FLAME RETARDANTS AND HEAT RELEASE: REVIEW OF DATA ON INDIVIDUAL POLYMERS

Marcelo M. Hirschler

GBH International
2 Friars Lane, Mill Valley, CA, 94941, US

ABSTRACT

This work is the second of two parts that considered the following issue: do flame retardants affect heat release of polymers? The reason for investigating the issue is because it is important to assess whether the addition of flame retardants positively decreases fire hazard. This part of the work considered the two following issues. (1) Analysis of the individual polymeric materials that need to be studied. (2) Analysis of the data found on heat release (particularly peak heat release rate), ignitability (if available) and other thermal properties (as available) of polymers in small scale test data in recent years. The effects are being presented in terms of the percentage of improvement. The work demonstrated that, almost without exception, when adequately compounded systems were developed, the peak heat release rate of the flame retarded system was lower than that of the non-flame retarded system. The overall conclusion of the two-part study was that flame retardants do indeed improve fire safety (when used appropriately) and that a key reason for the beneficial effect of flame retardants is that they decrease heat release.

1. INTRODUCTION

The first part of this two-part study [1] investigated the effects of flame retardants on heat release of products and of groups of polymers. It concluded 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.

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]. One key study has demonstrated that heat release rate is much more critical than either ignitability or smoke toxicity in affecting the probability of survival in a fire [2].

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, fire hazard assumes that ignition has occurred, so it is important to 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 or 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 will look primarily at the first aspect, namely additive flame retardants and fire hazard. Typical applications where fire safety can be critical are upholstered furniture, mattresses, wire and cable, interior finish, insulation, appliance and computer housings, among others.

2. KEY POLYMERS OR MATERIALS TO INVESTIGATE

The world of natural and synthetic polymers is enormous and it is literally impossible to study every polymer that is commercially available or that may become commercially available in the

near future. Therefore it is important to prioritize the polymers that are of major importance and that need to be investigated. Several criteria were considered in order to come to a determination of a list. First, it is essential to consider all synthetic polymers that are of major use worldwide (or at least in the developed world), and that decision can be made based on the amount of material sold. Another important criterion is that polymers that are important in critical applications where fire safety is a major concern need to be investigated. A third criterion used was to choose natural materials that have the potential to be flame retarded and that are used in key applications where fire safety matters and where synthetic polymers are possible alternatives. A fourth criterion was not to choose polymers that rarely require additional flame retardance, primarily because of their inherent excellent fire performance or because they are used in applications where fire safety is rarely a major concern.

Statistics from the American Chemistry Council (among others) show that the synthetic polymer with the highest production volume is polyethylene (including high density polyethylene, low density polyethylene, linear low density polyethylene and various blends). In terms of volume, polyethylene is followed by polypropylene, PVC and polystyrene. The major markets for these polymers are building and construction, transportation, electrical and electronics, furniture and furnishings, appliances and packaging. According to the American Chemistry Council sales of thermoplastics in the US in 2012 is distributed in the following markets: packaging (34%), consumer and institutional (20%), building and construction (16%), transportation (4%), furniture and furnishings (2%), electrical and electronic (2%), industrial and machinery (1%), with the remainder all others or export. In all of these areas (with the possible exception of packaging) multiple applications exist where fire safety needs to be considered.

In the area of building and construction, fire safety is an important consideration particularly for interior finish, insulation, roofing, siding and exterior veneers. Polymers of interest here include polyolefins, polystyrene, rigid PVC, wood, cellulose and rigid polyurethane. In the area of transportation, many polymers are used, including primarily the following (as analysed, for highway vehicles, for a recent NFPA document (NFPA 556): polyurethanes, polypropylene, PVC, polyethylene, nylons/polyamides, ABS and engineering thermoplastics. In the area of furniture and furnishings, fire safety is essential, especially for upholstered furniture and mattresses, because that is the area where the highest heat content in buildings is found. Polymers of interest here include flexible polyurethanes and materials used for fabrics, such as cotton, polyester, nylon, wool and silk and wood. Protective clothing is an area where fire safety is a consideration and the typical materials used are aromatic polyamides and cellulosics. In the area of electrical and electronics the key areas are wire and cable, connectors and circuit/wiring boards. Polymers of interest here include flexible PVC, polyolefins (including polyethylene and EVA), thermoplastic polyurethanes, epoxies and fluoropolymers. In the area of appliances, there are two types of products with fire safety considerations: housings for appliances and electronic/computer equipment and the interior circuitry for such products. Polymers of interest here include various engineering thermoplastics, such as styrenics (including ABS and high impact polystyrene or HIPS), polycarbonate, polyesters (including polyethylene terephthalate, PET, and polybutylene terephthalate, PBT), poly ether ether ketone and similar polymers, polyamides/nylons, polyphenylene oxide based blends and rigid PVC. In the area of packaging, there are relatively low fire safety concerns. A few of the polymeric materials mentioned above need not be investigated further in this work because they are rarely treated with flame retardants, due to their intrinsically excellent fire performance.

The resulting list of materials is not necessarily comprehensive but will cover a very significant range. With these criteria, the following list was created (in alphabetical order).

- ABS and/or other styrenics, including HIPS
- Cellulose or cotton fabrics
- Engineering thermoplastics (including polycarbonate)
- Epoxy resins
- EVA and/or other polyolefin blends and/or copolymers
- Flexible PVC
- LDPE
- Nylon and/or other polyamides
- Polyesters (including also PET fabrics)
- Polycarbonate
- Polypropylene
- Polystyrene
- Polyurethane (foam and thermoplastic polyurethane)
- Rigid PVC
- Wood (different species, if possible)

With the criteria above, the following short list was created of materials that need not be investigated (in alphabetical order).

- Aromatic polyamides {Very high thermal stability; often used without additives for protective clothing or barriers}
- Fluoropolymers (including polytetrafluoroethylene and others) {Superior fire performance; normally used as is for electrical and piping applications}
- Poly ether ether ketone and similar polymers {Superior fire performance; normally used as is for engineered plastics applications}
- Silk {sufficient fire performance for high-end textile applications}
- Wool {sufficient fire performance for certain textile applications}

The major polymeric system that was considered for analysis and was not investigated (because no data has been published) is cellulose loose fill insulation, a material which is extensively used, and almost always used in flame retarded form, but which does not seem to have been tested for heat release rate, either before or after the addition of flame retardants.

3. HEAT RELEASE EFFECTS OF FLAME RETARDANTS ON INDIVIDUAL POLYMERS

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 [9]) 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 cone calorimeter is the primary fire testing technique used in the studies reviewed here.

Another heat release technique was developed by Richard Lyon, at the Federal Aviation Administration (FAA) in 2004, namely the pyrolysis-combustion flow calorimeter (PCFC) or micro calorimeter [10]. This new fire test instrument was later standardized as ASTM D7309 [11], and it quickly and easily measures the combustibility or pyrolysis (aerobic or anaerobic) of materials, such as plastics, wood or textiles, with samples that are only a few milligrams and results that are obtained in minutes. Its output includes the heat release capacity, a fundamental material property that can be correlated with the heat release rate. Lyon and co-workers have developed correlations with other standard heat release instrument fire test data (including the cone calorimeter). Lyon and collaborators have published extensively using this technique and showed its effectiveness in classifying polymeric materials on the basis of their heat release capacity. These publications also include results using flame retarded materials. However, the direct comparisons of results of flame retarded materials with their non-flame retarded alternates are easier understood using the cone calorimeter, and that is the focus that will be used in this work.

The effects of the flame retardant additives on each of the individual properties studied is being presented in a variety of tables and calculated as a percentage improvement.

3.1 Polyolefins

Polyolefins are among the highest heat release polymers and are also among the most widely used materials for a variety of applications. The first part of this study [1] includes tables that contain data on the heat release of a variety of polyolefin systems [4, 12-14], and demonstrate the effectiveness of flame retardants in decreasing heat release for such polymers. An NBS/NIST study [14] discussed in detail in the first part of this work also included a cable coating compound that is composed of polyolefins. Some other recent work on polyolefins follows. Tables 1 and 2 include work on the effectiveness of inorganic and phosphorus-based flame retardants on EVA and on a PP copolymer, tested in the cone calorimeter at an initial test heat flux of 40 kW/m^2 [15]. The three flame retardant additives used were: aluminum trihydrate (ATH), magnesium hydroxide (MDH) and Fyrol P26 (a proprietary commercial additive with 36% phosphorus). It is notable that there is a significant improvement in heat release rate, particularly peak heat release rate (Pk HRR), for both polymers but a much lower effect on time to ignition (TTI) or on the ratio of the two properties (FPI or fire performance index). The percentage improvement in peak heat release rate in the EVA systems investigated is in the 76-88% range and in the PP systems it ranged from 60 to 79%.

A different study on EVA cable jacket compounds (containing calcium carbonate) uses several mineral fillers, namely ATH, magnesium hydroxide (MDH), huntite (HU) and hydromagnesite (HM) plus combinations of these additives [16] (Table 3). The numbers in the table following the HU and HM designations indicate the amount of each flame retardant added. The fire test is the cone calorimeter at initial test heat fluxes of 30, 50 and 70 kW/m^2. The range of improvements in peak HRR is in the range of 17-46%.

Some effects of adding clays and ammonium phosphate on HDPE are shown in Table 4 [17]. The testing was conducted in the cone calorimeter at an initial test heat flux of 35 kW/m^2. The three

additives used were: clay (sodium montmorillonite), ammonium phosphate monobasic (MB) and sodium montmorillonite modified with ammonium phosphate monobasic (M1). It is notable that there is a significant improvement in heat release rate, particularly peak heat release rate (Pk HRR) but a much lower effect on time to ignition (TTI) or on the ratio of the two properties (FPI or fire performance index). This is a consequence of the polymer being investigated and of the type of flame retardant additive used, which affects primarily heat release rate. The percentage improvement in peak heat release rate in the systems investigated ranged from 21 to 47%.

Table 5 shows the effects on another two wire and cable polyolefin systems, LDPE and ethyl butyl acetate (EBA) using inorganic additives and silicone coupling agents [18]. The mix of additives used was a masterbatch containing 30% calcium carbonate and 12.5% silicone. The test method is the cone calorimeter at an initial test heat flux of 35 kW/m^2. There are improvements in both heat release and ignitability, with the peak HRR being improved 77% in LDPE and 50-75% in EBA.

NFPA 556 [19] is a guide on hazard assessment of passenger road vehicles, and it contains heat and ignitability parameters from cone calorimeter tests for a set of 9 PP materials that have been flame retarded (see Table 6). It does not contain the data for the corresponding non-flame retarded PP but data from Hirschler [4] shows that Pk HRR for non-flame retarded PP was measured at 1,170 kW/m^2 at an incident heat flux of 20 kW/m^2 and 1,509 kW/m^2 at an incident heat flux of 40 kW/m^2. Similar information can be found in a table in part 1 of this study [1]. These data again show the positive effect of flame retardants on the heat release of this polyolefin.

Another study looked at the effects of adding, to polyethylene and to polypropylene, 3% of an organically modified clay (a proprietary commercial additive called Cloisite 30B) and 3% of various brominated materials, creating halogen-containing polymer nanocomposites [20]. The four brominated additives are: butyric acid pentabromobenzyl ester (FR1), pentabromobenzyl ester polyacrylate (FR2), methacrylate acid pentabromobenzyl ester (FR3) and acrylic acid pentabromobenzyl ester (FR4). The results are shown in Table 7. There is clearly a good reduction in peak heat release rate but the time to ignition and the total heat released remain virtually unchanged, within statistical significance. The fact that the time to ignition is lowered means the nanocomposites are usually easier to ignite than the virgin polymer and the fact that the THR is unchanged means that the nanocomposite essentially burns up completely.

Having introduced the concept of using nanocomposites as flame retardant additives it is worth mentioning here that such materials have been used in numerous studies with a variety of polymers (very often polyolefins and styrenics) and they show huge decreases in heat release rate (particularly peak heat release rate) but these decreases are often accompanied by the same type of effect discussed above: no effect (or detrimental effect) on time to ignition and no effect on total heat released. Moreover, the peak heat release rate of the flame retarded system is often still quite high. In a study by Kashiwagi et al. [21] the peak heat release rate of a polypropylene system decreased from over 3000 kW/m^2 to values ranging from 600 to 800 kW/m^2. The extensive amount of scientific literature on these systems will not be reviewed here since it would go beyond the scope of the present work. However, interested readers should consult work included in a Wilkie and Morgan book on flame retardants [22], including studies by Jiang [23], Lopez-Cuesta [24], Marosi [25] and Delichatsios [26], as well as a Wilkie and Morgan book entitled “Flame Retardants

Nanocomposites' [27] and additional work by Beyer [28], Gilman [29] and Schartel [30]. Typically, nanocomposites are parts of complex multi-component systems.

A pair of interesting NIST studies [31 and 32] looked at the fire testing of materials intended for use in electronic equipment, in small scale and in full scale. The small scale work [31] showed that the heat released by the type of polypropylene chosen for the cone calorimeter tests is very high and that not all flame retardant systems can be effective in reducing the heat release rate to manageable levels. However, the addition of a "non-halogen" flame retardant system resulted in a polypropylene material with a peak heat release rate of some 450 kW/m^2, compared to a corresponding value of more than 2,000 kW/m^2 for the (untested) non-flame retarded polypropylene material. No tabular data is presented because no direct comparison can be referenced. In later sections of this work, some of the data on other polymeric systems from the studies will be presented.

3.2 Styrenics

Polystyrene and ABS are widely used thermoplastic engineering polymers which are also poor fire performers in the absence of flame retardants. The NBS/NIST data [14] shows that the heat release rate of the TV cabinet material (made out of polystyrene) is improved by flame retardants and a table in part 1 of this study includes data that shows how the heat release rate of ABS and of polystyrene are also very positively affected by flame retardants [1]. The following data comes from more recent studies on specific polymers: three studies on polystyrene and one on ABS.

The same work that studied the effects of adding, to polyolefins, 3% of an organically modified clay (Cloisite 30B) and 3% of various brominated materials, creating halogen-containing polymer nanocomposites also studied the effects on polystyrene [20]. In this case an added flame retardant was also used, namely antimony trioxide (ATO). Conclusions are similar to those for the polyolefins and the data are shown in Table 8.

Table 9 shows that brominated additives are effective at decreasing heat release and ignitability of HIPS (high impact polystyrene) [33], particularly in the presence of antimony oxide as a synergist. The tests were conducted in a cone calorimeter at an incident heat flux of 40 kW/m^2. The combined systems have particularly strong effects on the fire performance index. One study investigated the effects of synthetic micas (or synthetic clays), and of natural clays (sodium montmorillonite and treated versions of sodium montmorillonite) on polystyrene and on a combination of polystyrene and a polystyrene co-maleic anhydride. The results are shown below in Tables 10-12 [34]. A recent study looked at layered double hydroxides as flame retardants for polystyrene (see Table 13) [35].

A different recent study, using a mass loss cone (ASTM E2102 [36]), looked at ABS and a combination of three flame retardants: ethane-1,2-bis pentabromophenyl, antimony oxide and zinc borate. The effects are very significant, as shown in Table 14 [37].

The NIST work discussed above, on materials for electronic equipment, [31] included comparisons for HIPS and the data is being analyzed in Table 15. The flame retardants used are identified simply as brominated and non-halogen. In both cases improvements can be found on peak heat release rate (31-57%) as well as in the other key parameters (time to ignition, effective heat of combustion and total heat released).

Recent cone calorimeter work compared the fire performance of a commercial expanded polystyrene foam (NFR EPS) with a commercial flame retarded expanded polyurethane foam (FR EPS) [38]. The work both conducted its own cone calorimeter work, at an incident heat flux of 35 kW/m^2, and compared work performed earlier [39, 40] with other foamed EPS systems, at incident heat fluxes ranging from 30-50 kW/m^2. The results (Table 16) show that a certain level of improvement was obtained on the peak heat release rate and on the time to ignition for all systems.

3.3 Engineering Thermoplastics

Engineering thermoplastics are widely used for a large number of applications, even if they are not as high volume as polyolefins or styrenics. The NBS/NIST study [14] included two products that fall under this category: the business machine housing (a polyphenylene oxide) and the laminated circuit board (a polyester). Some other recent work on engineering thermoplastics follows. A study on polycarbonate was recently conducted in the cone calorimeter at an incident heat flux of 50 kW/m^2, using intumescent flame retardants containing nitrogen and phosphorus (see Table 17) [41]. The next table (Table 18) shows the effect (based on mass loss cone data) of a variety of flame retardants on a polyamide 6 (nylon) [42]. One study on a plastic polyethylene terephthalate PET is shown in Table 19 [43]. The same work also addresses PET fabrics and that will be shown in the section on fibers. An engineering thermoplastic often used in wire and cable applications is thermoplastic polyurethane and a recent study will be shown here, although this could also have been added to a section on polyurethanes. The study used the cone calorimeter at an incident heat flux of 50 kW/m^2 and the results are shown in Table 20 [44].

The NIST work discussed above, on materials for electronic equipment, [31] included comparisons for polycarbonate (PC) and polycarbonate/ABS blends and the data is being analyzed in Table 21. The flame retardants used are identified simply as brominated, phosphorus-containing and non-halogen. In the case of PC alone, the brominated flame retarded materials have very significant improvements in peak heat release rate (57-68%), but the effects on other key parameters (time to ignition, effective heat of combustion and total heat released) are negligible or even detrimental. The non-halogen system used has little effect. In the case of PC/ABS very significant improvements were found in all the key fire properties, including 85% improvement in fire performance index.

3.4 Poly (vinyl chloride)

Poly(vinyl chloride) can be used as a rigid material (for pipes, conduits, siding and profiles) or as a flexible material (typically for wire and cable, wall coverings or floor coverings). The most common need for improved fire performance is in the area of flexible PVC since rigid PVC already has good fire performance. Numerous tables in part 1 of this study [1] include several examples of the positive effects of flame retardants on heat release of both rigid and flexible PVC. Some newer examples (3 for wire and cable compounds, one for wall coverings and one for conduits and window profiles) are also shown. In the case of rigid PVC the effects of flame retardants on heat release tend to be low because the primary reason these materials are being added is smoke release or other issues.

Table 22 shows heat release testing results for rigid PVC materials at incident heat fluxes of 30 and 50 kW/m^2 [45] in the Ohio State University calorimeter (OSU, ASTM E906 [46]). Tables 23 and 24 show results of wire and cable compounds tested in the cone calorimeter [47 and 48]. Significant improvements in heat release are evident. Work conducted in the cone calorimeter to look at the effects of various additives, with particular emphasis on a phosphate plasticizer as a flame retardant additive which also replaces traditional phthalate plasticizers, in wall coverings and in plenum cables is shown in Tables 25 and 26 [49].

3.5 Polyurethane foams

Polyurethane foams have been discussed extensively above, including in the NBS/NIST work. However it is worth noting that the improvement keeps being found, even in recent work, both on flexible foams (Table 27) [50] and on rigid foams (Tables 28 [50] and 29 [16]). Moreover, a recent analysis has looked at flexible polyurethane foam used in upholstered furniture [51] and found the significant positive contributions to heat release made by flame retardants, provided they are added at a sufficiently high level to be effective (i.e. beyond just the level needed to comply with the discredited automotive test FMVSS 302 [52]).

3.6 Epoxy resins

Epoxy resins are used extensively in two primary applications: printed wiring or circuit boards and adhesives. Table 30 presents some recent data [53]. The improvement in peak heat release rate from the addition of the flame retardants (in that particular system) exceeds 80%.

3.7 **Textiles**

Four examples are being presented associated with textiles: one work on PET polyester fibers (Table 31) [43], three types of work on cotton fibers (Tables 32 to 34 [54-56]) and one study on a glass-reinforced polyester composite, with and without a barrier (Table 35) [57]. In all cases, the cone calorimeter was used for the studies and showed significant improvements in peak heat release rate. The PET fabric study (Table 31) involved additives (based primarily on expanded graphite and nanocomposites) that were similar to those used in the PET plastic study presented above [44]; the peak heat release rate improvements exceeded 45% in all cases studied. The same team that did the PET studies also investigated cotton fabrics (Table 32); in this case the additives were able to decrease peak heat release rates by 18-39% (unfortunately the flame retardant additives are identified only by a trade name). Two other teams did cotton heat release additive studies on cotton fabrics relatively recently. In one case the peak heat release rate decreased significantly when burnt both in air (65%) and in a 30% oxygen atmosphere (53 and 69%); the additives were described by commercial trade names only (Table 33, [55]). The other cotton study (from the US Forest Products Lab) looked at the effect of adding diammonium phosphate (SRRC2) or a mixture of diammonium phosphate and dimethyloldihydroxyethyleneurea (SRRC1) to cotton fabrics; they found improvements of 43-65% depending on the heat flux (Table 34).

The data from study on GRP and barriers can be found in Table 35 [57]. The composite was studied as is or with a thin silicate insulative fabric. The flame retardant additives used were melamine phosphate (MP), melamine pyrophosphate (MPP), ammonium polyphosphate (APP), a halogenated

phosphate ester (FR) and aluminum trihydrate (ATH). The improvements in peak heat release rate were particularly impressive with the insulative fabric, but, even without it, and improvement of 49% was found, for example, with the halogenated phosphate ester.

3.8 Wood

The last series of examples being presented involve various wood products. Note that it has already been discussed, in the first paper of this project [1], that fire-retardant treated wood, a product that is regulated via a flame spread test and not a heat release test, exhibits reduced heat release in comparison with wood that is untreated. In all cases, flame retardants improve heat release. Two of the studies involved cone calorimeter testing (Tables 36 and 37 [58-59] and one involves mass loss cone testing (Table 38, [60]). In one case the information presented includes also the Euroclass achieved by the different wood specimens, showing that lower heat release also has regulatory implications, in the European Union in this case, but this effect is also valid in US codes (with different classifications).

4. DISCUSSION AND CONCLUSIONS

It is worth mentioning that a few other publications have investigated different aspects of the effects of flame retardants on fire safety. In one study [61] it was found 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. In a 1999 study [62] the seminal NBS/NIST work [14] was analyzed. The author concluded that the addition of flame retardants did not just have a positive effect on the overall time available for escape (a key fire hazard issue) but that it also positively affected 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 which investigated the safety, health and environmental aspects of flame retardants [63] 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 that specific study was based on earlier work that had received insufficient analysis.

The first part of this work, which included an in-depth analysis of the seminal NBS/NIST work [14] as well as a consideration of the importance of heat release rate in fire hazard and the usefulness of cone calorimeter data to predict real scale heat release information, was based on the best fire safety science. The initial work concluded that 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. It also showed that 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.

The studies reviewed in the present portion of the work were those conducted primarily in the initial 21st century years. The choice of studies was based on the availability of the data and some of the studies are of uneven quality. However, the breadth of the work covered and the similarity of the interpretation that can be obtained from the studies indicate that the conclusions that can be drawn are fully appropriate.

In summary, this work demonstrates that flame retardants, when added as appropriately researched with the correct systems and in the proper amounts, will decrease the heat release rate for virtually all polymeric materials. Thus, the correct use of flame retardants will decrease heat release rate and lower fire hazard and, thus, have a very positive effect on fire safety.

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Table 1 – Effectiveness of Inorganic and Phosphorus-containing Flame Retardants on Heat and Ignitability Properties of EVA [15]					
EVA	TTI	Pk HRR	FPI	Avg HRR	THR
	s	kW/m^2	(m^2skW^{-1})	kW/m^2	MJ/m^2
40 kW/m^2					
Untreated	25	1905	0.01	645	88
Plus 60% ATH	28	460	0.06	244	64
Improvement %	12	76	364	62	27
Plus 57% ATH 3% Fyrol	35	221	0.16	147	63
Improvement %	40	88	1107	77	28
Plus 60% MDH	44	381	0.12	286	68
Improvement %	76	80	780	56	23
Plus 57% MDH 3% Fyrol	38	311	0.12	183	63
Improvement %	52	84	831	72	28

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; THR: total heat released in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). ATH: aluminium trihydrate; MDH: magnesium hydroxide; Fyrol: Fyrol P26, a proprietary commercial phosphorus-containing flame retardant with 36% phosphorus. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 2 – Effectiveness of Inorganic and Phosphorus-containing Flame Retardants on Heat and Ignitability Properties of PP [15]					
PP copolymer	TTI	Pk HRR	FPI	Avg HRR	THR
	s	kW/m^2	(m^2skW^{-1})	kW/m^2	MJ/m^2
40 kW/m^2					
Untreated	19	2540	0.01	805	105
Plus 30% MDH	21	1010	0.02	550	91
Improvement%	11	60	178	32	13
Plus 25% MDH 5% Fyrol	12	545	0.02	355	84
Improvement%	-37	79	194	56	20

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; THR: total heat released in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). MDH: magnesium hydroxide; Fyrol: Fyrol P26, a proprietary commercial phosphorus-containing flame retardant with 36% phosphorus. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 3 – Effectiveness of Inorganic Flame Retardants on Heat and Ignitability Properties of an EVA Cable Jacket Compound [16]				
EVA cable jacket compound	TTI	Pk HRR	FPI	Avg HRR
	s	kW/m^2	$(m^2sk W^{-1})$	kW/m^2
30 kW/m^2				
Untreated (plus calcium carbonate)	210	186	1.13	107
Plus ATH	226	117	1.93	81
Improvement %	8	37	71	24
Plus Hydromagnesite	302	117	2.58	83
Improvement %	44	37	129	22
Plus HU24HM67	249	139	1.79	73
Improvement %	19	25	59	32
Plus HU43HM50	219	130	1.68	68
Improvement %	4	30	49	36
Plus HU77HM18	227	135	1.68	64
Improvement %	8	27	49	40
Plus HU95HM5	236	154	1.53	52
Improvement %	12	17	36	51
50 kW/m^2				
Untreated (plus calcium carbonate)	83	257	0.32	107
Plus ATH	98	169	0.58	84
Improvement %	18	34	80	21
Plus MDH	125	163	0.77	88
Improvement %	51	37	137	18
Plus Hydromagnesite	101	168	0.60	89
Improvement %	22	35	86	17
Plus HU24HM67	93	162	0.57	74
Improvement %	12	37	78	31
Plus HU41HM57	88	168	0.52	71
Improvement %	6	35	62	34
Plus HU43HM50	81	154	0.53	56
Improvement %	-2	40	63	48
Plus HU77HM18	90	138	0.65	41
Improvement %	8	46	102	62
Plus HU95HM5	78	174	0.45	57
Improvement %	-6	32	39	47
70 kW/m^2				
Untreated (plus calcium carbonate)	43	251	0.17	187
Plus ATH	54	208	0.26	102
Improvement %	26	17	52	45
Plus Hydromagnesite	48	197	0.24	106
Improvement %	12	22	42	43
Plus HU24HM67	44	190	0.23	90
Improvement %	2	24	35	52
Plus HU43HM50	40	191	0.21	84
Improvement %	-7	24	22	55
Plus HU77HM18	40	189	0.21	85
Improvement %	-7	25	24	55
Plus HU95HM5	43	202	0.21	103
Improvement %	0	20	24	45

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). ATH: aluminium trihydrate; HU: huntite; HM: hydromagnesite; numbers indicate amounts of HU and of HM. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 4 – Effectiveness of Clay and Phosphate-Treated Clay Flame Retardants on Heat and Ignitability Properties of HDPE [17]					
HDPE	**TTI**	**Pk HRR**	**FPI**	**Avg HRR**	**THR**
	s	**kW/m^2**	**(m^{2}skW^{-1})**	**kW/m^2**	**MJ/m^2**
35 kW/m^2					
Untreated	91	1744	0.05	502	174
Plus 5% clay	67	1218	0.06	550	171
Improvement %	-26	30	5	-10	2
Plus 7.5% clay	71	927	0.08	478	142
Improvement %	-22	47	47	5	18
Plus 10% clay	52	1006	0.05	483	165
Improvement %	-43	42	-1	4	5
Plus 5% M1	83	1288	0.06	456	143
Improvement %	-9	26	24	9	18
Plus 7.5% M1	88	1147	0.08	441	142
Improvement %	-3	34	47	12	18
Plus 10% M1	63	946	0.07	414	147
Improvement %	-31	46	28	18	16
Plus 5% MB + 5% M1	48	1361	0.04	510	165
Improvement %	-47	22	-32	-2	5
Plus 10% MB + 2.5% M1	53	1051	0.05	479	135
Improvement %	-42	40	-3	5	22
Plus 7.5% MB + 5% M1	43	1194	0.04	653	166
Improvement %	-53	32	-31	-30	5
Plus 10% MB + 5% M1	41	1372	0.03	506	159
Improvement %	-55	21	-43	-1	9
Plus 5% MB + 10% M1	42	1309	0.03	460	156
Improvement %	-54	25	-39	8	10

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; THR: total heat released in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Clay: sodium montmorillonite; MB: ammonium phosphate monobasic; M1: and sodium montmorillonite modified with ammonium phosphate monobasic. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 5 – Effectiveness of Calcium and Silicon Mixed Flame Retardants on Heat and Ignitability Properties of Polyolefin Wire and Cable Compounds [18]				
	TTI	**Pk HRR**	**FPI**	**Eff. Heat Comb.**
	(s)	**(kW/m^2)**	**(m^2skW^{-1})**	**(MJ/kg)**
LDPE alone	76	1420	0.05	41.0
LDPE & Ca Si mix	95	320	0.30	26.0
Improvement %	25	77	455	37
Ethyl butyl acetate	77	1304	0.06	40.9
EBA & Silicone alone	84	1044	0.08	33.4
Improvement %	9	20	36	18
EBA & Calcium carbonate only	102	658	0.16	26.3
Improvement %	32	50	163	36
EBA & Ca Si mix	148	326	0.45	24.1
Improvement %	92	75	669	41

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Eff. Heat Comb.: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). EBA: ethyl butyl acetate. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 6 - Cone Calorimeter Data for Nine Flame-Retarded Polypropylene Materials at Heat Flux Indicated (in kW/m²) [19]

	TTI	Pk HRR	FPI	Avg HRR 3	Eff. Heat Comb
	(s)	(kW/m^2)	(m^2skW^{-1})	(kW/m^2)	(MJ/kg)
At 20 kW/m^2					
# 1	382	236	1.62	183	23.6
# 2	325	168	1.93	136	29.8
# 3	377	207	1.82	173	24.4
# 4	384	195	1.97	157	25.3
# 5	396	301	1.32	199	24.3
# 6	387	215	1.80	131	25.9
# 7	402	228	1.76	185	27.1
# 8	377	207	1.82	173	26.8
# 9	386	202	1.91	173	27.8
At 40 kW/m^2					
# 1	80	243	0.33	170	23.9
# 2	63	206	0.31	144	28.6
# 3	62	209	0.30	167	25.2
# 4	72	206	0.35	144	25.4
# 5	74	231	0.32	160	25.2
# 6	70	193	0.36	155	26.1
# 7	75	193	0.39	138	25.9
# 8	71	188	0.38	139	25.8
# 9	67	172	0.39	127	25.7

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR 3: average heat release rate during the 3 minutes following ignition in cone calorimeter test; Eff. Heat Comb: effective heat of combustion in cone calorimeter test.

Table 7 – Effectiveness of Halogen-containing Nanocomposites as Flame Retardants on Heat and Ignitability Properties of Some Polyolefins [20]				
Cone Calorimeter	TTI	Pk HRR	FPI	THR
35 kW/m^2	s	kW/m^2	(m^2skW^{-1})	MJ/m^2
Polyethylene				
Untreated	73	1949	0.04	100
Plus FR4	75	1577	0.05	92
Improvement %	3	19	27	8
Plus FR2	64	1817	0.04	95
Improvement %	-12	7	-6	5
Plus FR1	75	1190	0.06	88
Improvement %	3	39	68	12
Plus FR3	67	1762	0.04	97
Improvement %	-8	10	2	3
Polypropylene				
Untreated	50	1642	0.03	60
Plus FR4	44	1656	0.03	72
Improvement %	-12	-1	-13	-20
Plus FR1	48	1281	0.04	73
Improvement %	-4	22	23	-22
Plus FR3	46	957	0.05	74
Improvement %	-8	42	58	-23
Plus FR2	67	1762	0.04	97
Improvement %	-6	54	103	-2

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). FR1: butyric acid pentabromobenzyl ester; FR2: pentabromobenzyl ester polyacrylate; FR3: methacrylate acid pentabromobenzyl ester; FR4: and acrylic acid pentabromobenzyl ester. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 8 – Effectiveness of Halogen-containing Nanocomposites and Antimony Oxide as Flame Retardants on Heat and Ignitability Properties of Polystyrene Materials [20]				
Cone calorimeter	TTI	Pk HRR	FPI	THR
35 kW/m^2	s	kW/m^2	(m^2skW^{-1})	MJ/m^2
Polystyrene				
Untreated	59	1242	0.05	100
Plus FR1	43	1065	0.04	77
Improvement %	-27	14	-15	23
Plus FR1 + ATO	41	590	0.07	50
Improvement %	-31	52	46	50
Plus FR2	33	707	0.05	62
Improvement %	-44	43	-2	38
Plus FR2 + ATO	42	541	0.08	45
Improvement %	-29	56	63	55
Plus FR3	34	967	0.04	71
Improvement %	-42	22	-26	29
Plus FR3 + ATO	43	813	0.05	51
Improvement %	-27	35	11	49
Plus FR4	34	813	0.04	75
Improvement %	-42	35	-12	25
Plus FR4 + ATO	44	875	0.05	61
Improvement %	-25	30	6	39

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). FR1: butyric acid pentabromobenzyl ester; FR2: pentabromobenzyl ester polyacrylate; FR3: methacrylate acid pentabromobenzyl ester; FR4: and acrylic acid pentabromobenzyl ester; ATO antimony oxide. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 9 – Effectiveness of Brominated Additives (with and without antimony oxide) as Flame Retardants on Heat and Ignitability Properties of High Impact Polystyrene [33]					
Cone @ 40 kW/m^2	TTI	Pk HRR	Av HRR 3 min	Eff. Ht Comb	FPI
	s	kW/m^2	kW/m^2	MJ/kg	(m^{2}skW^{-1})
HIPS	60	968	621	30.7	0.06
HIPS + SbO	62	910	580	28.6	0.07
HIPS + Deca	55	708	470	17.0	0.08
HIPS + Deca + SbO	72	360	255	10.1	0.20
HIPS + DBE	54	782	487	18.6	0.07
HIPS + DBE + SBO	78	393	302	10.8	0.20
HIPS + BT93	54	768	509	19.6	0.07
HIPS + BT93 + SbO	88	423	293	12.2	0.21
HIPS + HBCD	72	885	710	23.2	0.08
HIPS + HBCD + SbO	80	766	423	13.2	0.10
Improvement % SbO	3	6	7	7	10
Improvement % Deca	-8	27	24	45	25
Improvement % Deca + SbO	20	63	59	67	223
Improvement % DBE	-10	19	22	39	11
Improvement % DBE + SbO	30	59	51	65	220
Improvement % BT93	-10	21	18	36	13
Improvement % BT93 + SbO	47	56	53	60	236
Improvement % HBCD	20	9	-14	24	31
Improvement % HBCD + SbO	33	21	32	57	68
Brominated additives at 12%; antimony oxide at 4%					
Sb: antimony oxide					
Deca: decabromodiphenyl oxide					
DBE: Decabromodiphenyl Ethane					
BT93: Ethylenebis(tetrabromophthalimide)					
HBCDE: hexabromocyclododecane					

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR 3 min: average heat release rate during the 3 minutes following ignition in cone calorimeter test; Eff. Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test).

Table 10 – Effectiveness of Synthetic Micas as Flame Retardants on Heat and Ignitability Properties of Polystyrene Materials [34]					
Cone @ 50 kW/m^2	TTI	Pk HRR	FPI	Ht Comb	THR
Synthetic Micas	s	kW/m^2	(m^{2}skW^{-1})	MJ/kg	MJ/m^2
Polystyrene	65	1294	0.05	30.6	111
PS + 1 (18.6 wt% Mica O)	51	513	0.10	27.9	94
PS + 2 (9.3 wt% Mica O)	49	428	0.11	27.1	98
PS + 3 (1.9 wt% Mica O)	63	911	0.07	29.4	111
PS + 4 (10 wt% Mica N)	41	995	0.04	30.8	113
PS + 5 (5 wt% Mica N)	43	1146	0.04	31.7	117
PS + 6 (1 wt% Mica N)	52	1201	0.04	31.9	117
Mica O: dimethyl, di(hydrogenated tallow) ammonium treated sodium fluorinated synthetic mica					
Mica N: Sodium fluorinated synthetic mica					
Improvement % 1	-22	60	98	9	15
Improvement % 2	-25	67	128	11	12
Improvement % 3	-3	30	38	4	0
Improvement % 4	-37	23	-18	-1	-2
Improvement % 5	-34	11	-25	-4	-5
Improvement % 6	-20	7	-14	-4	-5

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 11 – Effectiveness of Sodium Montmorillonites as Flame Retardants on Heat and Ignitability Properties of Polystyrene Materials [34]					
Cone @ 50 kW/m^2	TTI	Pk HRR	FPI	Ht Comb	THR
Sodium montmorillonite	s	kW/m^2	(m^{2}skW^{-1})	MJ/kg	MJ/m^2
Polystyrene	65	1294	0.05	30.6	111
PS + 1 (16.2 wt% MMT O)	52	446	0.12	26.9	97
PS + 2 (8.1 wt% MMT O)	58	555	0.10	26.6	98
PS + 3 (1.6 wt% MMT O)	66	1080	0.06	29.9	111
PS + 4 (10 wt% MMT N)	40	792	0.05	29.2	106
PS + 5 (5 wt% MMT N)	41	993	0.04	29.5	111
PS + 6 (1 wt% MMT N)	57	1106	0.05	29.8	110
MMT O: dimethyl, di(hydrogenated tallow) ammonium treated montmorillonite (Cloisite 15A)					
MMT N: sodium montmorillonite (Cloisite Na+)					
Improvement % 1	-20	66	132	12	13
Improvement % 2	-11	57	108	13	12
Improvement % 3	2	17	22	2	0
Improvement % 4	-38	39	1	5	5
Improvement % 5	-37	23	-18	4	0
Improvement % 6	-12	15	3	3	1

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 12 – Effectiveness of Phosphonium Synthetic Micas as Flame Retardants on Heat and Ignitability Properties of Polystyrene and Associated Materials [34]					
Cone @ 50 kW/m^2	TTI	Pk HRR	FPI	Ht Comb	THR
Phosphonium treated synthetic micas	s	kW/m^2	(m^{2}skW^{-1})	MJ/kg	MJ/m^2
Polystyrene	65	1294	0.05	30.6	30.6
PS + 1 (styrene/maleic anhydride)	64	1280	0.05	30.8	30.8
PS + 2 (PS + 1 + 8.3 wt% Mica P)	65	557	0.12	26.5	26.5
PS + 3 (8.3 wt% Mica P)	64	586	0.11	26.6	26.6
Mica P: Triphenyl, n-hexadecyl phosphonium treated sodium fluorinated synthetic mica					
System 1: Addition of styrene/maleic anhydride					
Improvement % 1	-2	1	0	-1	-1
Improvement % 2	0	57	132	13	13
Improvement % 3	-2	55	117	13	13

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 13 – Effectiveness of Layered Double Hydroxides as Flame Retardants on Heat and Ignitability Properties of Polystyrene [35]				
Cone @ 35 kW/m^2	TTI	Pk HRR	FPI	THR
	s	kW/m^2	(m^{2}skW^{-1})	MJ/m^2
Polystyrene	88	813	0.11	138
PS + 5 wt% LDH-DBP	72	616	0.12	133
Improvement %	-18	24	8	4
PS + 5 wt%5 LDH - SMM 30 min DBP	65	517	0.13	133
Improvement %	-26	36	16	4
PS + 5 wt% LDH - SMM 60 min DBP	66	621	0.11	131
Improvement %	-25	24	-2	5
PS + 5 wt% LDH-syntal DBP	59	627	0.09	129
Improvement %	-33	23	-13	7
PS + 10 wt% LDH-DBP	74	444	0.17	127
Improvement %	-16	45	54	8
PS + 15 wt% LDH-DBP	95	402	0.24	125
Improvement %	8	51	118	9
DBP: 3,4-dihydroxybenzophenone				
LDH: layered double hydroxides				
SMM: surface modification				
LDH syntal: commercial material				

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 14 – Mass Loss Cone Study of the Effectiveness of Various Flame Retardants on Heat and Ignitability Properties of ABS [37]				
Mass loss cone @ 35 kW/m^2	TTI	Pk HRR	FPI	THR
	S	kW/m^2	(m^2skW^{-1})	MJ/m^2
Untreated ABS	83	900	0.09	134
Plus FR1	64	239	0.27	44
Plus FR2	67	257	0.26	40
Plus FR3	65	203	0.32	31
Plus FR4	60	265	0.23	35
Plus FR5	72	360	0.20	57
Plus FR6	64	336	0.19	92
Improvement % FR1	-23	73	190	67
Improvement % FR2	-19	71	183	70
Improvement % FR3	-22	77	247	77
Improvement % FR4	-28	71	146	74
Improvement % FR5	-13	60	117	57
Improvement % FR6	-23	63	107	31
FR1: EBP + 6 phr antimony oxide				
FR2: EBP + 4.5 phr antimony oxide + 1.5 phr zinc borate				
FR3: EBP + 3 phr antimony oxide + 3 phr zinc borate				
FR4: EBP + 1.5 phr antimony oxide + 4.5 phr zinc borate				
FR5: EBP + 6 phr zinc borate				
FR6: zinc borate only				
EBP: ethane-1,2-bis pentabromophenyl				

Notes: TTI: time to ignition in mass loss cone (ASTM E2102) test; Pk HRR: peak heat release rate in mass loss cone test with thermopile column; THR: total heat released during test in mass loss cone test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in mass loss cone test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 15 – Effectiveness of Flame Retardant Systems on Heat and Ignitability Properties of Polystyrene (HIPS) [31]					
Cone @ 50 kW/m^2	TTI	Pk HRR	FPI	THR	Ht Comb
	s	kW/m^2		MJ/m^2	MJ/kg
HIPS	30	723	0.04	59.5	33.9
HIPS + Brominated FR	33	318	0.10	23.8	12.3
HIPS + Brominated FR	41	502	0.08	33.8	16.4
HIPS + Non-Halogen FR	34	313	0.11	42.2	22.3
Improvement % Brominated FR (1)	10	56	150	60	64
Improvement % Brominated FR (2)	37	31	97	43	52
Improvement % Non-Halogen FR	13	57	162	29	34

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 16 – Effectiveness of Flame Retardant Systems on Heat and Ignitability Properties of Foamed Expanded Polystyrene (EPS) [38]			
Foamed EPS	TTI	Pk HRR	FPI
35 kW/m^2	s	kW/m^2	MJ/m^2
EPS	77.7	310.5	0.25
EPS Plus Commercial FR	81	230.6	0.35
Improvement % FR	4	26	40
Foamed EPS	TTI	Pk HRR	FPI
30 kW/m^2	s	kW/m^2	MJ/m^2
EPS	73	299	0.24
EPS Plus Commercial FR	77	238	0.32
Improvement % FR	5	20	33
Foamed EPS	TTI	Pk HRR	FPI
40 kW/m^2	s	kW/m^2	MJ/m^2
EPS	28	394	0.07
EPS Plus Commercial FR	40	321	0.12
Improvement % FR	43	19	75
Foamed EPS	TTI	Pk HRR	FPI
50 kW/m^2	s	kW/m^2	MJ/m^2
EPS	18	407	0.04
EPS Plus Commercial FR	24	379	0.06
Improvement % FR	33	7	43
Note: Data at 35 kW/m2 was determined by the authors [38], while data at 30, 40 and 50 kW/m^2 was obtained by comparison of published data from other authors [39, 40]			

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 17 – Effectiveness of Intumescent Flame Retardants on Heat and Ignitability Properties of a Polycarbonate Material [41]				
Polycarbonate	TTI	Pk HRR	FPI	THR
	s	kW/m^2	(m^2skW^{-1})	MJ/m^2
Cone @ 50 kW/m^2				
Untreated polycarbonate	58	357	0.16	80
Plus FR1	52	219	0.24	69
Plus FR2	54	192	0.28	52
FR1: Intumescent FR with P and N BASPB: bis-aminobenzyl spirocylic pentaerythritol bisphosphonate				
FR2: Intumescent FR with P and N ABDPP: arylene-N,N0-bis(2,2-dimethyl-1,3-propanediol phosphoramidate)				
Improvement % FR1	-10	39	46	14
Improvement % FR2	-7	46	73	35

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 18 – Mass Loss Cone Study of the Effectiveness of Various Flame Retardants on Heat Release of a Polyamide 6 [42]				
Nylon polyamide 6		Pk HRR	Avg HRR	THR
Mass loss cone @ 35 kW/m^2		kW/m^2	kW/m^2	MJ/m^2
PA6		975	375	163
PA6 + OP2		695	300	158
PA6 + OP3		480	235	136
PA6 + OP4		335	190	122
PA6 + OP5		755	345	160
PA6 + OP6		720	325	149
PA6 + OP7		575	315	143
PA6 + OP8		380	186	135
PA6 + OP9		535	288	141
Improvement % OP2		29	20	3
Improvement % OP3		51	37	17
Improvement % OP4		66	49	25
Improvement % OP5		23	8	2
Improvement % OP6		26	13	9
Improvement % OP7		41	16	12
Improvement % OP8		61	50	17
Improvement % OP9		45	23	13
OP2: 15% organic phosphinate				
OP3: 14% OP 1% Zn borate				
OP3: 12% OP 3% Zn borate				
OP5: 14% OP 1% borophosphate				
OP6: 12% OP 3% borophosphate				
OP7: 14% OP 1% organo clay				
OP8: 13% OP 1% zinc borate 1% organo clay				
OP9: 13% OP 1% borophosphate 1% organo clay				

Notes: Pk HRR: peak heat release rate in mass loss cone test with thermopile column (ASTM E2102); THR: total heat released during test in mass loss cone test; Avg HRR: average heat release rate during mass loss cone test. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 19 – Effectiveness of Expanded Graphite Flame Retardants on Heat and Ignitability Properties of a PET Material [41]			
PET plastic	TTI	Pk HRR	FPI
Cone @ 35 kW/m^2	s	kW/m^2	(m^2skW^{-1})
Untreated PET plastic	209	523	0.40
Plus Exp. Graphite (EG)	189	303	0.62
Plus Nano1	187	349	0.54
Plus Nano 2	174	440	0.40
Plus Nano 3	220	438	0.50
Plus EG + Nano1	179	231	0.77
Plus EG + Nano2	210	304	0.69
Plus EG + Nano 3	222	347	0.64
Improvement % EG	-10	42	56
Improvement % Nano1	-11	33	34
Improvement % Nano2	-17	16	-1
Improvement % Nano3	5	16	26
Improvement % EG Nano1	-14	56	94
Improvement % EG Nano2	0	42	73
Improvement % EG Nano3	6	34	60

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 20 – Effectiveness of Nanocomposites as Flame Retardants on Heat and Ignitability Properties of a Thermoplastic Polyurethane [44]					
Thermoplastic polyurethane (TPU)	TTI	Pk HRR	FPI	Avg HRR 3 min	Ht Comb
Cone @ 50 kW/m^2	s	kW/m^2	(m^2skW^{-1})	kW/m^2	MJ/kg
Untreated TPU	28	1031	0.03	515	27
TPU + 5% Cloisite 30B	27	518	0.05	376	28
TPU + 5% Multiwalled carbon nanotubes (MWNT)	21	571	0.04	492	28
TPU + 5% Carbon nanofibers	21	808	0.03	361	27
Improvement % - Cloisite 30B	-4	50	92	27	-4
Improvement % - carbon nanotubes	-25	45	35	4	-4
Improvement % - carbon nanofibers	-25	22	-4	30	0
Cloisite 30B: Montmorillonite (MMT) surface treated with methyl, tallow, bis-2-hydroxyethyl, quaternary ammonium					

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR 3 min: average heat release rate during 3 minutes following ignition in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 21 – Effectiveness of Flame Retardant Systems on Heat and Ignitability Properties of Polycarbonate and Polycarbonate/ABS Blends [31]					
Cone @ 50 kW/m^2	TTI	Pk HRR	FPI	THR	Ht Comb
	s	kW/m^2		MJ/m^2	MJ/kg
PC	77	885	0.09	37.5	24.0
PC + Brominated FR	51	378	0.13	25.2	22.3
PC + Brominated FR	41	280	0.15	45.9	21.2
PC + Non-Halogen FR	46	829	0.06	38.8	23.6
Improvement % Brominated FR (1)	-34	57	55	33	7
Improvement % Brominated FR (2)	-47	68	68	-22	12
Improvement % Non-Halogen FR	-40	6	-36	-3	2
Cone @ 50 kW/m^2	TTI	Pk HRR	FPI	THR	Ht Comb
	s	kW/m^2		MJ/m^2	MJ/kg
PC/ABS	34	543	0.06	44.4	29.7
PC/ABS + Phosphorus FR	45	388	0.12	35	20.6
Improvement % Phosphorus FR	32	29	85	21	31

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 22 – Effectiveness of Molybdenum Smoke Suppressants as Flame Retardants on Heat Release of Rigid PVC Materials [45]			
OSU Calorimeter		Pk HRR @ 30	Pk HRR @ 50
		kW/m^2	kW/m^2
PVC for conduits		60	76
PVC + AOM 0.5 phr		64	60
PVC + AOM 1 phr		62	63
PVC + AOM 2.5 phr		50	53
PVC + AOM 5 phr		47	54
Improvement % AOM 0.5 phr		-7	21
Improvement % AOM 1 phr		-3	17
Improvement % AOM 2.5 phr		17	30
Improvement % AOM 5 phr		22	29
PVC for window profile		70	
PVC + AOM 1.3 phr		58	
PVC + AOM 2.5 phr		60	
PVC + AOM 5 phr		57	
PVC + Mo tri 1.3 phr		58	
PVC + Mo tri 2.5 phr		57	
Improvement % AOM 1.3 phr		17	
Improvement % AOM 2.5 phr		14	
Improvement % AOM 5 phr		19	
Improvement % Mo Tri 1.3 phr		17	
Improvement % Mo Tri 2.5 phr		19	
AOM: ammonium molybdate			
Mo tri: Molybdenum trioxide			

Notes: Pk HRR: peak heat release rate from Ohio State University (ASTM E906) heat release test at relevant heat flux. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 23 – Effectiveness of Flame Retardants on Heat and Ignitability Properties of PVC with Phosphorus-containing Plasticizers [47]			
Cone @ 50 kW/m^2)	TTI	Pk HRR	FPI
With P plasticizers	s	kW/m^2	(m^{2}skW^{-1})
PVC for cables	29	190	0.15
PVC + system 1	23	115	0.20
PVC + system 2	28	123	0.23
PVC + system 3	25	141	0.18
PVC + system 4	30	118	0.25
PVC + system 5	25	121	0.21
PVC + system 6	26	121	0.21
Improvement % 1	-21	39	31
Improvement % 2	-3	35	49
Improvement % 3	-14	26	16
Improvement % 4	3	38	67
Improvement % 5	-14	36	35
Improvement % 6	-10	36	41

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 24 – Effectiveness of Tin-based Flame Retardants on Heat and Ignitability Properties of PVC with Phosphorus-containing Plasticizers [48]			
PVC for cables with P plasticizers	TTI	Pk HRR	FPI
Cone @ 50 kW/m^2	s	kW/m^2	(m^2skW^{-1})
PVC control	22	260	0.08
PVC + ATH	45	163	0.28
PVC + ATH + LDH	52	72	0.72
PVC + ATH + Sn LDH1	46	74	0.62
PVC + ATH + Sn LDH2	48	73	0.66
PVC + ATH + Sn LDH3	56	59	0.95
Improvement % ATH	105	37	226
Improvement % ATH + LDH	136	72	754
Improvement % ATH Sn LDH1	109	72	635
Improvement % ATH Sn LDH2	118	72	677
Improvement % ATH Sn LDH3	155	77	1022
Plasticizer: 8-Methylnonyl diphenyl phosphate			
LDH: layered double hydroxide with Mg + Al nitrates			
LDH Sn: LDH + Sn, various ratios			
ATH: alumina trihydrate			

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 25 – Effectiveness of Flame Retardants on Heat Release of PVC Wall Coverings Using Phosphorus-containing Plasticizers [49]				
Cone @ 50 kW/m^2	Pk HRR	Improvement	Avg HRR	Ht Comb
PVC wall coverings	kW/m^2	%	kW/m^2	MJ/kg
PVC + 40 DOP + 20 Ca (control)	228	0	146	16.9
Additive system 1	167	27	116	14.0
Additive system 2	191	16	127	11.2
Additive system 3	203	11	132	13.0
Additive system 4	135	41	104	10.8
Additive system 5	90	61	83	11.9
Additive system 6	91	60	89	11.3
Additive system 7	102	55	84	9.8
Additive system 8	94	59	79	10.7
Additive system 9	102	55	83	11.7
Additive system 10	99	57	81	9.9
Additive system 11	99	57	82	10.1
Additive system 12	107	53	85	9.3
Additive system 13	109	52	90	9.6
Additive system 14	95	58	77	8.5
Additive system 15	91	60	73	8.3
Additive system 16	81	64	69	8.8
Additive system 17	159	30	102	10.5
Additive system 18	165	28	101	13.0
Additive system 19	105	54	80	10.6
Additive system 20	83	64	63	11.0
Additive system 21	98	57	67	10.4
DOP: dioctyl phthalate plasticizer				
Ca: calcium carbonate				

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in Pk HRR based on the untreated material.

Table 26 – Effectiveness of Flame Retardants on Heat Release of PVC Plenum Cable Compounds Using Phosphorus-containing Plasticizers [49]				
Cone @ 40 kW/m^2	Pk HRR	Improvement	Avg HRR	Ht Comb
PVC cables (for plenum)	kW/m^2	%	kW/m^2	MJ/kg
PVC Non FR + DOP (control)	283	0	170	15.7
Additive system 1	161	43	47	12.9
Additive system 2	132	53	76	11.5
Additive system 3	134	53	64	12.0
Additive system 4	158	44	83	10.7
Additive system 5	128	55	80	10.8
Additive system 6	127	55	94	11.4
Additive system 7	117	59	76	11.4

Notes: Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; Ht Comb: effective heat of combustion in cone calorimeter test. Improvement %: percentage improvement in Pk HRR based on the untreated material.

Table 27 – Effectiveness of Flame Retardants on Heat Release of a Flexible Polyurethane Foam [50]						
Cone @ 25 kW/m^2	TTI	Pk HRR	Improvement	FPI	Avg HRR	THR
Flexible PU foam	S	(kW/m^2)	%	(m^{2}skW^{-1})	(kW/m^2)	(MJ/ m^2)
Control	15.6	412	0	0.04	225	57.4
Additive System 1	13.7	249	40	0.06	126	54.2
with Zn Stearate	372	340	17	1.09	174	64.4
with Mg Stearate	39.1	444	8	0.09	194	70.8
with ATH	16.0	401	3	0.04	218	60.1
with Fyrol RDP	22.6	429	4	0.05	210	56.7
with Fyrol FR2	18.4	326	21	0.06	163	48.2
with Cl P ester	28.4	315	24	0.09	144	19.9
with alkyl aryl phosphate	26.1	274	33	0.10	154	49.2

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; THR: total heat released during test in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in Pk HRR based on the untreated material.

Table 28 – Effectiveness of Flame Retardants on Heat Release of a Rigid Polyurethane Foam [50]				
Cone @ 25 kW/m^2	TTI (s)	Pk HRR	Improvement	FPI
Rigid PU foam	s	(kW/m^2)	%	(m^{2}skW^{-1})
Control	26	890	0	0.03
with alkyl aryl phosphate	41	548	38	0.07
with Fyrol RDP	65	910	2	0.07
with Fyrol RDP + Zn stearate	33	720	19	0.05
with Zn stannate & Zn stearate	9	485	46	0.02
with Zinc stannate	31	424	52	0.07
with Zn hydroxystannate	36	471	47	0.08

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in Pk HRR based on the untreated material.

Table 29 – Effectiveness of Flame Retardants on Heat Release of a Polyisocyanurate Foam [16]					
Cone @ 40 kW/m^2	TTI	Pk HRR	FPI	Av HRR	THR
Polyisocyanurate foam	s	kW/m^2	(m^{2}skW^{-1})	kW/m^2	MJ/m^2
40 kW/m2					
Untreated	4.3	161	0.03	69	11
Plus TCPP	4.6	87	0.05	19	5
Improvement%	7	46	98	72	55

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; THR: total heat released during test in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material. TCPP: Tris (1-chloro-2-propyl) phosphate.

Table 30 – Effectiveness of Flame Retardants on Heat Release of an Epoxy Resin [53]						
Cone @ 50 kW/m^2	TTI	Pk HRR	FPI	THR	Avg HRR	Eff. Ht Combust
	s	kW/m^2	(m^{2}skW^{-1})	MJ/m^2	kW/m^2	MJ/kg
Epoxy	62	1192	0.05	184	350	26.8
Epoxy + APP	41	200	0.21	104	107	23.8
Epoxy + Mod APP	47	184	0.26	98	77	20.5
Improvement % APP	-34	83	294	43	69	11
Improvement % ModAPP	-24	85	391	47	78	24
APP: Ammonium polyphosphate						
Mod APP: APP modified with silane						

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Eff. Ht Combust: effective heat of combustion during cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 31 – Effectiveness of Expanded Graphite Flame Retardants on Heat and Ignitability Properties of a PET Fiber Material [43]			
PET fibers	TTI	Pk HRR	FPI
Cone @ 35 kW/m^2	s	kW/m^2	(m^2skW^{-1})
Untreated PET fibers	128	510	0.25
Plus Exp. Graphite (EG)	102	92	1.11
Plus Nano1	128	213	0.60
Plus EG + Nano1	106	272	0.39
Improvement % EG	-20	82	342
Improvement % Nano1	0	58	139
Improvement % EG Nano1	-17	47	55

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 32 – Effectiveness of a Flame Retardant Additive on Heat Release of Cotton Fabric and Fiber [54]				
	Cotton fabric		Cotton fiber	
Cotton	Pk HRR	THR	Pk HRR	THR
Cone @ 50 kW/m^2	kW/m^2	MJ/m^2	kW/m^2	MJ/m^2
Untreated cotton	220	2.7	145	2.4
Cotton + FR 50 g/L	180	2.5	115	2.2
Cotton + FR 100 g/L	170	2.3	105	1.7
Cotton + FR 150 g/L	160	2.0	100	1.6
Cotton + FR 200 g/L	155	2.0	90	1.4
Cotton + FR 250 g/L	150	2.0	75	1.3
Cotton + FR 300 g/L	135	1.9	70	1.3
Improvement % 50	18	7	21	8
Improvement % 100	23	15	28	29
Improvement % 150	27	26	31	33
Improvement % 200	30	26	38	42
Improvement % 250	32	26	48	46
Improvement % 300	39	30	52	46

Notes: Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 33 – Effectiveness of Flame Retardants on Heat and Ignitability Properties of Cotton in Normal and Enriched Atmospheres [55]					
Cotton fabric	TTI	Pk HRR	FPI	Eff. Ht Combust	Avg HRR
Cone @ 25 kW/m^2	s	kW/m^2	$(m^2sk W^{-1})$	MJ/kg	kW/m^2
Atmosphere: air					
Untreated cotton	22	340	0.06	12	200
Cotton + N FR	34	120	0.28	7	60
Improvement % N FR	55	65	338	42	70
Atmosphere: 30% oxygen					
Untreated cotton	21	360	0.06	13.0	230
Cotton + N FR	34	170	0.20	7.0	70
Cotton + M FR	39	110	0.35	3.5	30
Improvement % N FR	62	53	243	46	70
Improvement % M FR	86	69	508	73	87

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR: average heat release rate during test in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Eff. Ht Combust: effective heat of combustion during cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 34 – Effectiveness of Flame Retardants on Heat and Ignitability Properties of Cotton [56]				
Cone testing of cotton	TTI	Pk HRR	FPI	Eff. Ht Combust
	s	kW/m^2	(m^2skW^{-1})	MJ/kg
20 kW/m^2				
Untreated	14	137	0.10	15.9
Cotton + SRRC 1	23	57	0.40	10.4
Cotton + SRRC 2	28	48	0.58	8.2
Improvement % SRRC1	64	58	295	35
Improvement % SRRC2	100	65	471	48
30 kW/m^2				
Untreated	9	152	0.06	16.5
Cotton + SRRC 1	10	86	0.12	13.2
Cotton + SRRC 2	12	86	0.14	10.9
Improvement % SRRC1	11	43	96	20
Improvement % SRRC2	33	43	136	34
50 kW/m^2				
Untreated	5	196	0.03	17.7
Cotton + SRRC 1	8	102	0.08	13.5
Cotton + SRRC 2	12	83	0.14	11.6
Improvement % SRRC1	60	48	207	24
Improvement % SRRC2	140	58	467	34
SRRC 1 Mix: with N and P				
SRRC 2 Mix: with P				

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Eff. Ht Combust: effective heat of combustion during cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.

Table 35 – Effectiveness of Flame Retardants on Heat and Ignitability Properties of GRP Composites [57]				
GRP composites	TTI	Pk HRR	Eff. Ht Comb	THR
Cone @ 50 kW/m^2	s	kW/m^2	MJ/kg	MJ/m^2
Polyester + glass				
GRP	29	343	25.0	52
GRP + MP	28	262	19.0	36
GRP + APP	23	268	23.0	37
GRP + MPP	24	303	22.0	41
GRP + ATH	30	243	23.0	45
GRP + FR	29	176	12.0	28
Improvement % MP	-3	24	24	31
Improvement % APP	-21	22	8	29
Improvement % MPP	-17	12	12	21
Improvement % ATH	3	29	8	13
Improvement % FR	0	49	52	46
GRP composites/barrier				
Polyester + glass				
GRP	229	220	20.0	45
GRP + MP	200	196	20.0	38
GRP + APP	230	175	21.0	49
GRP + MPP	213	210	19.0	46
GRP + ATH	251	196	19.0	42
GRP + FR	204	148	17.0	37
Improvement % MP	590	43	20	27
Improvement % APP	693	49	16	6
Improvement % MPP	634	39	24	12
Improvement % ATH	766	43	24	19
Improvement % FR	603	57	32	29
MP: melamine phosphate				
APP: ammonium polyphosphate				
MPP: melamine pyrophosphate				
FR: halogenated phosphate ester				
ATH: alumina trihydrate				

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; THR: total heat released during test in cone calorimeter test; Eff. Ht Combust: effective heat of combustion during cone calorimeter test. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 36 – Effectiveness of Flame Retardants on Heat Release of Some Particleboards [58]			
Wood Materials	TTI	Pk HRR	Avg HRR 3 min
Cone @ 50 kW/m^2	s	kW/m^2	kW/m^2
Untreated low density particleboards			
1	45	225	176
2	39	212	161
3	32	227	158
4	36	202	156
5	34	227	160
6	41	256	185
7	47	213	160
8	25	238	140
9	33	261	169
Average of above	37	229	163
FRT low density particleboards			
1	55	118	66
2	54	151	92
3	47	183	107
Average of above	52	151	88
Improvement % due to FR	41	34	46
Untreated medium density particleboards			
1	35	248	160
2	38	264	168
3	31	254	157
4	32	290	168
Average of above	34	264	163
FRT medium density particleboards			
1	641	117	84
2	942	68	94
3	29	175	102
4	38	166	109
5	828	81	93
Average of above	496	121	96
Improvement % due to FR	1358	54	41

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; Avg HRR 3 min: average heat release rate during 3 minutes following ignition in cone calorimeter test. Improvement % due to FR: percentage improvement in relevant property based on the untreated material. Average of above: average values of the individual cone calorimeter tests above this row.

Table 37 – Effectiveness of Flame Retardants on Heat Release of Two Different Species of Wood [59]				
	TTI	Pk HRR	FPI	Euroclass
Cone @ 50 kW/m^2	s	kW/m^2	(m^{2}s kW^{-1})	
Wood (larch)				
Untreated	17	171	0.10	C
Plus FRT treatment 1	38	136	0.28	C
Plus FRT treatment 2	26	76	0.34	B
Improvement % FRT treatment 1	124	20	181	
Improvement % FRT treatment 2	53	56	244	
Wood (thermowood pine)				
Untreated	14	165	0.08	C
Plus FR treatment 3	108	56	1.93	B
Plus FR treatment 4	31	84	0.37	B
Plus FR treatment 5	125	51	2.45	B
Improvement % FRT treatment 3	535	67	1840	
Improvement % FRT treatment 4	82	51	271	
Improvement % FRT treatment 5	635	70	2365	

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Euroclass: classification in the European Union classification system for construction materials. Improvement %: percentage improvement in relevant property based on the untreated material.

Table 38 – Mass Loss Cone Study of the Effectiveness of Various Flame Retardant Systems on Heat and Ignitability Properties of Pine Wood [60]			
Wood (pine)	TTI	Pk HRR	FPI
Mass loss cone @ 35 kW/m^2	s	kW/m^2	(m^{2}skW^{-1})
Untreated	98	182	0.54
Plus FR1	115	139	0.83
Plus FR2	101	121	0.83
Plus FR3	127	144	0.88
Plus FR4	81	103	0.79
Plus FR5	120	107	1.12
Plus FR6	70	107	0.65
Plus FR7	68	137	0.50
Plus FR8	55	97	0.57
Plus FR9	72	78	0.92
Improvement % FR1	17	24	54
Improvement % FR2	3	34	55
Improvement % FR3	30	21	64
Improvement % FR4	-17	43	46
Improvement % FR5	22	41	108
Improvement % FR6	-29	41	21
Improvement % FR7	-31	25	-8
Improvement % FR8	-44	47	5
Improvement % FR9	-27	57	71
FR1: Cu based wood preservative Cu: 0.11% w/w			
FR2: tribromoneopentyl alcohol 1.1% - 0.81% Br			
FR3: phosphoric acid 3-(diphenoxy-phosphoryloxy)-phenyl ester diphenyl ester 5.5% - 0.58% P			
FR4: chlorinated paraffin with 65% Cl content 22.7% - 14.8% Cl			
FR5: tetrabromobisphenol A bis (2,3-dibromopropyl ether) 1.9% - 0.65% aliphatic Br & 0.65% aromatic Br			
FR6: Cu preservative + FR2			
FR7: Cu preservative + FR3			
FR8: Cu preservative + FR4			
FR9: Cu preservative + FR5			

Notes: TTI: time to ignition in cone calorimeter test; Pk HRR: peak heat release rate in cone calorimeter test; FPI: fire performance index (ratio of time to ignition and peak heat release rate, in cone calorimeter test). Improvement %: percentage improvement in relevant property based on the untreated material.