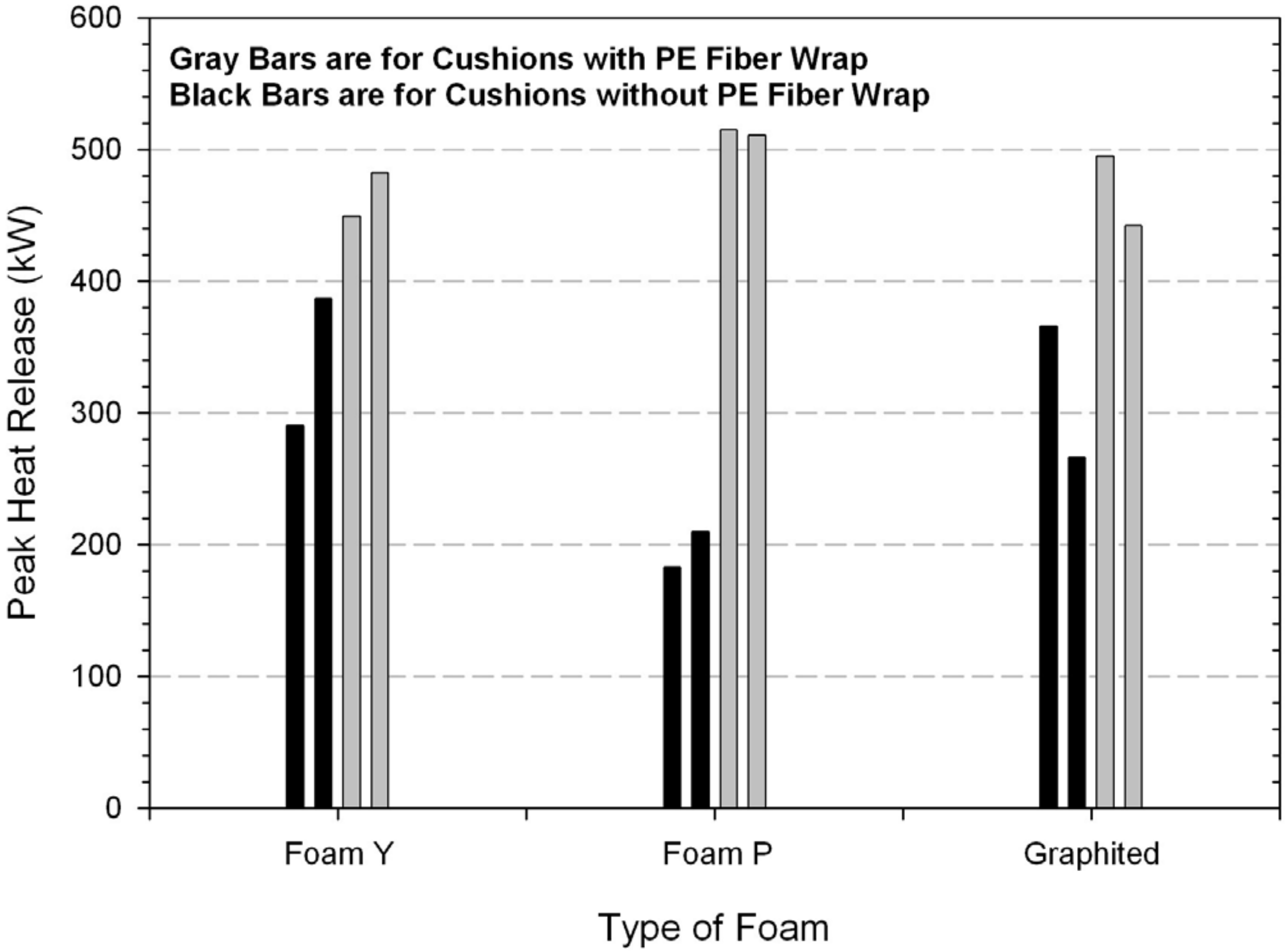

Figure 10. Effect of polyester fiber wrap on peak heat release rate in four cushion mock-up tests.

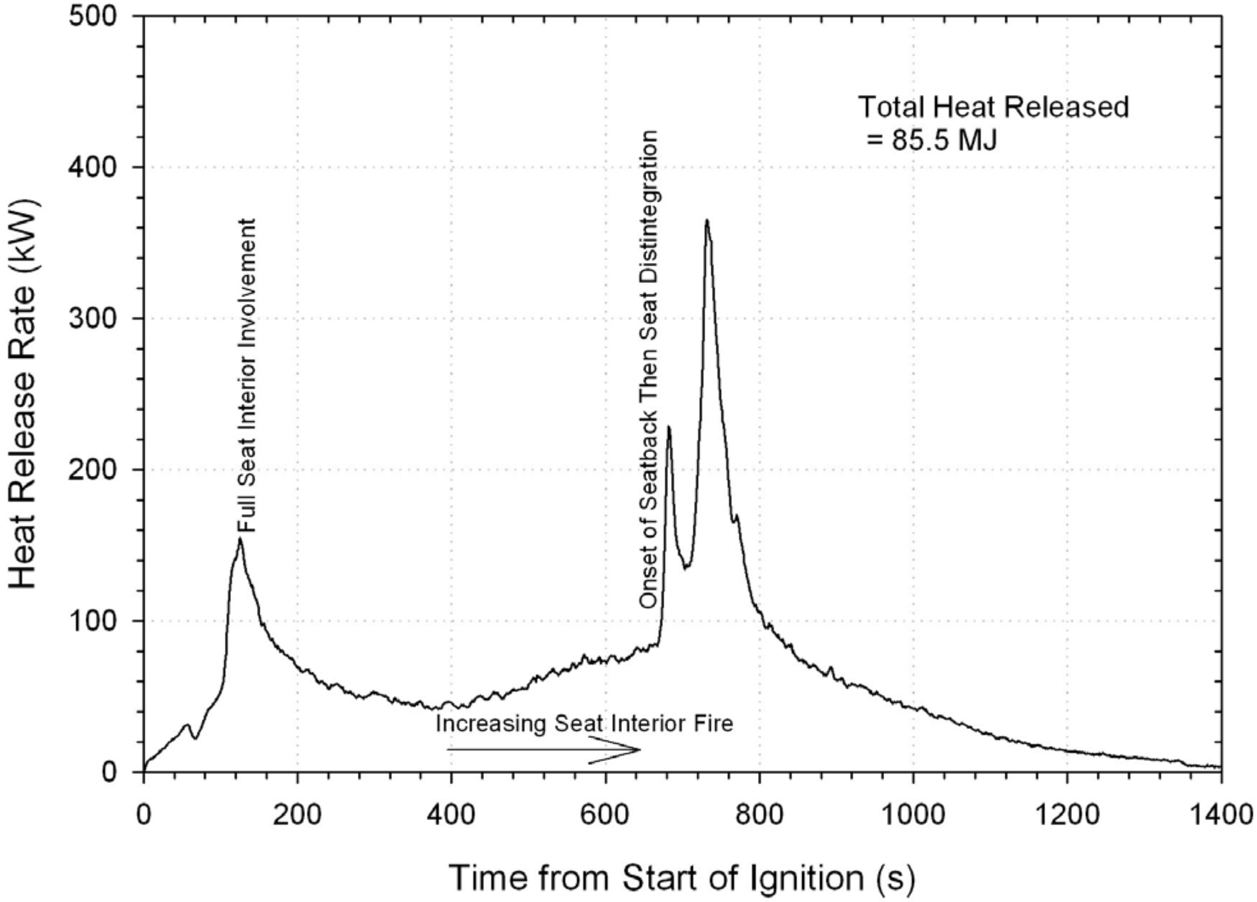

Figure 11. Heat release rate from four cushion mock-up test; Graphited Foam with PP fabric "A".

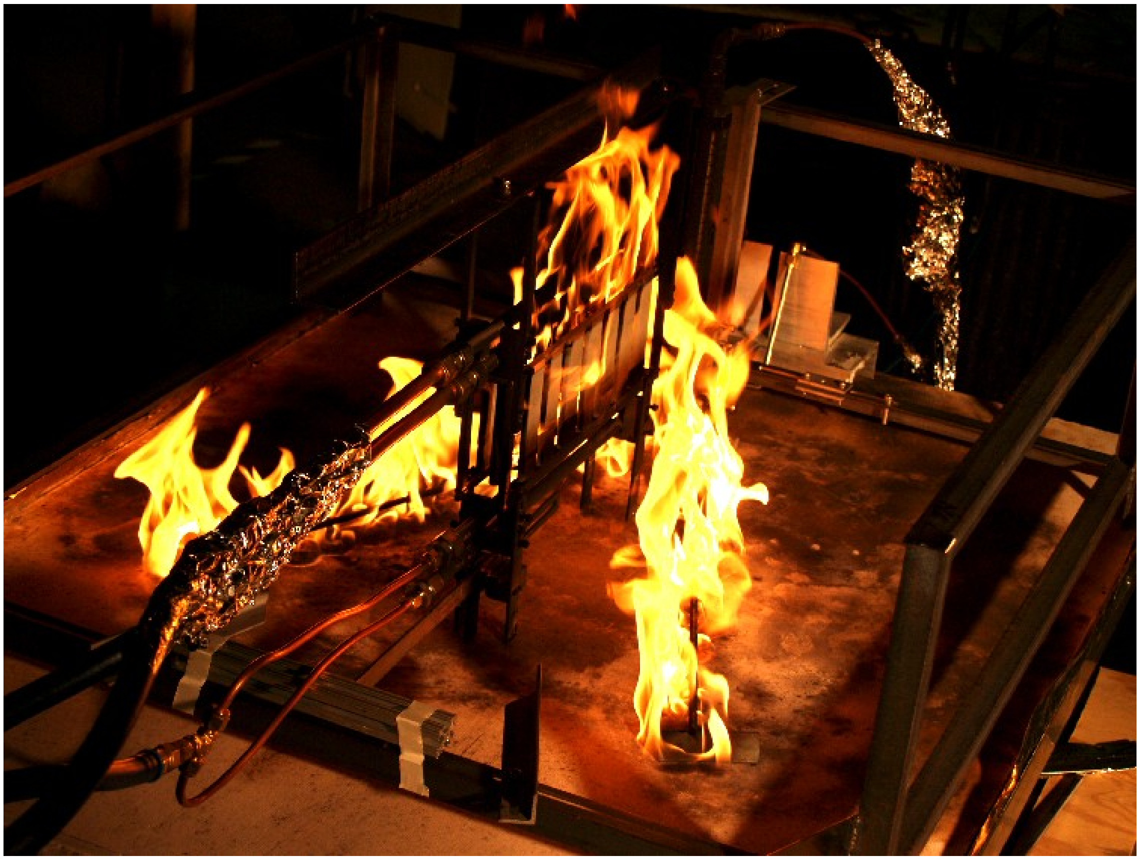

Figure 12. Vee test apparatus with radiator and pool pilots but no sample present.

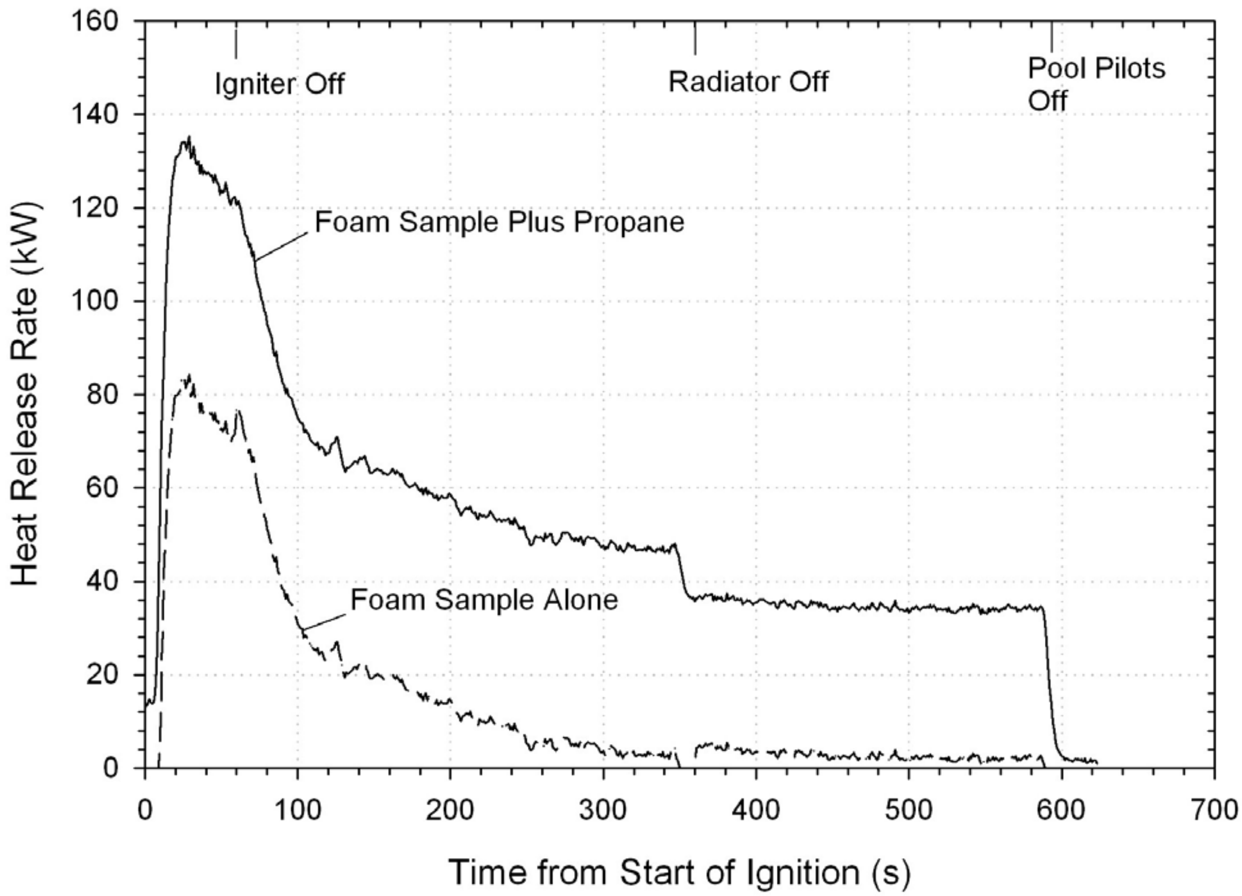

Figure 13. Modified Vee test of Foam G showing raw HRR data and HRR contribution from sample alone

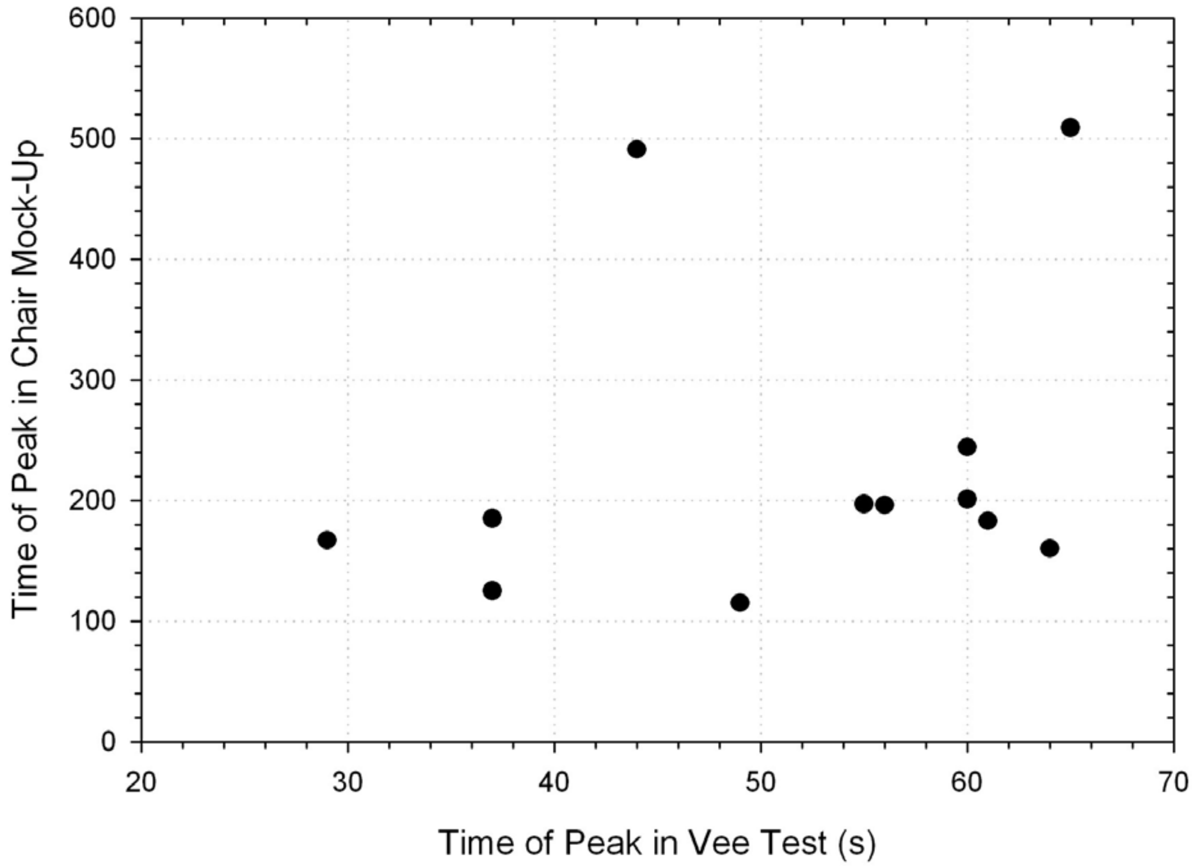

Figure 14. Relation of times to peak heat release rate in modified Vee test and in chair mock-up.

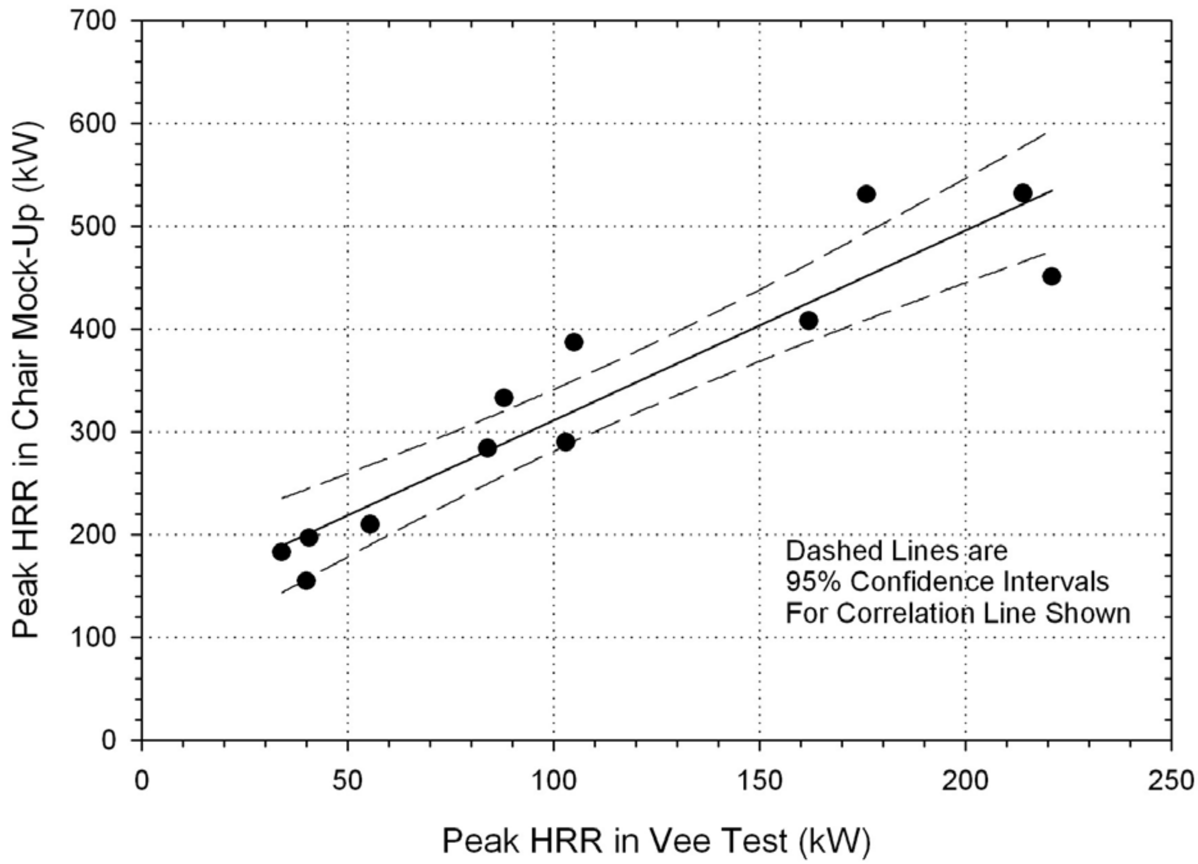

Figure 15. Peak heat release rate correlation between modified Vee test and four cushion chair mock-up (with 11 oz/sq yd polypropylene fabric)