

# **Heat release from plastic materials**

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**HEAT**

**RELEASE**

**IN FIRES**

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**PLASTICS**

Unlike for wood materials, considered in the previous chapter, there does not yet exist a model for predicting the HRR of plastics which would be both adequately general and computationally practical. Thus, products and materials need to be tested empirically and the data handled accordingly. (Of course, actual wood products also have to be tested empirically if data are needed for product acceptance purposes, as opposed to fire modeling). We begin this chapter with a general examination of Cone Calorimeter data illustrative of a wide variety of plastics; from this data certain performance measures are derived. In the next section, a number of studies on fire-retardant additives to plastics are examined. From these it is possible to observe some aspects of effective and ineffectual retardants. Finally, we conclude with a section of composite materials. Composites are resins which are reinforced with glass, carbon, or other fibres. These are often used where product performance is required which is not achievable with simple plastic formulations.

## (a) Heat release from plastic materials

by

Marcelo M. Hirschler

### Introduction

This section starts by first examining the chemical nature of some of the major families of man-made polymers. The thermal decomposition mechanisms of the various families are then discussed. Since a predictive theory is not available, an experimental program using the Cone Calorimeter is described. In this test program, a wide variety of plastics (34 plastics, plus Douglas Fir for reference) was tested in the horizontal orientation in the Cone Calorimeter at three incident heat fluxes: 20, 40 and 70 kW/m<sup>2</sup>. The Douglas fir was included in order to put the other materials in perspective with a material which has been well characterised. The materials tested are representative of commercial materials available in the 1990's. They cover a very wide range in fire performance, with peak heat release rates ranging from a few kW/m<sup>2</sup> (within the range of experimental error of the equipment) to almost 3000 kW/m<sup>2</sup>. The results presented include, as well as the heat release rate (full curves, peak values, average values and integrated values): time to ignition, effective heat of combustion and smoke obscuration measurements; several useful fire performance parameters are also calculated. The fire performance of the materials presented is then discussed in regard to what is known of their chemical composition and thermal decomposition mechanism. Material fire performance categories are then proposed to classify materials according to fire performance properties of interest: heat release rate, ignitability, propensity to flashover and smoke obscuration. A short discussion is made to emphasise the importance of testing products rather than materials, in order to ensure an adequate representation of full scale fire performance.

### Classification of Polymers

Polymers can be classified in a variety of ways [1]. In particular there are two ways that are worth mentioning. Firstly, they have often been classified, based

on their origin, into natural and synthetic (and sometimes including a third category of semi natural, or synthetic modifications of natural polymers). However, of more interest perhaps, is a classification based on their physical properties, in particular the elastic modulus and the degree of elongation. Under this criterion, polymers can be classified into elastomers, plastics and fibres. Elastomers (or rubbers) are characterised by a long-range extensibility which is almost completely reversible at room temperature. Plastics have only partially reversible deformability, while fibres have very high tensile strength but low extensibility. Plastics are often further subdivided between thermoplastics (whose deformation at elevated temperature is reversible) and thermosets (which undergo irreversible changes when heated). Elastomers have moduli between  $10^5$  and  $10^6$  N/m<sup>2</sup>, plastics have moduli between  $10^7$  and  $10^8$  N/m<sup>2</sup> and fibres have moduli between  $10^9$  and  $10^{10}$  N/m<sup>2</sup>. In terms of the elongation: elastomers can be stretched roughly up to 500-1000%, plastics between 100-200% and fibres only 10-30%.

Polymers can also be classified in terms of their chemical composition, and these give a very important indication as to their reactivity, including their fire performance. In order to help understand the heat release results to be presented a short indication of the main classes of polymers follows.

### Chemical Classes of Polymers

The main carbonaceous polymers with no heteroatoms are polyolefins, polydienes and aromatic hydrocarbon polymers (typically styrenics). The main polyolefins are thermoplastics: polyethylene (repeating unit:  $-(CH_2-CH_2)-$ ) and polypropylene (repeating unit:  $-(CH(CH_3)-CH_2)-$ ), which are two of the three most widely used synthetic polymers. Some of their major uses are in packaging, electrical wire and cable coatings, films, mouldings and tubing. Polydienes are generally elastomeric and contain one double bond per repeating unit. Other than polyisoprene (which can be synthetic or natural, e.g. natural rubber) and polybutadiene (used mostly as substitutes for rubber) most other polydienes are used as copolymers or blends with other materials (e.g. in ABS, SBR (styrene butadiene rubbers), MBS, EPDM (ethylene propylene diene rubbers), etc.). Their main uses tend to focus on their high abrasion resistance and high impact strength. The most important aromatic hydrocarbon polymers are based on polystyrene (repeating unit  $-(CH(Phenyl)-CH_2)-$ ). It is extensively used as a foam (for thermal insulation and acoustic ceiling tiles) and as a plastic for injection moulded articles (cutlery, household containers, appliance housings, etc.). A number of styrenic copolymers also have tremendous usage, including principally acrylonitrile butadiene styrene terpolymers (ABS).

polyesters. Polyacrylics are the only major oxygen containing polymers with carbon-carbon chains. The most important cellulosics, natural materials, are used by the timber industry and in the manufacture of paper and textiles. Different grades of wood contain approximately 20-50% of cellulose. The main polyacrylic is poly(methyl methacrylate) (repeating unit  $-(\text{CH}_2-\text{C}(\text{CH}_3)-\text{CO}-\text{OCH}_3)-$ ; PMMA), widely used as a substitute for glass, for its high light transmittance and in the manufacture of items where easy dyeability and transparency are important. The most important polyesters are manufactured from glycols (such as polyethylene terephthalate, PET, or polybutylene terephthalate, PBT, made from ethylene or butylene glycol) or from bisphenol A (polycarbonate). They are used as engineering thermoplastics in applications such as soft drink bottles (PET), as fibres (PET) and for injection moulded articles or unbreakable replacements for glass (polycarbonate). Other oxygenated polymers include phenolic resins, resulting from the condensation of phenols and aldehydes and often used as polymeric additives, polyethers, such as polyphenylene oxide (PPO), a very thermally stable engineering polymer, polyacetals (such as polyformaldehyde, used for its intense hardness and resistance to solvents).

Nitrogen containing materials include nylons, polyurethanes and polyacrylonitrile. Nylons, having repeating units containing the characteristic group  $-\text{CO}-\text{NH}-$ , are made into fibres and also into a number of injection moulded articles, as well as being used in the wire and cable industry. Nylons are synthetic aliphatic polyamides, but there exist also natural polyamides (wool, silk, leather) and synthetic aromatic polyamides (of exceptionally high thermal stability, and used for protective clothing). Polyurethanes (with repeating units containing the characteristic group  $-\text{NH}-\text{COO}-$ ), are normally manufactured from the condensation of polyisocyanates and polyols. Their principal area of application is as foams (flexible, for use in furniture or as filling materials and rigid, for use in packaging or as thermal insulation). Other polyurethanes are made into thermoplastic elastomers, which are chemically very inert and can be used in automotive applications (shock absorbers, bumpers), disposable diapers and wire and cable coatings. Both these types of polymers have carbon-nitrogen chains, but nitrogen can also be contained in materials with carbon-carbon chains, the main example being polyacrylonitrile (repeating unit  $-(\text{CH}_2-\text{CH}-\text{CN}-)$ ). It is used mostly to make into fibres and as a constituent of engineering copolymers (SAN, ABS).

Chlorine containing polymers are characterised by poly(vinyl chloride) (PVC, repeating unit  $-(\text{CH}_2-\text{CHCl})-$ ). It is the most widely used synthetic polymer, together with polyethylene and polypropylene. It is unique in the sense that it is used both as a rigid material (unplasticised, as pipes, sheets, rods, bottles

manufactured into pipes and wire and cable materials. Through the additional chlorination of PVC another member of the family of vinyl materials is made: chlorinated poly(vinyl chloride) (CPVC), with very different physical and fire properties from PVC. CPVC is made into sprinkler pipe, hot water plumbing, or rigid sheet and is also used as a flame retardant component. Two other chlorinated materials are of commercial interest: a polydiene (viz. polychloroprene, used for oil resistant wire and cable materials) and poly(vinylidene chloride) (PVDC, with a repeating unit:  $-(CH_2-CCl_2)-$ ) used for making films and fibres. All these polymers have carbon-carbon chains.

Fluorine containing polymers are characterised by high thermal and chemical inertness and low coefficient of friction. The most important material in the family is polytetrafluoroethylene (PTFE), while others include poly(vinylidene fluoride) (PVDF), poly(vinyl fluoride) (PVF) and fluorinated ethylene polymers (FEP). They are used as insulators, particularly in the wire and cable industry, in printed circuits and in gaskets, diaphragms and as metal coatings for "non stick" surfaces.

### Thermal Decomposition of Polymers

Polymer burning takes place, probably, by a series of stages, but the first one is almost inevitably the thermal decomposition of the polymer to yield volatile or gaseous products [1, 2]. These gaseous products will then continue to burn by the chain propagation process associated with free radicals. It is important, thus, to have a basic understanding of the mechanism by which these polymers decompose. However, although thermal decomposition is essential for flammability, there is poor correlation between minimum thermal decomposition temperatures and low flammabilities.

The first polymers to be analysed are those with a general repeating formula of  $-(CWX-CYZ)-$ . They decompose by an end chain scission mechanism if the W and X are H atoms but neither Y nor Z are. This means that all scissions occur in the main carbon-carbon chain and that each breakdown occurs by eliminating a repeating unit from the end of the polymeric chain. In that case the yield of monomer is very high, usually over 90%. A typical example of such polymers is PMMA. The thermal decomposition will, thus, be a steady process, normally leading to a fairly flammable gas mixture. If only one of the four substituents on the carbon atoms is not an H atom, but it is a hydrocarbon group, decomposition will generally occur by random chain scission or by a combination of random chain scission and end chain scission. Random chain scission means that carbon chains are broken at those positions which present the least resistance and that tends to

or to a very low yield of monomer (as in the case of polypropylene).

If one or more of the substituents in the same repeating formula discussed is a halogen, a hydroxyl or an acetate, the most common decomposition mechanism will be chain stripping rather than chain scission. In this case the substituent will be eliminated, together with a H atom, leading to a solid polydiene and a small gaseous molecule, generally non carbonaceous and non flammable. Examples of such polymers are PVC, PVDC, PVF, PVDF and poly(vinyl alcohol) which lead to hydrogen chloride (HCl), hydrogen fluoride (HF) and water, respectively. This means that the vapour phase will be of very low flammability or even cause a clear destruction of the chain propagating free radicals. Halogen acids, for example, will react with the free radicals causing the rapid chain propagation and convert them into less reactive radicals, thus slowing the burning process. Moreover, the elimination of small incombustible molecules decreases the concentration of flammable gases, by dilution. The condensed phase residues remaining tend to be highly carbonaceous and high in char. Such residues, with low hydrogen content, tend to be less flammable than those of materials that undergo chain scission. A variant which is intermediate between PVC and PVDC is chlorinated PVC (CPVC), which has a structure where between one and two H atoms (on average) have been replaced by chlorine, and its thermal decomposition mechanism, also by chain stripping, reflects this [3].

If all four substituents in the repeating formula are fluorine atoms, as in PTFE, the decomposition mechanism is a chain end scission, but this leads to gaseous molecules of very low flammability (tetrafluoroethylene) and the residue is identical to the starting polymer. Curiously, however, if all 4 substituents are halogens, but they are not all the same (e.g. polychlorotrifluoroethylene), this yields a combination of end chain scission and chain stripping, providing low monomer yields and large yields of other small halogenated gases.

A special case is polyacrylonitrile, with formula  $-(CH_2-CHCN)-$ , where thermal decomposition occurs via solid phase cross-linking, with elimination of some volatile molecules, but very low monomer yield.

Some polymers do not have structures with that repeating formula. In that case, the mechanism of thermal breakdown is more complicated and less predictable. Polymers such as those are dienes, polyesters, polyamides or polyurethanes. They will, almost invariably, yield no monomers and, usually, low char residues.

Polymers with high aromatic content and low hydrogen content are usually very thermally stable [4]. They lead to carbonaceous chars, following mainly cross linking reactions, and do not break down into highly flammable small molecules. They yield very little monomer but the gases contain mostly small molecules such as water or carbon oxides. One example of such behaviour is polyphenylene oxide. However, a variety of other, much more stable, polymers exist, few of

which have, as yet, reached abundant commercial use. The use of highly aromatic very stable polyimides is now starting to grow and commercial examples exist.

The presence of some heteroatoms in the polymer structure may be indicative of changes in the thermal decomposition or flammability performance. In particular, the effect of halogens has already been addressed: they change the thermal decomposition mechanism and improve the fire performance of a polymer containing no heteroatoms. Nitrogen content will also tend to improve fire performance, but only under some specific conditions. Instead of having heteroatoms in the structure, the use of additives can also substantially change both the thermal decomposition mechanism and the flammability of the base polymer. However, these tend to be complex issues and there are significant commercial confidentiality issues involved, so that no further discussion will be undertaken here. Discussions of the mechanisms of action of flame retardants have been published elsewhere [e.g.2].

### Materials Tested

In practice, materials are rarely used in the form of a pure polymer, but always contain additives. Here, plastics will simply be assumed to be a synonym for synthetic polymers.

Thirty-five materials were tested in the Cone Calorimeter [5] for in this experimental programme, all under the same conditions: irradiance values of 20, 40 and 70 kW/m<sup>2</sup>, all in a horizontal orientation. A minimum of two runs was carried out for each material at each flux. If the runs differed significantly, a third run was carried out. The software used was developed at BFGoodrich. All the properties of interest were measured every 3 s. In order to avoid spurious peaks, a smoothing routine was used, of the type suggested by the Center for Fire Research, National Institute for Standards and Technology. This involved taking each set of successive 5 points and predicting, via a cubic spline curve fit, the value at the center point and using this value for any further calculations.

The materials were tested using samples 100 mm x 100 mm in surface area, with a thickness of 6 mm (with two exceptions). The two exceptions were polyurethane foam and poly(methyl methacrylate) (PMMA, with a cardboard lining on the side) which were tested at 25 mm thickness.

Most of the materials used were commercial samples and, thus, their composition is not disclosed by the manufacturer.

in the late 1980's and early 1990's. Three materials were chosen because they have been used extensively for other testing programs and their fire performance can be used, thus, as an indicator for that of the other materials: Douglas fir wood, PMMA (plus cardboard) and "standard flexible PVC" (FL PVC PVC).

The standard flexible PVC has been used for several other applications, including smoke corrosivity testing [6, 7], smoke toxicity testing [8] and the cone calorimeter ASTM round robin [9].

#### Description of materials:

(All samples are at 6 mm thickness, except as indicated.)

#### NON VINYLs

- ABS: Cycolac CTB acrylonitrile butadiene styrene terpolymer (Borg Warner) (# 29)
- ABS FR: Cycolac KJT acrylonitrile butadiene styrene terpolymer fire retarded with bromine compounds (Borg Warner) (# 20)
- ABS FV: Polymeric system containing acrylonitrile butadiene styrene and some poly(vinyl chloride) as additive (# 19)
- ACET: Polyacetal: polyformaldehyde (Delrin, Commercial Plastics) (# 24)
- DFIR: Douglas fir wood board (# 22)
- EPDM: Copolymer of ethylene propylene diene rubber (EPDM) and styrene acrylonitrile (SAN) (Rovel 701) (# 31)
- KYDEX: Kydex: fire retarded acrylic panelling, blue, (samples were 4 sheets at 1.5 mm thickness each, Kleerdex) (# 15)
- PCARB: Polycarbonate sheeting (Lexan 141-111, General Electric) (# 5)
- PCARB B: Commercial polycarbonate sheeting (Commercial Plastics) (# 16)
- NYLON: Nylon 6,6 compound (Zytel 103 HSL, Du Pont) (# 28)
- PBT: Polybutylene terephthalate sheet (Celanex 2000-2 polyester, Hoechst Celanese) (# 32)
- PE: Polyethylene (Marlex HXM 50100) (# 34)
- PET: Polyethylene terephthalate soft drink bottle compound (# 33)
- PMMA: Poly(methyl methacrylate) (25 mm thick, lined with cardboard, standard RHR sample) (# 26)
- PP: Polypropylene (Dypro 8938) (# 35)
- PPO/PS: Blend of polyphenylene oxide and polystyrene (Noryl N190, General Electric) (# 18)
- PPO GLAS: Blend of polyphenylene oxide and polystyrene containing 30%

PS FR: Fire retarded polystyrene, Huntsman 351 (Huntsman) (# 23)  
 PTFE: Polytetrafluoroethylene sheet (samples were two sheets at 3 mm thickness each, Du Pont) (# 1)  
 PU: Polyurethane flexible foam, non fire retarded (Jo-Ann Fabrics) (# 25)  
 THM PU: Thermoplastic polyurethane containing fire retardants (estane, BFGoodrich) (# 27)  
 XLPE: Black non-halogen flame retardant, irradiation crosslinkable, polyethylene copolymer cable jacket compound (DEQD-1388, Union Carbide) (# 11)

#### VINYLS:

Rigid

PVC EXT: Poly(vinyl chloride) rigid weatherable extrusion compound with minimal additives (BFGoodrich) (# 13)  
 PVC LS: Poly(vinyl chloride) rigid experimental sheet extrusion compound with smoke suppressant additives (BFGoodrich) (# 10)  
 PVC CIM: Poly(vinyl chloride) general purpose rigid custom injection moulding compound with impact modifier additives (BFGoodrich) (# 8)  
 CPVC: Chlorinated poly(vinyl chloride) sheet compound (BFGoodrich) (# 7)

#### Flexible PVC's

FL PVC: Standard flexible poly(vinyl chloride) compound (non-commercial; similar to a wire and cable compound) used for various sets of testing (including Cone Calorimeter RHR ASTM round robin; it contains PVC resin 100 phr; diisodecyl phthalate 65 phr; tribasic lead sulphate 5 phr; calcium carbonate 40 phr; stearic acid 0.25 phr) (# 21)  
 PVC WC: Flexible wire and cable poly(vinyl chloride) compound (non fire retarded) (BFGoodrich) (# 14)  
 PVC WC SM: Flexible wire and cable poly(vinyl chloride) compound (containing minimal amounts of fire retardants) (BFGoodrich) (# 12)  
 PVC WC FR: Flexible wire and cable poly(vinyl chloride) compound (containing fire retardants) (BFGoodrich) (# 9)  
 VTE 1: Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the first of several families of VTE alloys (# 6)

- VTE 2: Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the second of several families of VTE alloys (# 3)
- VTE 3: Flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of the third of several families of VTE alloys (# 2)
- VTE 4: Semi flexible vinyl thermoplastic elastomer alloy wire and cable jacket experimental compound, example of a family of VTE alloys containing CPVC (# 4)

The numbers following the description of each material are those used throughout the paper for Tables and Figures. They originate in the decreasing order of peak heat release rate at the lowest incident flux used, viz. 20 kW/m<sup>2</sup>.

### Results

The results presented will include up to 11 properties for each material. These will be:

- TTI: Time to ignition, at each flux, in s. The time to ignition was determined visually and taken to be the time to a sustained combustion of at least 10 s duration. If no ignition was observed, after 1 h of exposure, time to ignition was recorded as 10,000 s.
- Pk RHR: Peak value of the heat release rate vs. time curve, in kW/m<sup>2</sup>, of the sample. Heat release rate was measured by the principle of oxygen consumption [10, 11].
- THR: Total heat released by the sample, at the end of the test, in MJ/m<sup>2</sup>. It is calculated by integrating the curve of heat release rate over time.
- Ht Comb: Effective heat of combustion, in MJ/kg. The value reported is the average for the entire test.
- Av RHR: Average heat release rate during the period between ignition and 3 min after ignition. If the sample did not ignite this value was taken to be zero. Some materials have been tested before the measurement of this magnitude was feasible, and it appears as "not measured" in the tables.
- Pk RSR: Peak value of the rate of smoke release vs. time curve, in 1/s. The rate of smoke released is the product of the extinction coefficient and the volumetric air flow rate divided by the sample surface area and the light path length (with the appropriate corrections) [12].
- TSR: Total smoke released by the sample, at the end of the test (non dimensional). Just like the THR, it is calculated by integrating the curve of rate of smoke release vs. time.

- AvExtAr:** Average extinction area, measured at 5 min into the test, in  $m^2/kg$ .
- SmkFct:** Smoke factor, measured at 5 min into the test, in  $MW/m^2$ . It is the product of the peak heat release rate and the total smoke released, at 5 min. It has been shown that it can be an indication of the relative propensity of materials to generate smoke in full scale tests [12-16].
- MLRP:** Mass loss rate parameter, in  $g/m^2s^2$ . It is calculated as the product of the average mass loss rate (between the times at which the sample loses 10% and 90% of its total weight loss) and the time to ignition [17, 18].
- TTI/RHR:** Ratio of the time to ignition to the peak heat release rate (in s.  $m^2/kW$ ). This parameter has been shown to give an indication of propensity to flashover, because it relates to the time to flashover [19-22].

### Discussion of results

Figures 1-35 show the curves of heat release rate versus time for each of the materials tested, at all three incident fluxes. These materials are all homogeneous, i.e. there is no difference either between successive layers or between different exposed areas. It is not surprising, thus, that the heat release rate curves do not, generally, show multiple peaks. This does not mean, however, that the curves are

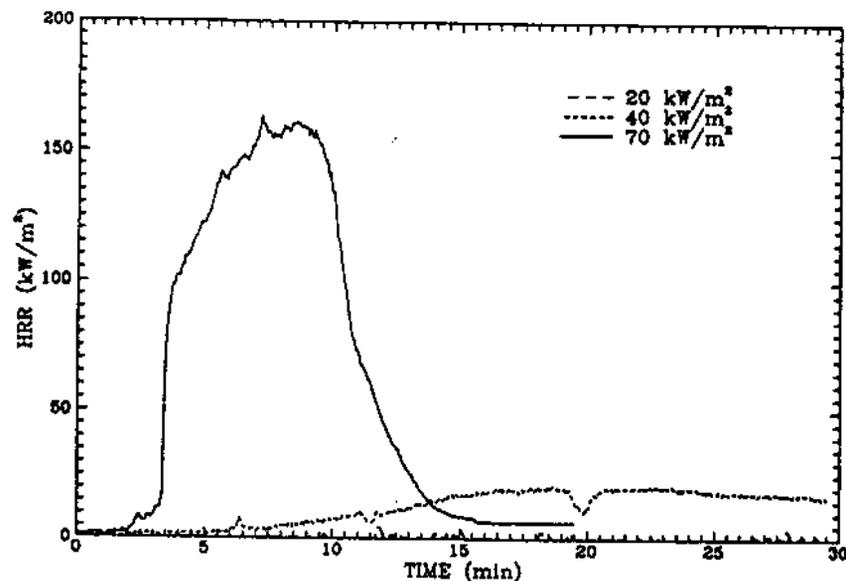


Figure 1. Heat release rate versus time for PTFE, at all three incident fluxes used, 20, 40 and 70  $kW/m^2$ .

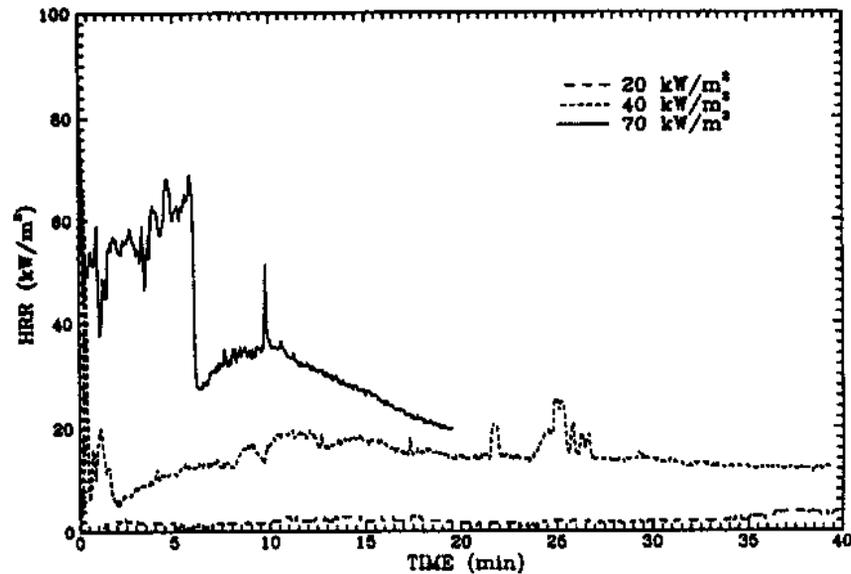


Figure 2. Heat release rate versus time for VTE-3, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

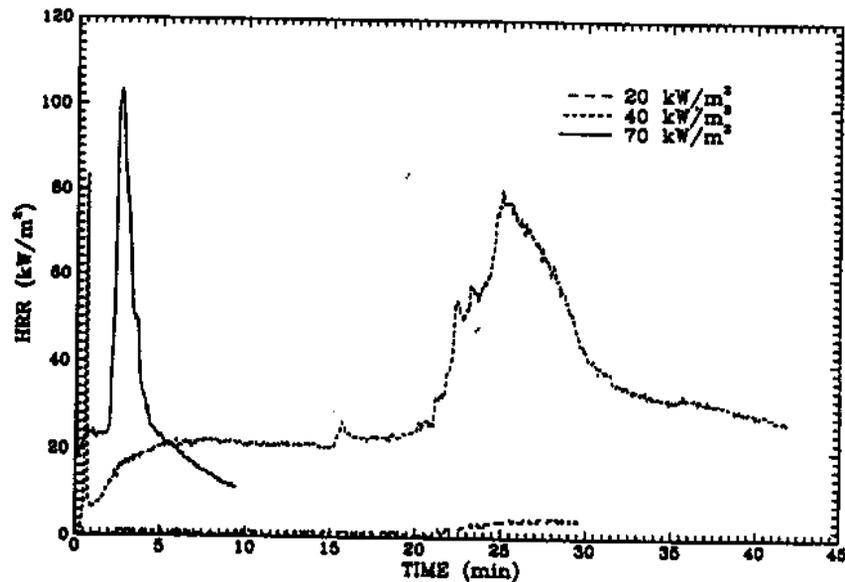


Figure 3. Heat release rate versus time for VTE-2, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

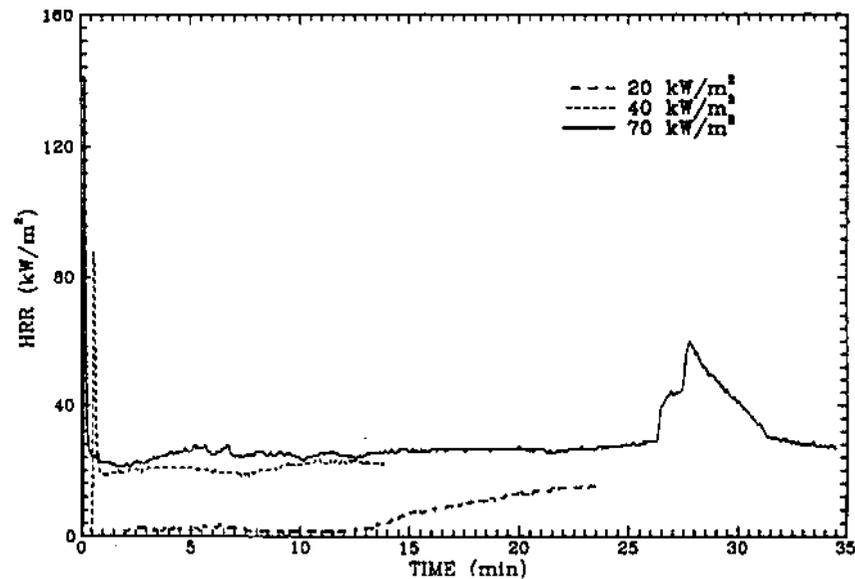


Figure 4. Heat release rate versus time for VTE-4, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

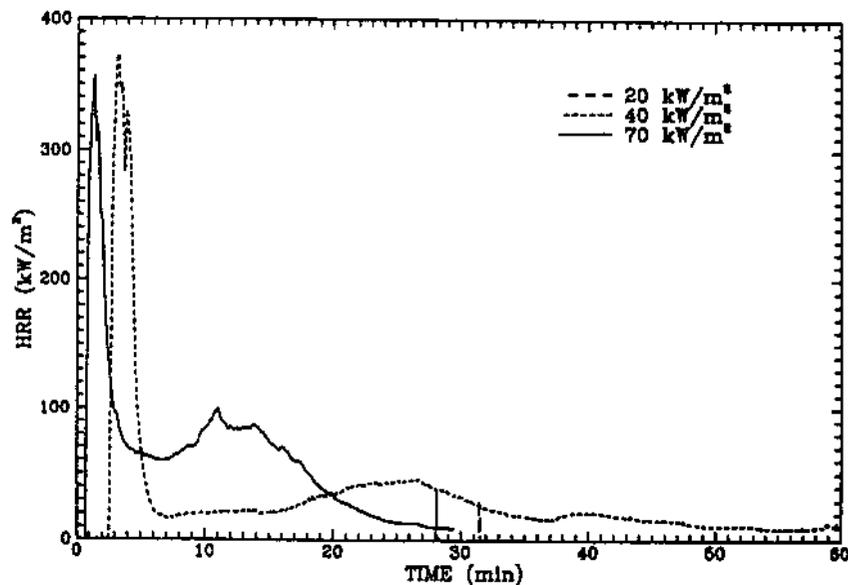


Figure 5. Heat release rate versus time for VTE-1, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

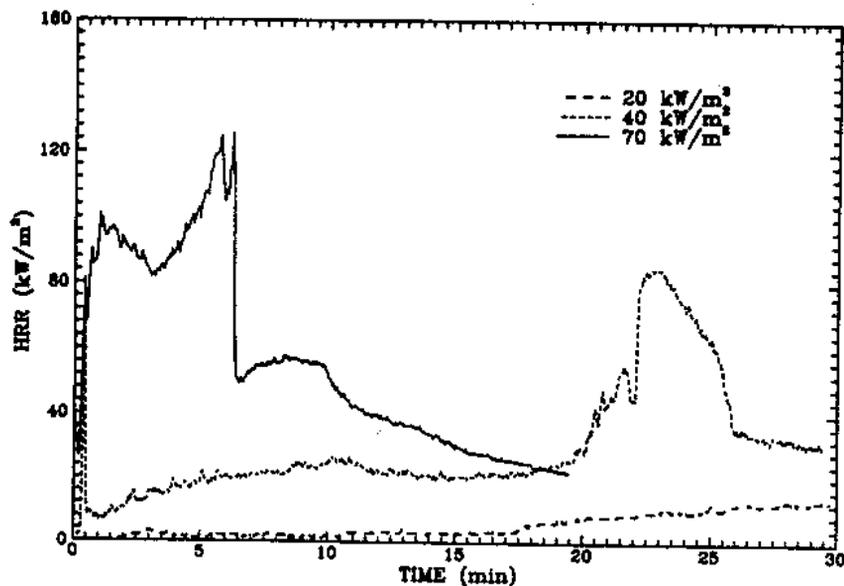


Figure 6. Heat release rate versus time for VTE-1, at all three incident fluxes used, 20, 40 and 70  $\text{kW/m}^2$ .

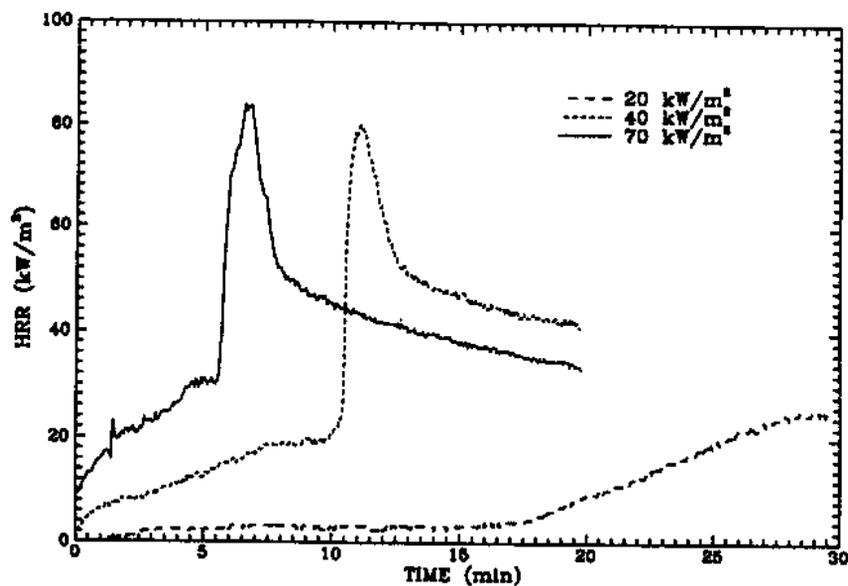


Figure 7. Heat release rate versus time for CPVC, at all three incident fluxes used, 20, 40 and 70  $\text{kW/m}^2$ .

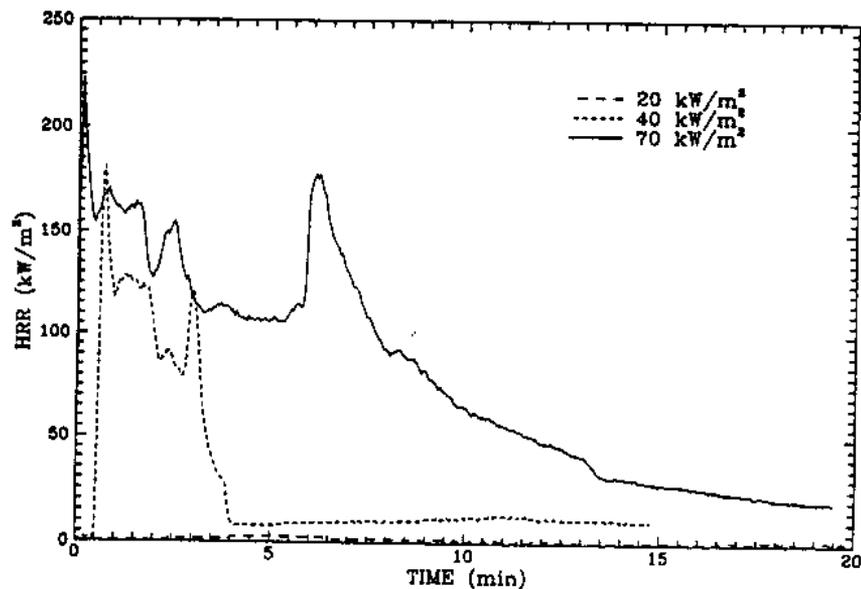


Figure 8. Heat release rate versus time for PVC CIM, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

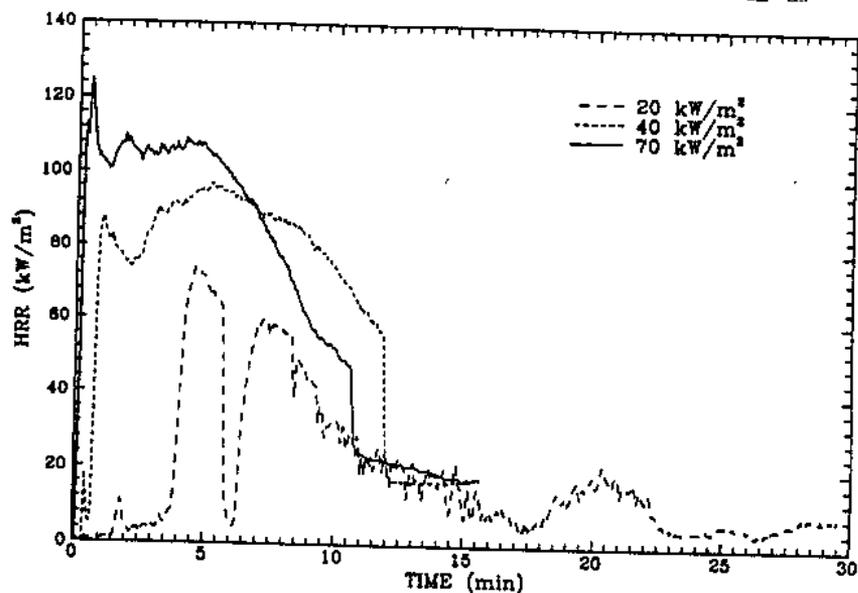


Figure 9. Heat release rate versus time for PVC WC FR, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

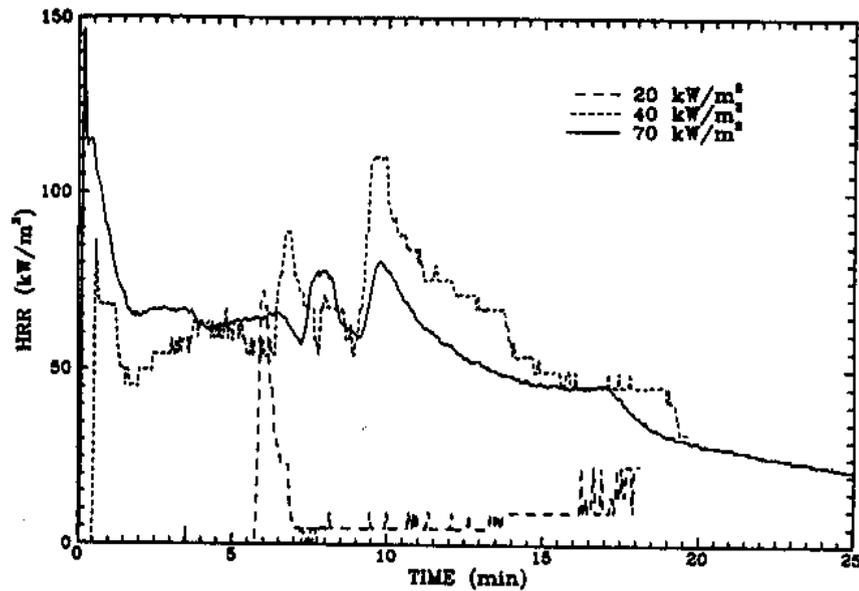


Figure 10. Heat release rate versus time for PVC LS, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

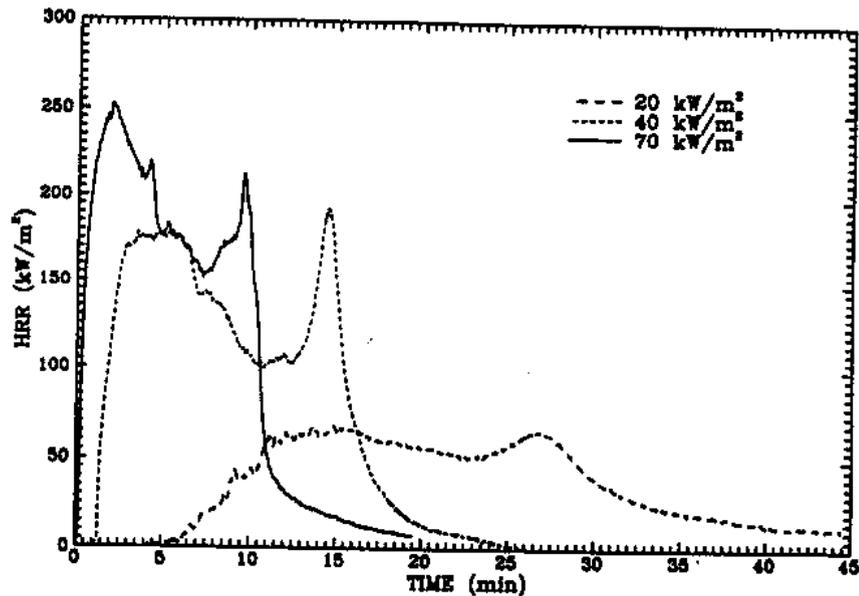


Figure 11. Heat release rate versus time for XLPE, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

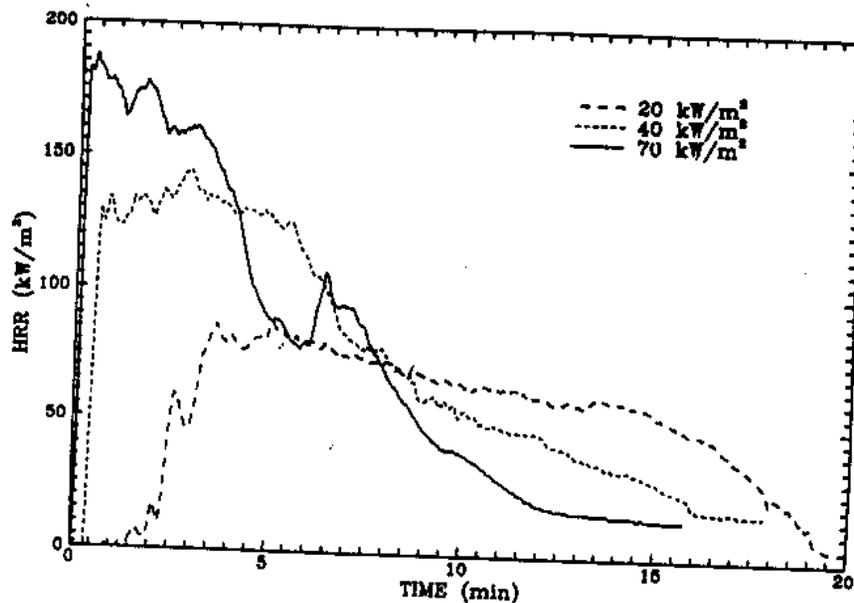


Figure 12. Heat release rate versus time for PVC WC SM, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

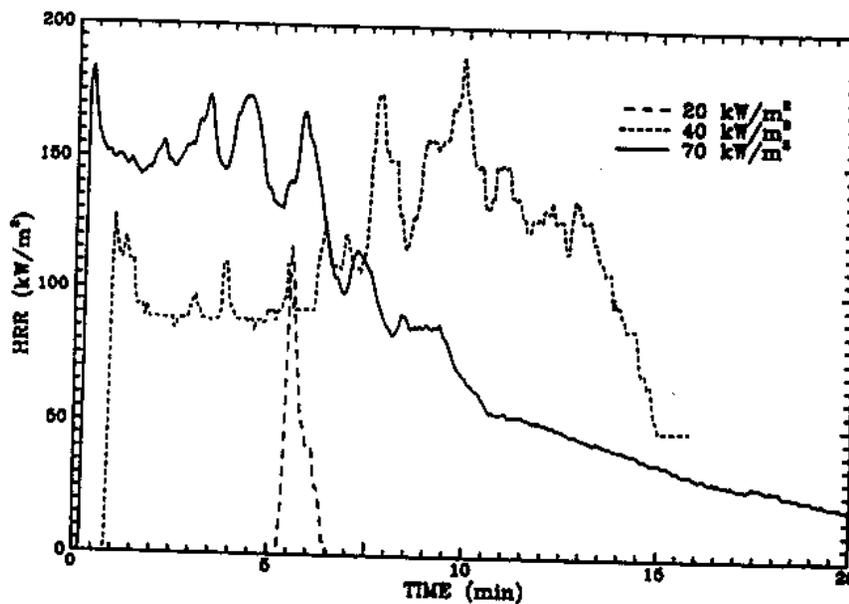


Figure 13. Heat release rate versus time for PVC EXT, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

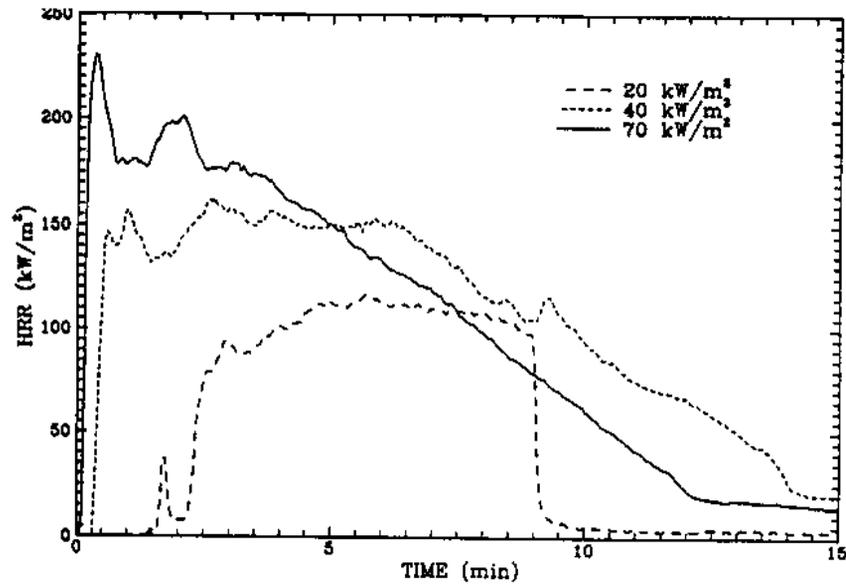


Figure 14. Heat release rate versus time for PVC WC, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

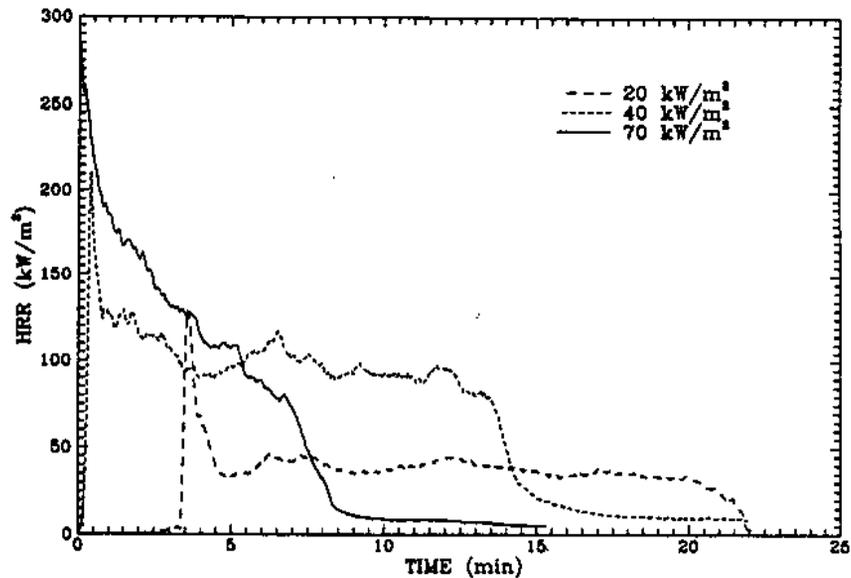


Figure 15. Heat release rate versus time for KYDEX, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

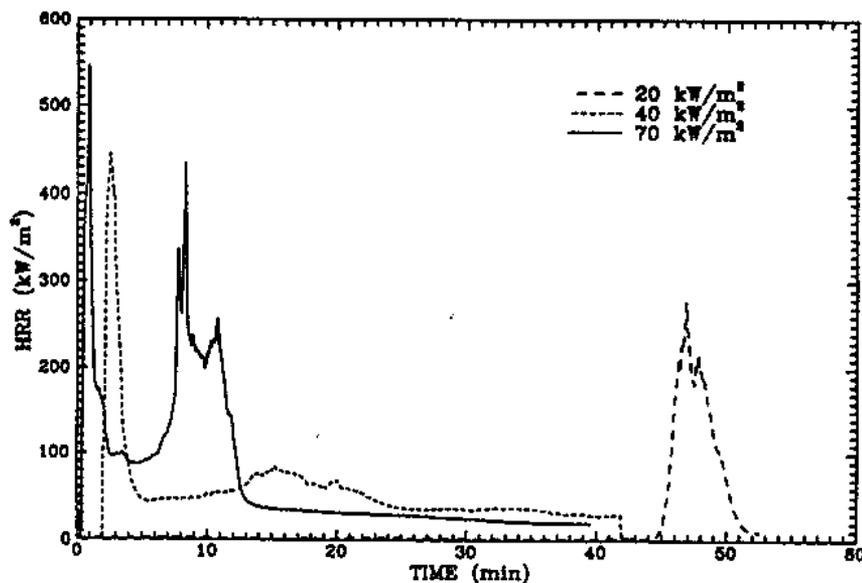


Figure 16. Heat release rate versus time for PCARB B, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

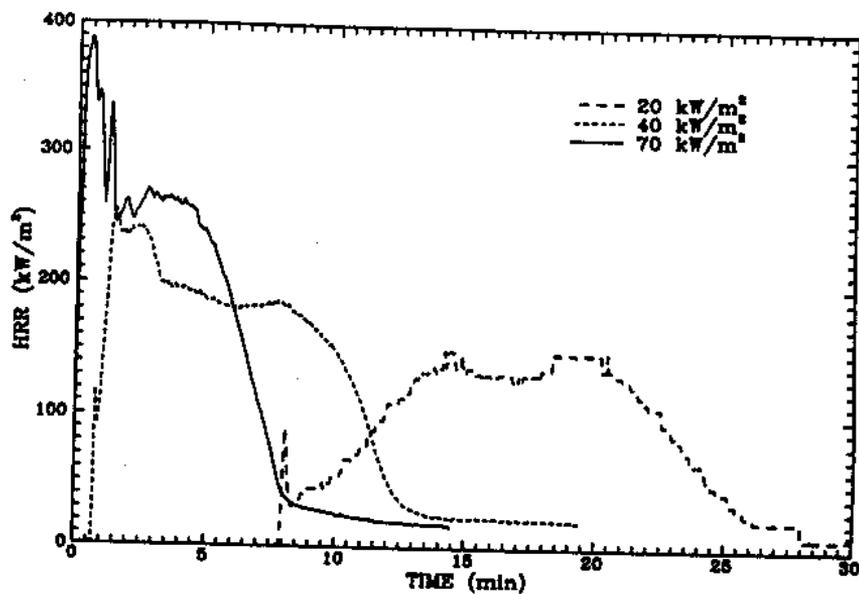


Figure 17. Heat release rate versus time for PPO GLAS, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

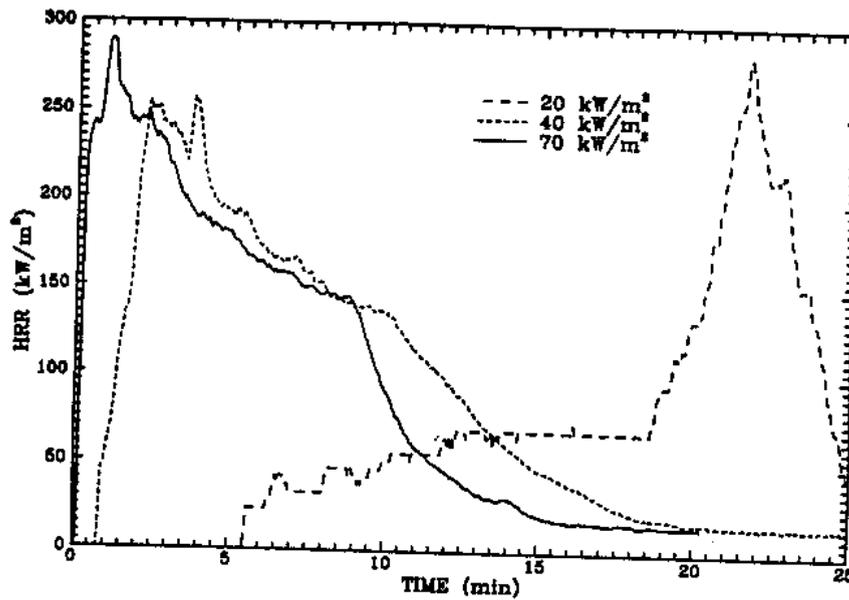


Figure 18. Heat release rate versus time for PPO/PS, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

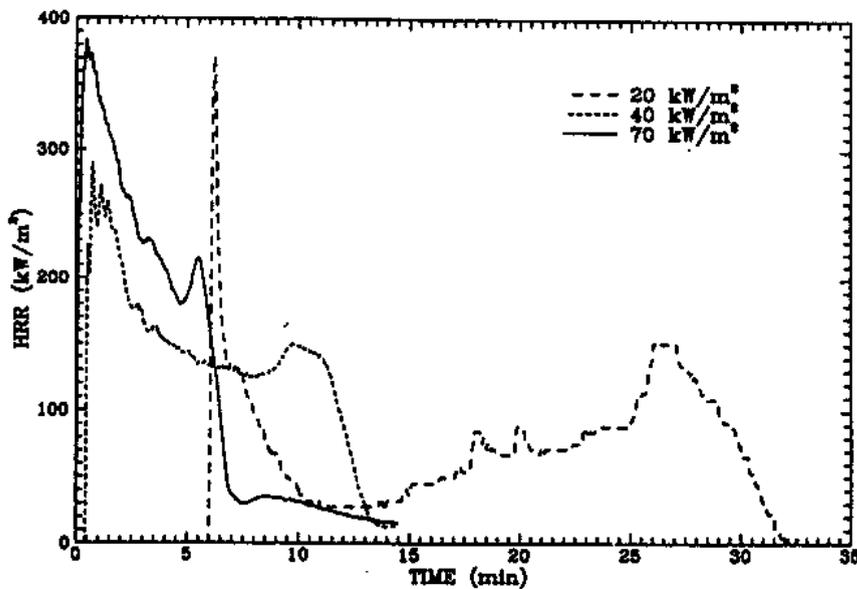


Figure 19. Heat release rate versus time for ABS FV, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

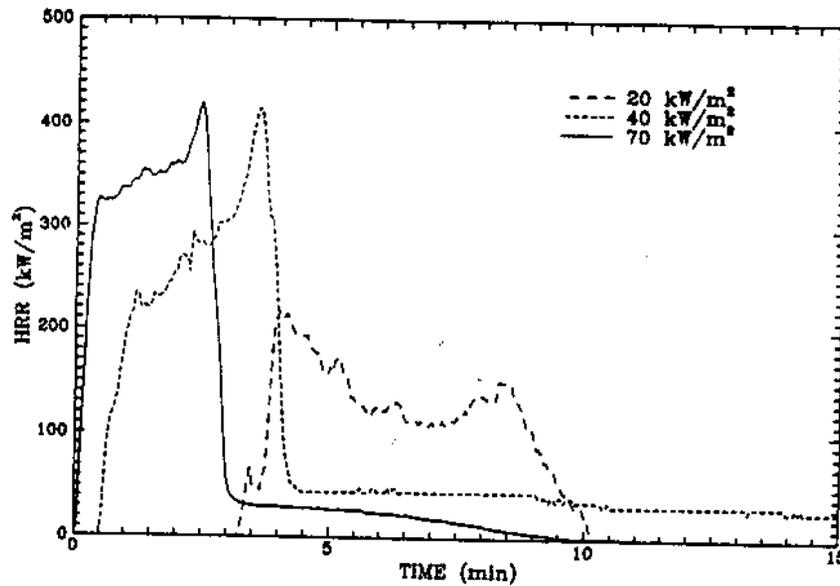


Figure 20. Heat release rate versus time for ABS FR, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

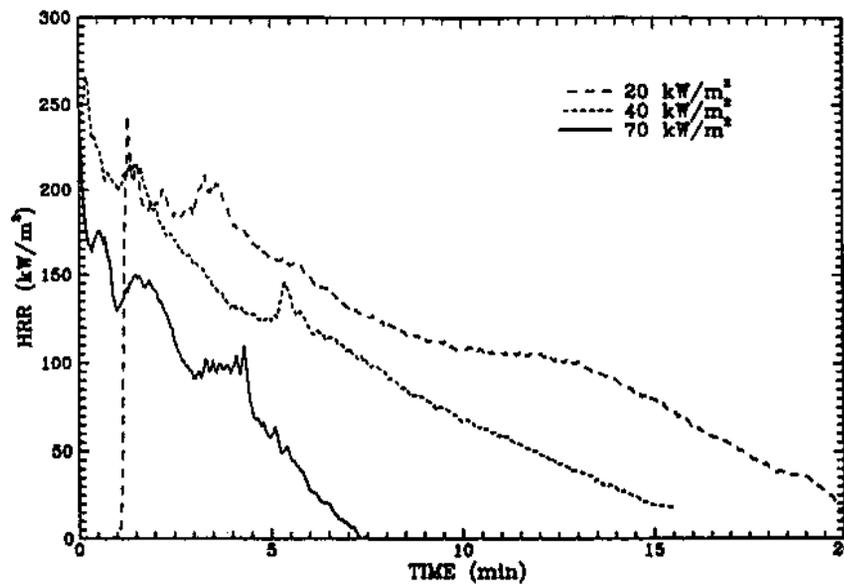


Figure 21. Heat release rate versus time for FL PVC, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

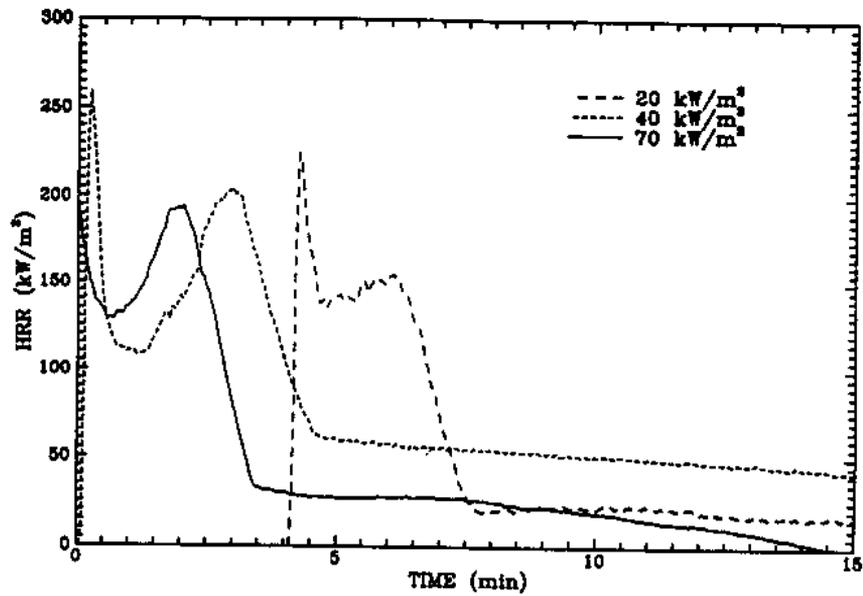


Figure 22. Heat release rate versus time for DFIR, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

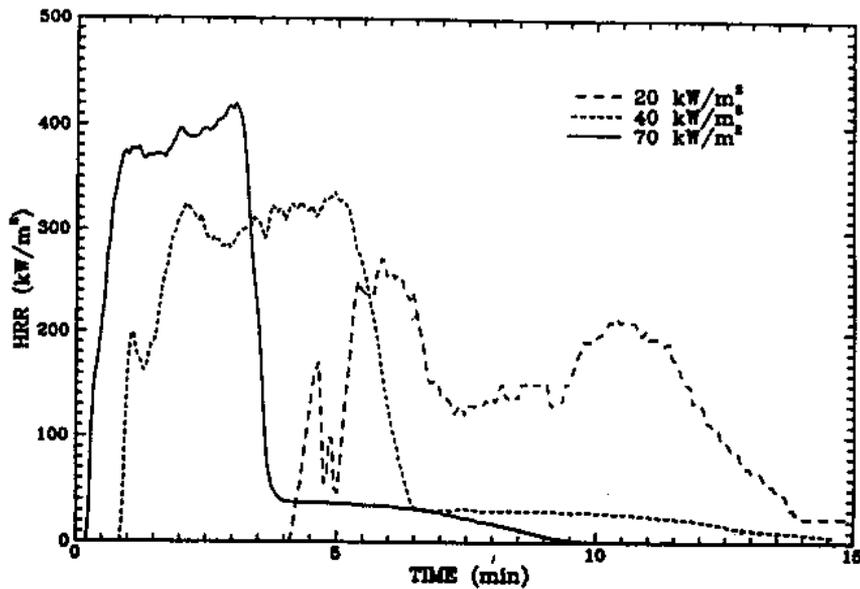


Figure 23. Heat release rate versus time for PS FR, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

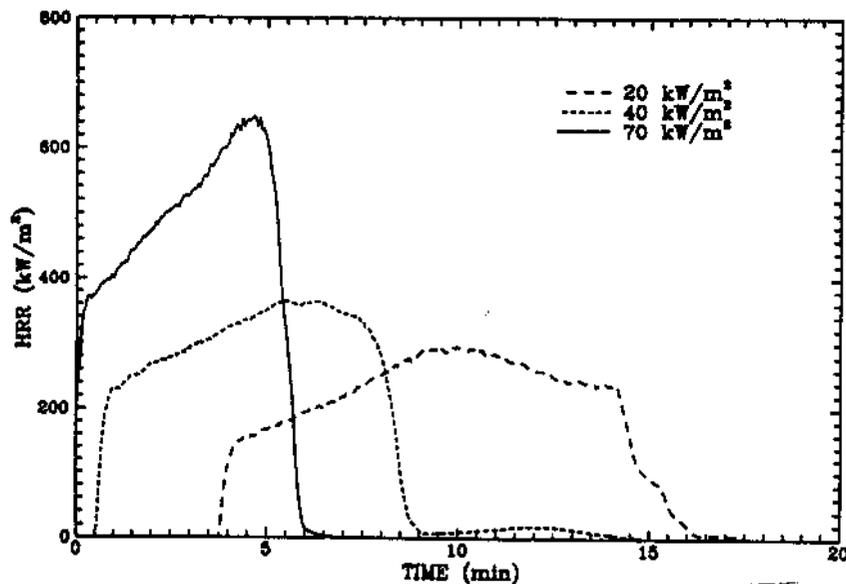


Figure 24. Heat release rate versus time for ACET, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

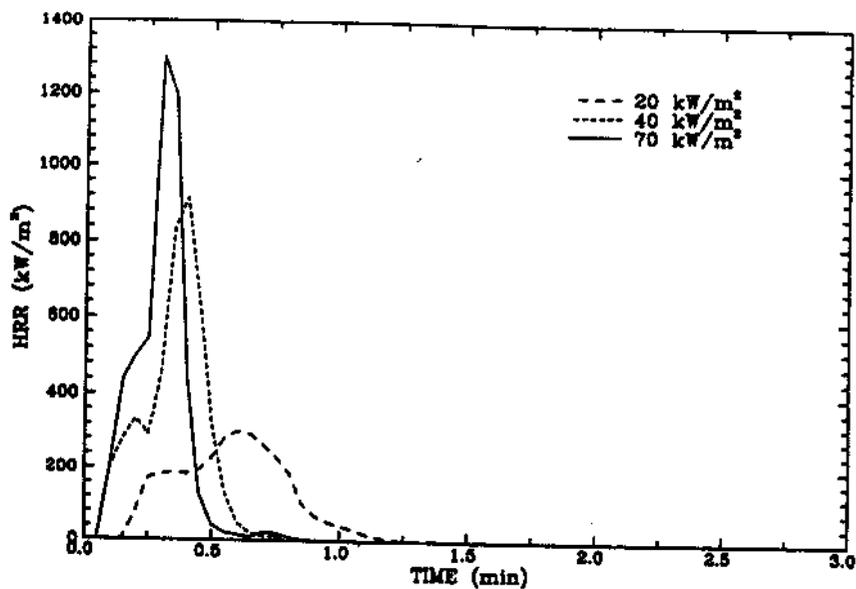


Figure 25. Heat release rate versus time for PU, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

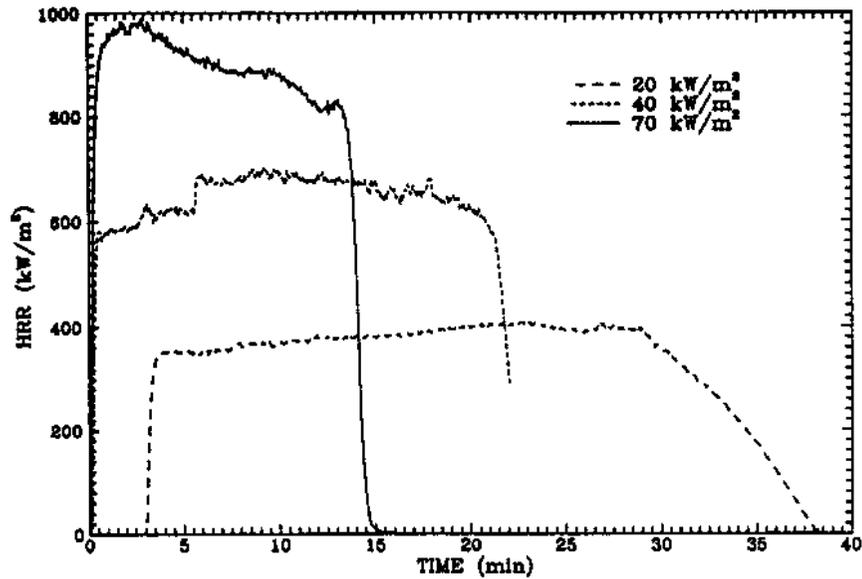


Figure 26. Heat release rate versus time for PMMA, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

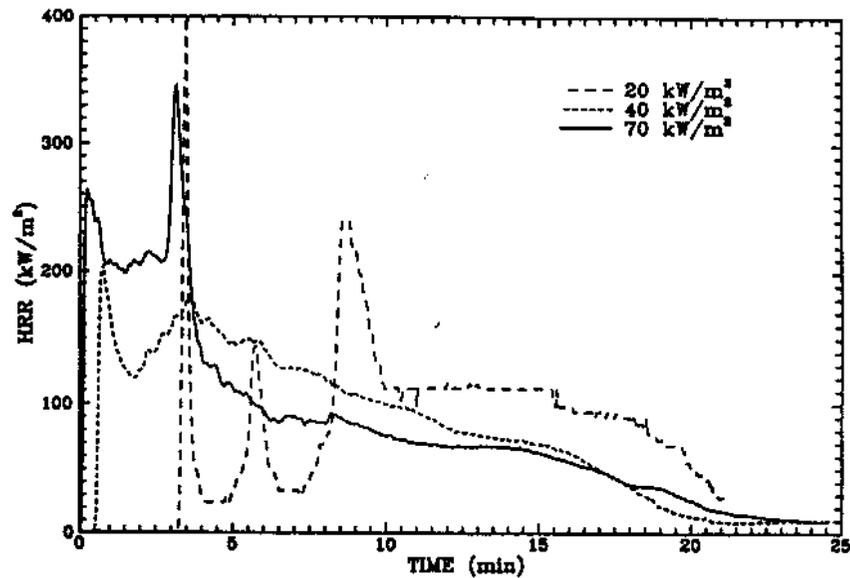


Figure 27. Heat release rate versus time for THM PU, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

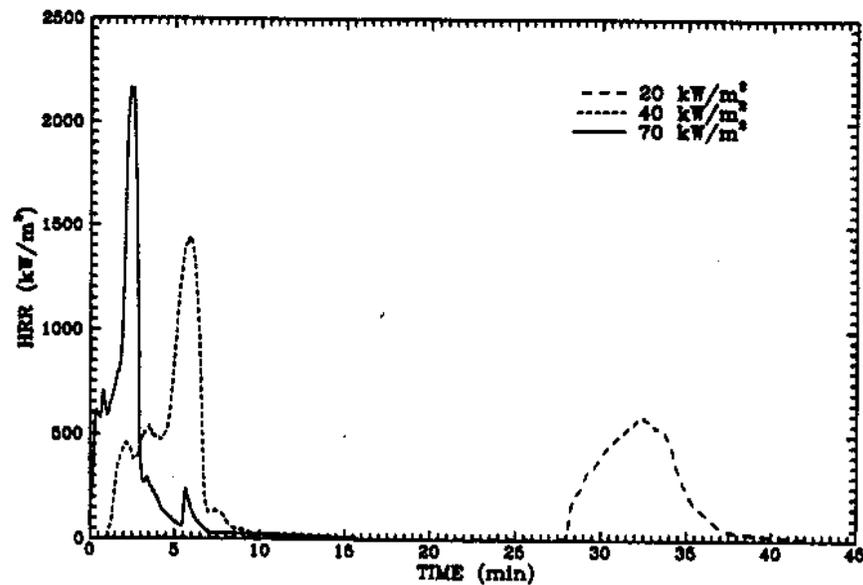


Figure 28. Heat release rate versus time for NYLON, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

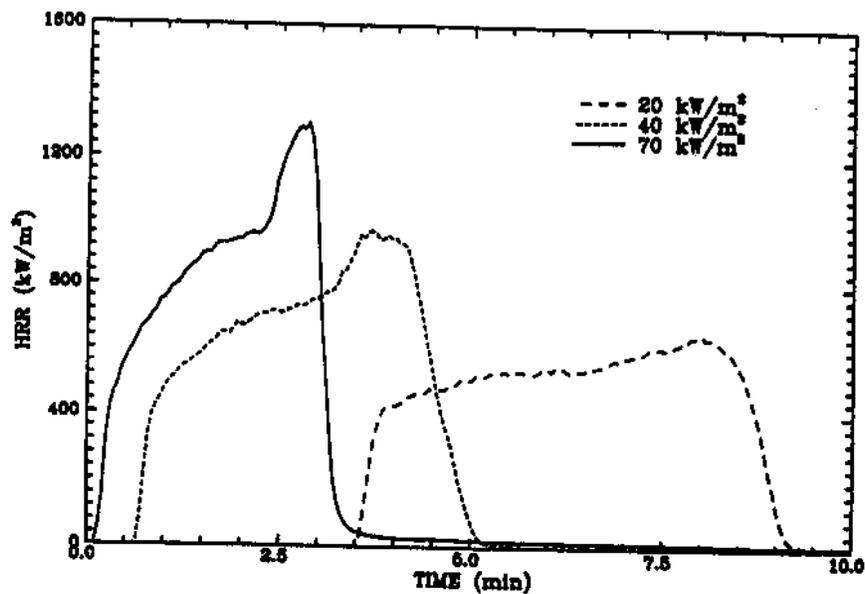


Figure 29. Heat release rate versus time for ABS, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

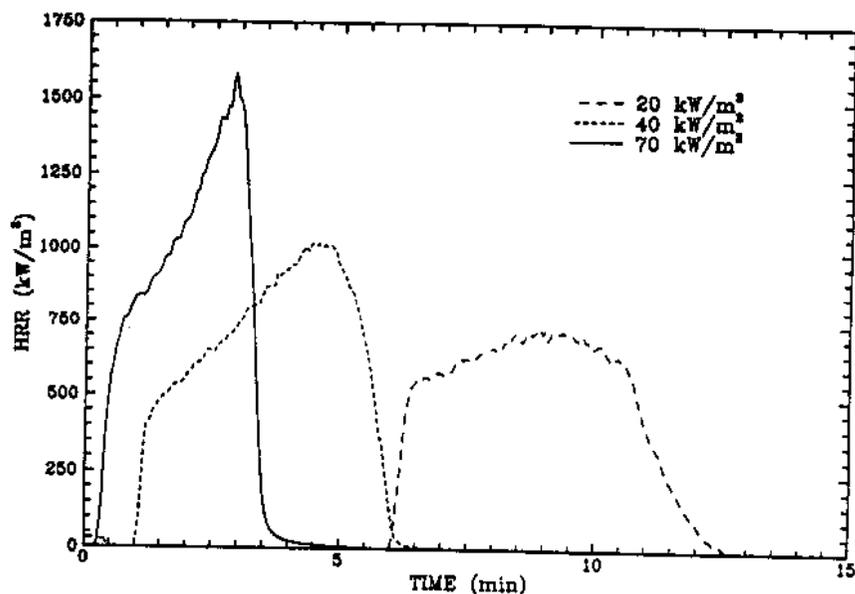


Figure 30. Heat release rate versus time for PS, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

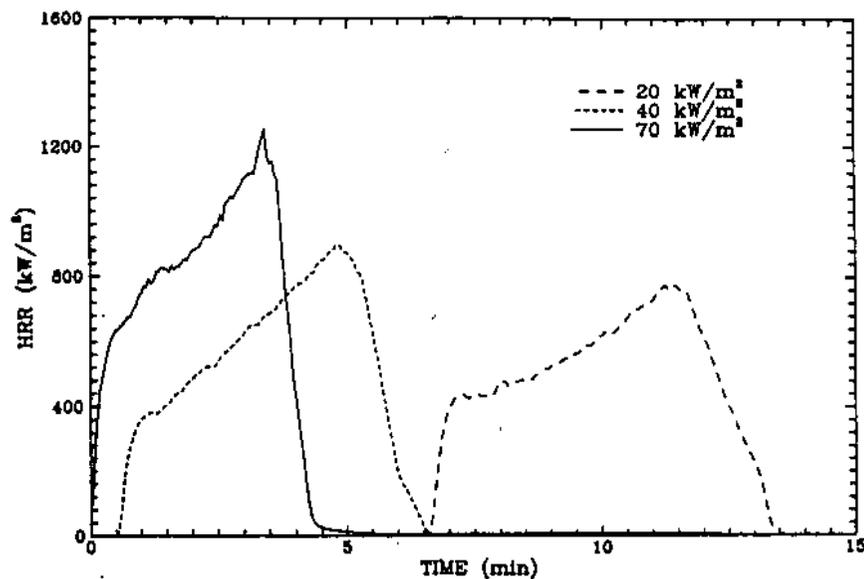


Figure 31. Heat release rate versus time for EPDM, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

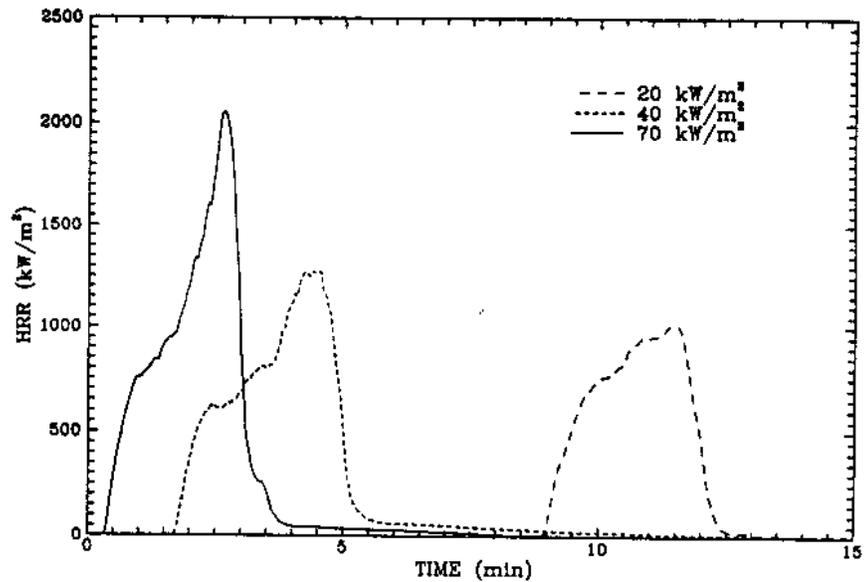


Figure 32. Heat release rate versus time for PBT, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

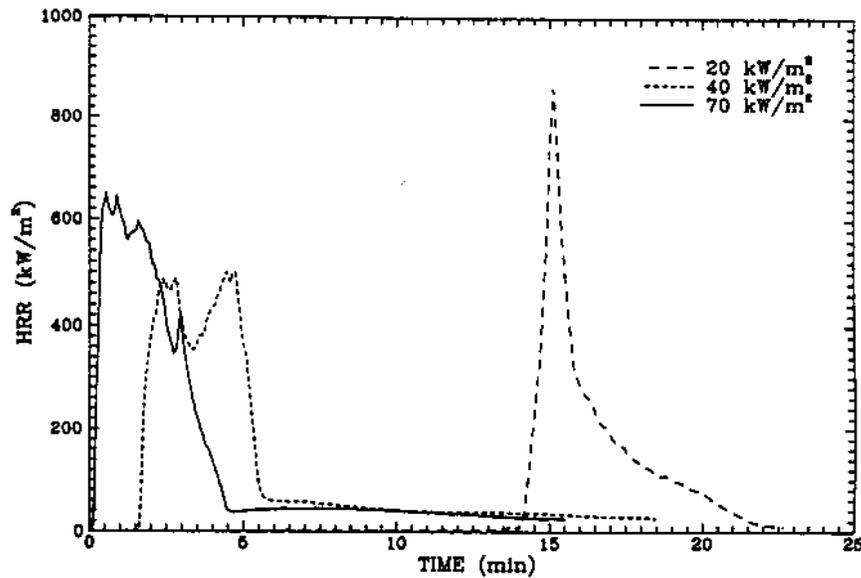


Figure 33. Heat release rate versus time for PET, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

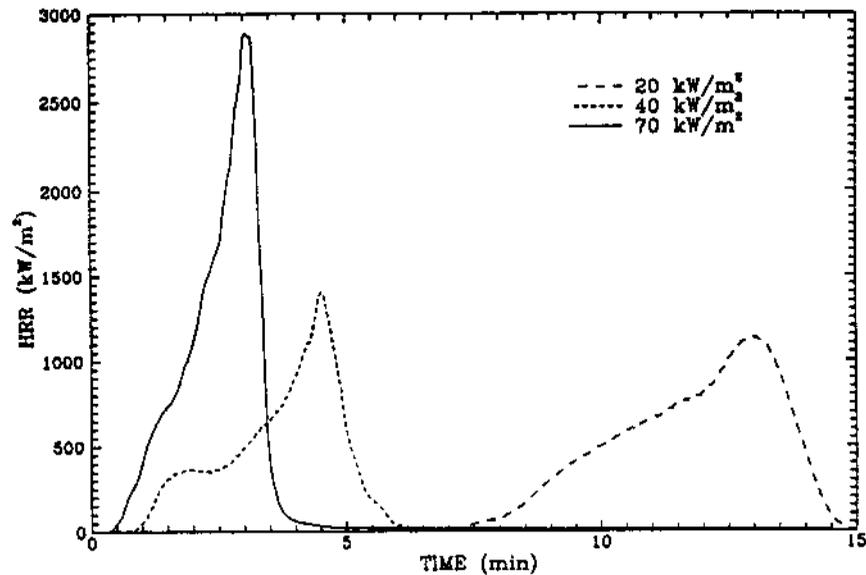


Figure 34. Heat release rate versus time for PE, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

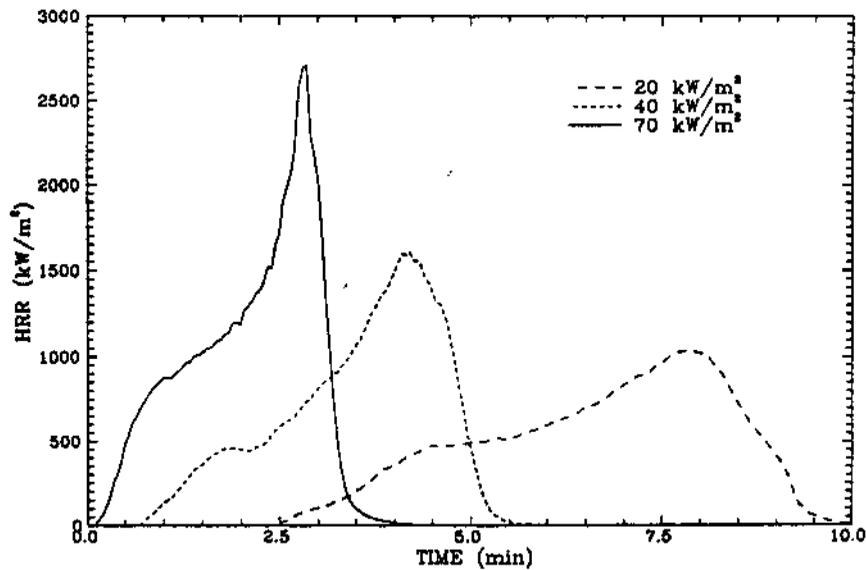


Figure 35. Heat release rate versus time for PP, at all three incident fluxes used, 20, 40 and 70 kW/m<sup>2</sup>.

all similar: they show very distinctive features. For example, some curves are very sharp, and others are much broader. This may simply be associated with the mass of sample (a lighter material will only burn for a shorter period). Of more interest however is when it is associated with burning characteristics: some materials show long periods of sustained burning without many distinguishing features, while others burn differently once the surface has been pierced (either more or less intensely).

Tables 1-3 contain all the data related to heat release, at each incident flux. The materials are placed in order of ascending peak heat release rate at an incident flux of  $20 \text{ kW/m}^2$ . Tables 4-6 present the appropriate values of properties associated with smoke obscuration. Table 7 presents average values for the main fire properties at all three incident fluxes and Table 8 presents weighted average values for the same properties (except for effective heat of combustion, which should not be affected by the incident heat flux). The weighting was done by averaging the following: the value at 20 multiplied by 2, the value at 40 multiplied by 4 and the value at 70 multiplied by 7, and dividing the result by 13 (sum of  $2+4+7$ ). All these Tables also contain the average and median values of every magnitude, to give an indication of overall fire performance of the type of materials available in the world of the 1990's.

Table 9 presents the incident fluxes estimated to be required for a time to ignition of 100 or of 600 s. Because of the relatively large errors involved in broad extrapolations, values of  $15 \text{ kW/m}^2$  and less were all lumped together as were those of  $90 \text{ kW/m}^2$  and more.

The materials chosen cover a very wide range of fire performance. The peak heat release rate values cover three orders of magnitude. They range from virtually zero, within the experimental uncertainty, to  $> 1100 \text{ kW/m}^2$ , at an incident flux of  $20 \text{ kW/m}^2$  and from  $< 70$  to  $> 2700 \text{ kW/m}^2$ , at an incident flux of  $70 \text{ kW/m}^2$ . The effective heats of combustion only cover one order of magnitude however: they range from a few MJ/kg (3-5) up to over 50 MJ/kg. The times to ignition cover over 2 orders of magnitude: they range from no ignition (10000 s) to 12 s at  $20 \text{ kW/m}^2$  and from 1583 s to 1 s at  $70 \text{ kW/m}^2$ . The ratio (TTI/RHR) which is an indicator of propensity to flashover, covers over 4 orders of magnitude; it ranges from  $> 6000$  to  $0.04 \text{ s m}^2/\text{kW}$  at  $20 \text{ kW/m}^2$  and from  $> 24$  to  $0.0008 \text{ s m}^2/\text{kW}$  at  $70 \text{ kW/m}^2$ .

The smoke obscuration also covers a wide range of performance. Interestingly, the rate of smoke release and the average extinction area cover roughly two orders of magnitude, while the total smoke release and the smoke factor range

Table 1  
Heat Release Rate Results at a Flux of 20 kW/m<sup>2</sup>

No. Material	Pk RHR	TTI	THR	Av RHR	MLRP	TTI/RHR	Ht Comb
1 PTFE	3	10000	0.3	0.0	0	6780	3.6
2 VTE 3	4	10000	5.1	0.0	0	2850	1.5
3 VTE 2	9	10000	5.7	0.0	0	1301	0.9
4 VTE 4	14	10000	13.2	0.0	0	1027	3.0
5 PCARB	16	10000	0.1	0.0	0	5173	4.5
6 VTE 1	19	10000	12.2	0.0	0	591	2.2
7 CPVC	25	10000	14.7	0.0	0	392	2.4
8 PVC CIM	40	5159	3.0	0.0	2.85	1343	1.4
9 PVC WC FR	72	236	36.5	23.6	0.94	3.49	7.0
10 PVC LS	75	5171	6.6	ND	0.22	72.4	2.0
11 XLPE	88	750	87.6	8.6	0.52	8.08	22.4
12 PVC WC SM	90	176	49.0	40.1	1.63	1.96	8.5
13 PVC EXT	102	3591	2.9	ND	0.13	31.4	7.3
14 PVC WC	116	117	47.3	53.8	2.46	1.00	10.5
15 KYDEX	117	200	20.5	16.4	0.87	1.70	5.4
16 PCARB B	144	6400	35.4	5.3	0.09	474	13.1
17 PPO GLAS	154	465	111.0	ND	0.33	3.03	59.0
18 PPO/PS	219	479	103.6	ND	0.53	2.45	52.5
19 ABS FV	224	5198	80.7	ND	0.17	66.3	17.0
20 ABS FR	224	212	38.3	ND	1.36	0.93	12.5
21 FL PVC	233	102	116.4	111.1	2.63	0.44	19.3
22 DFIR	237	254	46.5	53.7	1.01	1.10	13.1
23 PS FR	277	244	93.0	ND	2.34	0.90	15.0
24 ACET	290	259	143.9	82.2	3.18	0.90	13.0
25 PU	290	12	9.4	33.8	0.86	0.04	18.4
26 PMMA	409	176	691.5	167.5	4.17	0.43	23.5
27 THM PU	424	302	110.0	ND	0.77	0.72	23.5
28 NYLON	517	1923	188.0	31.0	0.40	3.85	23.3
29 ABS	614	236	159.8	ND	2.77	0.38	56.7
30 PS	723	417	202.6	ND	1.95	0.58	40.7
31 EPDM/SAN	737	486	213.1	ND	1.54	0.66	37.5
32 PBT	850	609	96.7	47.8	0.51	0.75	16.1
33 PET	881	718	93.3	82.9	0.99	0.82	16.2
34 PE	913	403	161.9	81.1	1.58	0.44	41.1
35 PP	1170	218	231.3	0.0	3.33	0.19	72.0
Average	295	2986	92.3	24.0	1.15	575.3	19.0
Median	219	479	49.0	20.0	0.86	2.0	13.1

Table 2  
Heat Release Rate Results at a Flux of 40 kW/m<sup>2</sup>

No.	Material	Pk RHR	TTI	THR	Av RHR	MLRP	TTI/RHR	Ht Comb
1	PTFE	13	10000	11.7	0.0	0	839	3.5
2	VTE 3	43	1212	31.5	2.1	0.55	36.4	5.3
3	VTE 2	64	1253	66.1	5.9	0.13	21.4	8.5
4	VTE 4	87	10000	25.9	0.0	0	115	4.5
5	PCARB	429	182	119.2	88.7	0.91	0.43	22.3
6	VTE 1	77	1271	48.1	8.5	0.19	16.7	5.7
7	CPVC	84	621	37.4	13.8	0.48	7.44	5.4
8	PVC CIM	175	73	24.3	41.6	3.49	0.42	5.1
9	PVC WC FR	92	47	51.7	62.7	6.25	0.50	9.5
10	PVC LS	111	187	73.6	0.0	2.06	1.65	17.0
11	XLPE	192	105	126.2	94.7	1.48	0.55	24.2
12	PVC WC SM	142	36	75.4	109.8	9.15	0.25	11.5
13	PVC EXT	183	85	90.8	0.0	4.90	0.46	13.3
14	PVC WC	167	27	95.7	127.6	12.16	0.16	15.5
15	KYDEX	176	38	86.7	96.9	12.47	0.22	11.0
16	PCARB B	420	144	134.7	112.0	0.75	0.34	24.4
17	PPO GLAS	276	45	125.8	167.5	5.87	0.16	27.0
18	PPO/PS	265	87	128.5	148.8	2.51	0.33	23.3
19	ABS FV	291	61	108.5	152.1	6.47	0.21	17.4
20	ABS FR	402	66	70.3	214.8	17.91	0.16	12.4
21	FL PVC	237	21	98.2	168.5	17.18	0.09	15.7
22	DFIR	221	34	64.1	122.7	4.75	0.15	17.6
23	PS FR	334	90	94.5	200.7	8.49	0.27	14.6
24	ACET	360	74	141.3	192.2	8.38	0.20	12.7
25	FU	710	1	13.2	62.8	14.99	0.0014	45.3
26	PMMA	665	36	827.9	486.4	43.48	0.05	23.3
27	THM FU	221	60	119.3	108.2	3.54	0.28	17.4
28	NYLON	1313	65	226.3	277.9	6.15	0.05	31.0
29	ABS	944	69	162.5	543.9	16.09	0.07	30.8
30	PS	1101	97	210.1	503.7	11.36	0.09	38.0
31	EPDM/SAN	956	68	199.8	416.3	9.02	0.07	28.8
32	PBT	1313	113	169.9	463.2	3.67	0.09	21.1
33	PET	534	116	113.7	262.1	4.63	0.22	11.6
34	PE	1408	159	220.9	455.9	5.18	0.06	46.6
35	PP	1509	86	206.9	557.0	7.25	0.06	42.1
	Average	443	761	125.7	179.1	7.20	29.8	19.0
	Median	265	85	98.2	122.7	5.18	0.22	17.0

Table 3  
Heat Release Rate Results at a Flux of 70 kW/m<sup>2</sup>

No. Material	Pk RHR	TTI	THR	Av RHR	MLRP	TTI/RHR	Ht Comb
1 PTFE	161	252	69.1	52.7	3.22	1.56	4.6
2 VTE 3	70	17	48.8	45.8	15.03	0.24	7.7
3 VTE 2	100	424	39.0	18.7	1.17	6.01	6.8
4 VTE 4	66	1583	57.4	5.5	0.12	24.3	7.2
5 PCARB	342	75	121.7	114.9	1.96	0.22	21.4
6 VTE 1	120	60	63.4	63.3	7.36	0.49	7.1
7 CPVC	93	372	44.9	20.7	0.82	4.06	6.1
8 PVC CIM	191	45	93.0	111.6	8.13	0.24	12.7
9 PVC WC FR	134	12	65.5	104.5	27.85	0.09	10.4
10 PVC LS	126	43	75.5	59.4	6.11	0.34	12.0
11 XLPE	268	35	129.2	193.7	6.62	0.13	24.7
12 PVC WC SM	186	14	73.4	153.9	26.43	0.07	10.7
13 PVC EXT	190	48	96.5	120.5	10.02	0.25	10.8
14 PVC WC	232	11	94.4	179.2	33.68	0.05	15.2
15 KYDEX	242	12	77.2	165.3	74.23	0.05	9.4
16 PCARB B	535	45	143.5	133.5	8.20	0.08	20.7
17 PPO GLAS	386	35	125.7	245.1	6.78	0.09	23.8
18 PPO/PS	301	39	134.3	201.0	4.70	0.13	22.9
19 ABS FV	409	39	114.1	236.2	11.79	0.10	18.5
20 ABS FR	419	39	61.0	224.8	23.76	0.09	10.3
21 FL PVC	252	15	86.3	183.5	25.11	0.06	14.2
22 DFIR	196	12	50.0	140.2	15.31	0.06	13.5
23 PS FR	445	51	82.0	275.1	23.62	0.11	11.9
24 ACET	566	24	167.1	357.3	25.20	0.04	14.6
25 FU	1221	1	13.3	66.5	18.59	0.0008	37.5
26 PMMA	988	11	757.1	873.9	147.24	0.01	25.9
27 THM FU	319	38	120.1	170.2	5.42	0.12	17.9
28 NYLON	2019	31	233.8	805.9	29.84	0.02	29.3
29 ABS	1311	48	162.5	627.5	25.87	0.04	28.0
30 PS	1555	50	197.8	796.8	39.04	0.03	28.8
31 EPDM/SAN	1215	36	215.7	758.8	11.35	0.03	29.2
32 PBT	1984	59	197.4	664.2	8.38	0.09	25.6
33 PET	616	42	125.5	367.2	10.10	0.07	15.2
34 PE	2735	47	227.5	910.7	9.42	0.02	42.6
35 PP	2421	41	231.1	957.3	10.70	0.02	43.1
Average	640	106	131.3	297.3	19.52	1.1	18.3
Median	319	39	96.5	179.2	10.70	0.09	15.2

Table 4

Heat Release Rate Apparatus Results on Smoke Obscuration at a Flux of 20 kW/m<sup>2</sup>

No.	Material	Pk RSR	TSR	SmkFct	AvExtAr
1	PTFE	0.3	200	0.4	0.0
2	VTE 3	2.0	730	0.4	305.3
3	VTE 2	1.2	422	0.6	93.9
4	VTE 4	1.7	417	1.1	131.5
5	PCARB	0.2	15.1	0.1	2.6
6	VTE 1	2.0	1249	4.3	331.2
7	CPVC	0.4	225	1.3	51.3
8	PVC CIM	7.9	933.8	13.7	96.3
9	PVC WC FR	4.8	2149	27.7	440.4
10	PVC LS	8.3	465.0	9.3	54.1
11	XLPE	1.0	387	1.5	606.7
12	PVC WC SM	7.8	4127	77.6	645.5
13	PVC EXT	22.3	1226.7	24.3	185.8
14	PVC WC	7.8	3608	100.4	676.2
15	KYDEX	11.0	1409	65.0	512.1
16	PCARB B	6.2	1033	2.7	414.7
17	PPO GLAS	7.7	4145.0	1.8	0.0
18	PPO/PS	18.3	7830.0	25.9	0.0
19	ABS FV	20.8	6650.0	22.3	0.0
20	ABS FR	38.1	9053.3	456.2	0.0
21	FL PVC	12.8	4912	481.6	914.0
22	DFIR	1.2	318	30.4	113.7
23	PS FR	39.5	12090.0	290.1	864.9
24	ACET	0.5	249	13.0	73.9
25	FU	3.4	138	33.1	225.1
26	PMMA	1.8	2506	51.6	67.0
27	THM FU	24.6	3970.0	216.3	0.0
28	NYLON	8.3	1966	2.7	118.1
29	ABS	20.2	5520.0	793.3	0.0
30	PS	29.0	6653.3	44.6	106.5
31	EPDM/SAN	25.5	7795.0	28.6	0.0
32	PBT	12.3	41362.3	1.4	7.5
33	PET	18.3	2308	2.8	1.2
34	PE	7.0	892.5	29.9	1981.8

Table 5  
Heat Release Rate Apparatus Results on Smoke Obscuration at a  
Flux of 40 kW/m<sup>2</sup>

No.	Material	Pk RSR	TSR	SmkFct	AvExtAr
1	PTFE	0.7	376	0.3	672.8
2	VTE 3	7.2	1571	13.5	319.3
3	VTE 2	9.0	2253	24.9	357.9
4	VTE 4	23.6	670	35.9	246.0
5	PCARB	22.4	3619.6	733.2	992.5
6	VTE 1	8.1	3198	76.1	546.6
7	CPVC	3.1	200	3.8	17.6
8	PVC CIM	25.1	6653.3	298.2	569.2
9	PVC WC FR	5.9	2391	104.6	565.5
10	PVC LS	12.1	1936.7	78.6	590.8
11	XLPE	3.1	837	24.0	92.5
12	PVC WC SM	14.7	5880	473.0	937.0
13	PVC EXT	25.6	7026.7	459.6	3458.6
14	PVC WC	14.6	5652	503.5	939.3
15	KYDEX	17.5	6825	535.0	838.9
16	PCARB B	20.5	3142	616.0	813.9
17	PPO GLAS	16.9	5550.0	853.8	1341.5
18	PPO/PS	26.8	8055.8	1143.3	1731.0
19	ABS FV	32.4	9691.5	1499.2	1527.2
20	ABS FR	59.1	9705.4	3740.9	1771.5
21	FL PVC	19.4	6075	914.5	1053.0
22	DFIR	1.5	287	42.9	64.9
23	PS FR	55.7	12798.6	3461.7	1869.6
24	ACET	0.6	198	17.5	10.5
25	PU	6.5	301	134.4	571.9
26	PMMA	4.4	3646	429.0	76.8
27	THM PU	16.5	3591.9	367.6	565.7
28	NYLON	36.2	3088	887.9	217.0
29	ABS	32.0	4772.6	4457.4	884.5
30	PS	41.0	7738.0	6791.5	1292.6
31	EPDM/SAN	33.4	7569.8	5785.4	1013.7
32	PBT	33.0	3941.2	4711.2	466.3
33	PET	20.7	2837	1207.9	285.9
34	PE	10.2	1870.4	1822.0	299.5
35	PP	15.9	2503.3	3416.5	474.8
	Average	19.3	4184.4	1304.7	785.0
	Median	16.9	3591.9	503.5	571.9

Table 6

Heat Release Rate Apparatus Results on Smoke Obscuration at a Flux of 70 kW/m<sup>2</sup>

No.	Material	Pk RSR	TSR	SmkFct	AvExtAr
1	PTFE	2.7	764	4.4	32.5
2	VTE 3	11.3	2077	42.4	302.2
3	VTE 2	12.0	1725	80.3	266.0
4	VTE 4	19.2	945	25.7	174.4
5	PCARB	24.8	3900.1	728.4	977.6
6	VTE 1	17.6	4888	239.1	572.0
7	CPVC	4.5	405	7.9	33.4
8	PVC CIM	27.3	6919.6	701.8	1040.7
9	PVC WC FR	10.4	3754	283.9	664.5
10	PVC LS	19.2	2285.3	148.6	527.9
11	XLPE	6.0	1427	133.8	198.4
12	PVC WC SM	23.5	6512	872.6	1019.9
13	PVC EXT	37.0	8916.9	1143.8	1129.9
14	PVC WC	24.5	6419	969.7	1046.0
15	KYDEX	33.4	7786	1368.9	951.4
16	PCARB B	23.9	4784	1124.1	878.8
17	PPO GLAS	27.3	6159.6	1830.5	1334.0
18	PPO/PS	31.9	7829.6	1519.0	1626.5
19	ABS FV	35.1	8611.6	2561.8	1242.8
20	ABS FR	64.5	8221.7	3438.2	1331.4
21	FL PVC	26.1	6809	1277.0	1155.5
22	DFIR	2.2	307	59.7	96.1
23	PS FR	67.9	10574.7	4490.1	1445.0
24	ACET	1.3	477	103.3	24.8
25	PU	9.1	297	239.9	545.2
26	PMMA	4.4	3009	1012.1	96.9
27	THM PU	22.3	4036.6	746.1	684.2
28	NYLON	33.3	2130	4003.4	251.2
29	ABS	44.6	3896.6	5035.5	666.2
30	PS	48.5	5906.1	9152.8	851.6
31	EPDM/SAN	45.0	8585.8	10376	1162.0
32	PBT	58.4	4704.4	9656.5	660.2
33	PET	21.8	4009	2355.9	503.3
34	PE	21.0	4009.5	3975.8	275.1

Table 7  
Properties Averaged out over Fluxes of 20, 40 and 70 kW/m<sup>2</sup>

No. Material	Pk RHR	TTI	TTI/RHR	MLRP	Ht Comb	SmkFct
1 PTFE	59	6751	2540	1.1	3.9	2
2 VTE 3	39	3743	962	5.2	4.8	19
3 VTE 2	58	3892	443	0.4	5.4	35
4 VTE 4	56	7194	389	0.04	4.9	21
5 PCARB	262	3419	1725	1.0	16.0	487
6 VTE 1	72	3777	203	2.5	5.0	106
7 CPVC	67	3664	135	0.4	4.6	4
8 PVC CIM	135	1759	448	4.8	6.4	338
9 PVC WC FR	99	98	1.4	11.7	9.0	139
10 PVC LS	104	1800	24.8	2.8	10.3	79
11 XLPE	183	297	2.9	2.9	23.8	53
12 PVC WC SM	139	75	0.76	12.4	10.2	474
13 PVC EXT	158	1241	10.7	5.0	10.5	543
14 PVC WC	172	52	0.40	16.1	13.7	525
15 KYDEX	179	83	0.66	29.2	8.6	656
16 PCARB B	366	2196	158	3.0	19.4	581
17 PPO GLAS	272	182	1.1	4.3	36.6	895
18 PPO/PS	262	202	0.97	2.6	32.9	896
19 ABS FV	308	1766	22.2	6.1	17.6	1361
20 ABS FR	349	106	0.40	14.3	11.8	2545
21 FL PVC	241	46	0.20	15.0	16.4	891
22 DFIR	218	100	0.44	7.0	14.7	44
23 PS FR	352	128	0.43	11.5	13.8	2747
24 ACET	405	119	0.38	12.3	13.5	45
25 FU	740	5	0.015	11.5	33.7	136
26 PMMA	687	74	0.16	65.0	24.2	498
27 THM PU	322	133	0.37	3.2	19.6	443
28 NYLON	1283	673	1.3	12.1	27.9	1631
29 ABS	956	118	0.16	14.9	38.5	3429
30 PS	1126	188	0.23	17.5	35.8	5330
31 EPDM/SAN	970	197	0.26	7.3	31.8	5397
32 PBT	1382	260	0.31	4.2	20.9	4790
33 PET	677	292	0.37	5.2	14.3	1189
34 PE	1685	203	0.17	5.4	43.4	1943
35 PP	1700	115	0.09	7.1	52.4	3154

Table 8  
Weighted Average of Properties (Fluxes of 20, 40 and 70 kW/m<sup>2</sup>)

No. Material	Pk RHR	TTI	TTI/RHR	MLRP	SmkFct	THR
1 PTFE	31	1584	434	0.58	0.85	14
2 VTE 3	17	640	150	2.8	9.0	12
3 VTE 2	25	717	70.0	0.22	17.0	14
4 VTE 4	21	1823	68.8	0.02	8.3	14
5 PCARB	106	545	265	0.4	206	34
6 VTE 1	30	654	32.1	1.3	50.9	17
7 CPVC	27	643	21.6	0.20	1.9	13
8 PVC CIM	54	280	68.9	2.0	157	19
9 PVC WC FR	37	19	0.25	5.7	63.1	19
10 PVC LS	38	292	3.9	1.3	35.2	21
11 XLPE	72	55	0.49	1.4	26.6	41
12 PVC WC SM	52	15	0.14	5.8	209	23
13 PVC EXT	58	202	1.7	2.3	254	27
14 PVC WC	65	11	0.08	7.4	231	29
15 KYDEX	68	16	0.12	14.6	304	24
16 PCARB B	147	351	24.3	1.6	265	41
17 PFO GLAS	106	35	0.19	1.8	416	41
18 PFO/PS	92	40	0.18	1.1	391	43
19 ABS FV	115	280	3.44	2.8	615	36
20 ABS FR	128	25	0.08	6.2	1024	20
21 FL PVC	81	10	0.04	6.4	348	32
22 DFIR	70	19	0.08	3.3	16.7	18
23 PS FR	128	31	0.09	5.2	1176	29
24 ACET	153	25	0.07	5.5	21.0	52
25 PU	307	1	0.002	4.9	58.5	4
26 PMMA	266	15	0.03	31.1	228	256
27 THM PU	102	28	0.09	1.4	183	39
28 NYLON	524	111	0.21	6.0	810	75
29 ABS	364	28	0.03	5.3	1402	54
30 PS	429	40	0.04	8.3	2342	67
31 EPDM/SAN	354	38	0.05	3.0	2457	70
32 PET	534	53	0.06	2.9	2216	58
33 PET	211	56	0.08	2.3	547	39
34 PE	682	45	0.03	2.3	902	72
35 PP	649	27	0.02	2.8	1367	75
Average	176	250	32.8	4.3	525	41
Median	102	41	0.14	0.3	231	32

Table 9  
 Predicted Flux (in kW/m<sup>2</sup>) for Times to ignition of 100 s and  
 10 min

Materials	Flux for TTI of:	
	600 s	100 s
PTFE	63	83
VTE 3	45	64
VTE 2	60	≥ 90
VTE 4	86	≥ 90
PCARB	34	43
VTE 1	47	65
CPVC	42	≥ 90
PVC CIM	30	39
PVC WC FR	≤ 15	31
PVC LS	33	44
XLPE	22	40
PVC WC SM	≤ 15	27
PVC EXT	30	39
PVC WC	≤ 15	22
KYDEX	≤ 15	28
PCARB B	32	42
PPO PS FGLAS	18	33
PPO PS	17	38
ABS FV	30	38
ABS FR	≤ 15	33
FL PVC	≤ 15	20
DFIR	≤ 15	29
PS FR	≤ 15	38
ACET	≤ 15	35
FU	≤ 15	≤ 15
PMMA	≤ 15	27
THMPLAS FU	≤ 15	34
NYLON	27	37
ABS	≤ 15	34
PS	≤ 15	40
EPDM SAN	18	36
PBT	20	41
PET	22	42
PE	≤ 15	50
PP	≤ 15	37

material, also covers a range of performance. It ranges from 0 to  $> 300 \text{ g/m}^2\text{s}^2$  at  $20 \text{ kW/m}^2$  and from 0.1 to almost  $2000 \text{ g/m}^2\text{s}^2$  at  $70 \text{ kW/m}^2$ .

The amount of smoke released in a full scale fire is a function of both the smoke production tendency of the product and the amount of material burnt. It has thus been found that direct measures of smoke obscuration, viz. rate of smoke release, extinction area or total smoke release, can often not be directly correlated with fire performance, but the smoke factor does provide, usually, guidelines to improvements made in fire behaviour. The better predictability of the smoke factor is most noticeable as the fire performance of a product improves. The reason for this is that as a product becomes less flammable (or more "fire retarded", although this term should be used with extreme care, since it does not mean containing more fire retardants) it will burn less readily in a full scale scenario. Thus, while in a small scale test the entire sample being tested is normally burnt up completely, in full scale fires less flammable materials often do not burn totally.

#### Comparisons with Material composition

It is interesting to note that some fire performance predictions that could have been made based on the chemical composition are borne out. For example, the inclusion of heteroatoms, particularly halogens, does, indeed, improve fire performance. This can be seen by the fact that PTFE, rigid PVC and CPVC, which have high contents of fluorine and chlorine respectively in the formulation of the polymer itself, are among the better performers. However such a statement is not absolute, as exemplified by another one of the top performers: a compound based on polycarbonate, a polymer containing only C, H and O in its base formulation.

The polymers which contain no heteroatoms (other than oxygen) in their base formulation tend to be the poorest performers, as made clear by the results of the PE, PP, PET PBT and PSTests.

It is also very important to notice that composition can make a significant difference. In the case of those materials which are known to be simply fire retarded and non fire retarded versions of the same base polymer, the fire retarded version has improved fire performance. This can be seen by several series: ABS and ABS FR or ABS FV, PS and PS FR, PE and XLPE, PMMA and Kydex, or PVC WC, PVC WC SM and PVC WC FR. However, other variations can be made, with a common base polymer, which affect fire performance. This can be seen when comparing the two polycarbonates, the two polyphenylene oxide/polystyrene formulations or the foamed polyurethane and the thermoplastic polyurethane.

The case of the vinyl compounds has been put forward as a series of examples of the range of fire performance possible with a particular base chemistry. These

materials need to be distinguished between flexibles (plasticised) and rigids, with the latter having much better fire performance, generally. The poorest fire performance is found on a material (FL PVC) heavily loaded with plasticisers and containing no flame retardant additives. Even without incorporating flame retardant additives, proper compounding techniques can generate a commercial flexible PVC material with much better fire performance (PVC WC). Thus, standard flexible PVC compounds can range in peak heat release rate from 70 to 230 kW/m<sup>2</sup>, at 20 kW/m<sup>2</sup> and from 130 to 250 kW/m<sup>2</sup> at 70 kW/m<sup>2</sup>. The use of the vinyl thermoplastic elastomer technology can improve those values by an order of magnitude at the lower fluxes, while also significantly lowering the ignitability.

The rigid vinyls also vary in fire performance, but the differences are smaller, since the fraction of additives tends to be much lower. It is interesting to notice that appropriate compounding techniques can generate flexible compounds with better fire performance than rigids, which means that additive packages can overcome the, generally, negative impact on fire performance added by the plasticiser.

Another interesting aspect is a comparison of CPVC and rigid PVC. It would be expected that the addition of chlorine to a structure would improve fire performance [1], e.g. as measured by heat release. This is indeed the case between rigid PVC and CPVC. A less predictable result, but which can be explained nevertheless, is the fact that the resulting smoke obscuration values also tend to be lower. This can be explained by understanding the mechanism of smoke formation from vinyl compounds [3]. It has already been stated that vinyl compounds break down by chain stripping and yield HCl and a carbonaceous char. The dehydrochlorination of PVC yields a polyacetylene (-CH=CH-) while that of PVDC yields a purely carbonaceous char, (-C=C-), with an almost graphitic structure, with CPVC yielding values somewhere in between. These chars will tend to continue breaking down by chain scission. If there are sufficient hydrogen atoms present, the fragments will cyclise into aromatic structures and these, in turn, generate significant amounts of soot per unit mass when burnt. As the remaining hydrogen atom concentration is decreased, the probability of forming aromatic structures, and thus soot, decreases.

The effect of nitrogen as a fire retardant element is very weak on its own, as becomes clear from the fire performance of nylon, foamed polyurethane or EPDM/SAN. However, it has been demonstrated often that synergism can exist between nitrogen and other elements (phosphorus, halogens). Unfortunately, the lack of knowledge of the composition of these retardant elements is a

### Effects Due to Test Apparatus Used

It is important to note that, although all of the results presented here were obtained with the cone calorimeter, similar results can be obtained with other heat release rate calorimeters. In particular it has been found, with two different series of materials, that results from the cone calorimeter and from the Ohio State University heat release rate calorimeter (OSU [23]) show excellent linear correlations, both in terms of heat release and in terms of smoke release [12, 15]. The two series of experiments involved: (a) a variety of plastics, including 17 of the materials in this work (VTE 4, PCARB, PVC CIM, PVC LS, PVC EXT, PPO GLAS, PPO/PS, ABS FV, ABS FR, PS FR, THM PU, ABS, PS, EPDM, PBT, PE and PP) [15] and (b) a variety of vinyl wire and cable formulations, including three used in this work (numbers PVC WC FR, PVC WC SM and PVC WC) [12].

There are two principal methods used for making heat release measurement on plastics in bench scale: the cone calorimeter and the Ohio State University Calorimeter (OSU). The former was developed as an improvement to the latter and the problems associated with the older OSU apparatus are described in chapter 3. Nonetheless industrial groups have generated, and continue to generate, and quote, OSU data generated both from conventional and modified units. Modified units have been retrofitted with some of the technology developed for the cone. Such units will, probably, give better results. Thus the improvements are attractive options for some existing OSU owners because they are less costly than a full new instrument. A totally new improved system is, probably less attractive because costs approach that of the cone calorimeter.

The differences between the cone and the OSU operation is outlined here so that practitioners can make meaningful comparisons of data generated in each instrument. These have been discussed recently, in detail [24]. There are eight main differences, viz.:

- (a) The Cone Calorimeter uses the oxygen consumption principle, while the OSU apparatus was designed as an insulated box for enthalpy flow sensing. The OSU apparatus can be modified to allow heat release measurement by oxygen consumption, but this is not used in existing standards.
- (b) Cone Calorimeter samples are normally burnt horizontally, while the OSU is normally used with vertical samples. Samples can be burnt in the other orientation in either apparatus, but this may not be advisable for various reasons. Many materials melt and drip in the vertical orientation and this, along with problems of irreproducible ignition for vertical samples, has led to ASTM recommending, in ASTM E1354, to limit teasing to the horizontal

- (c) The OSU radiant source is a set of four glow bars, sited directly across from the vertical sample. The Cone Calorimeter has a truncated conical radiant heater.
- (d) The OSU apparatus specifies one of two alternate flame igniters, while the Cone Calorimeter uses a spark igniter. The 'impinging pilot' used in the OSU apparatus imposes a significant local heating flux, in addition to the radiant heating flux. Thus, the thermal boundary conditions would need to be modelled differently for each a configuration. i.e. it represents a different type of fire. A fire model has been devised to to use OSU data as input to produce wall lining room burns [39] and has been used for some plastic materials [40]. This model suffers from the serious problem that it was developed in the late 1970's and has not been updated properly since. One problem inherent with a pilot flame, as used in the OSU apparatus, is that, at very low incident heat fluxes, the flame imposes more energy than does the glow bars. This is of particular concern when testing foams destined for furniture use [41]. another problem is testing flame inhibitors which extinguish the igniter. The latter can be partially, overcome, by adding a spark igniter to reigniter the flame.
- (e) The Cone Calorimeter has a load cell for continuous mass measurements, while the OSU apparatus does not. Attempts have been made to build OSU units with a load cell, but test results are not yet widely available.
- (f) The Cone Calorimeter uses a laser beam to measure smoke obscuration while the OSU apparatus uses a white light source. Results<sup>1</sup> from both measuring systems are virtually equivalent, for small scanning times ( $\leq 3$  s [25, 26]) and smoke measurement trends have been shown to correlate well (12,15). Alternative photometers can be installed in either apparatus.
- (g) The sample sizes are different: normally 0.1 x 0.1 m in the cone and ca. 0.15 x 0.15 m in the OSU apparatus.
- (h) The air flow rates through the apparatus are different in the two units. They are much larger in the OSU apparatus, which makes burning much more fuel lean.

Full scale fire tests, which are much more desirable in order to obtain the fullest information on a particular fire, can only, realistically, be carried out to a limited extent. Moreover, they are most relevant when carried out with a variety of products present, whereby it is somewhat more difficult to separate the effect on fire performance of a single material or product. However, a number of recent sets of tests have shown that there is good predictability from heat release rate equipment test results to full scale test results [27-31]. This is particularly true

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<sup>1</sup> Editor's note: Published smoke measurements from the OSU apparatus are scant, and the majority of users (e.g., the aircraft industry, as discussed in Chapter 17) do not use the smoke measurement facility of the OSU. This is partly because the photometer specified in the ASTM E 906 standard lacks means for effective collimation and exclusion of ambient light.

for upholstered furniture [28, 29, 32-35] and electrical cables [12, 35, 36].

On the other hand, some widely used tests, such as a flame spread test (Steiner tunnel: ASTM E 84 [37]) or a static smoke obscuration test (NBS smoke density chamber: ASTM E 662 [14]) have been shown to yield results which are misleading in terms of full scale fire performance.

The reason for discussing these issues here is because it has become clear that material or product heat release rate testing is one of the most adequate means of predicting fire performance of products, and this can be accomplished in a variety of ways.

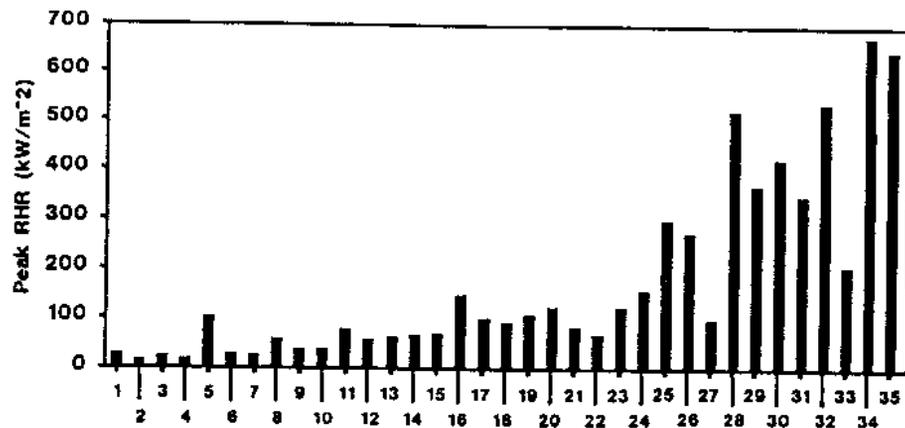


Figure 36. Weighted average of the heat release rate of all materials tested, at the three incident fluxes used, in terms of the peak heat release rate (in kW/m<sup>2</sup>).

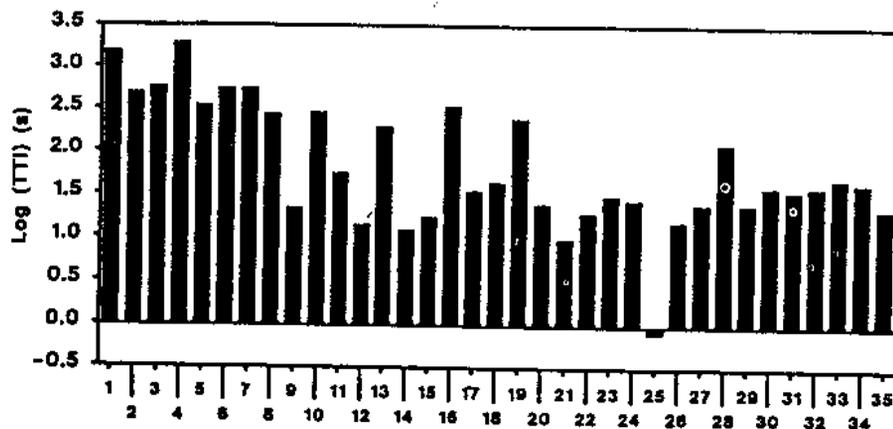


Figure 37. Weighted average of the ignitability of all materials tested, at the three incident fluxes used, in terms of the log of the time to ignition (in s).

## Classification of Fire Performance

In view of the wide range of results obtained it is probably important to attempt to obtain some overall categories of fire performance of materials. Figures 36 - 39 show the weighted averages of peak heat release rate, ignitability, propensity to flashover and smoke factor for all these materials, the three latter ones on logarithmic scales.

The materials performance can be assessed for heat release ignitability propensity to flashover and smoke by grouping performances in of each these in categories defined within the following ranges.

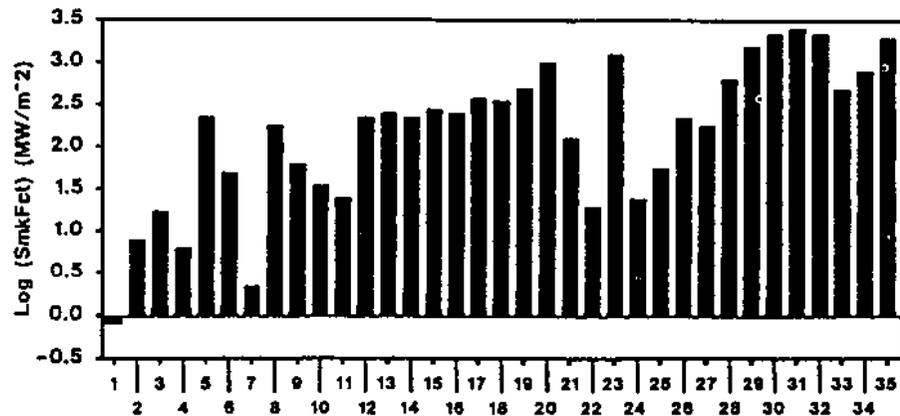


Figure 38. Weighted average of the smoke release of all materials tested, at the three incident fluxes used, in terms of the log of the smoke factor (in MW/m<sup>2</sup>).

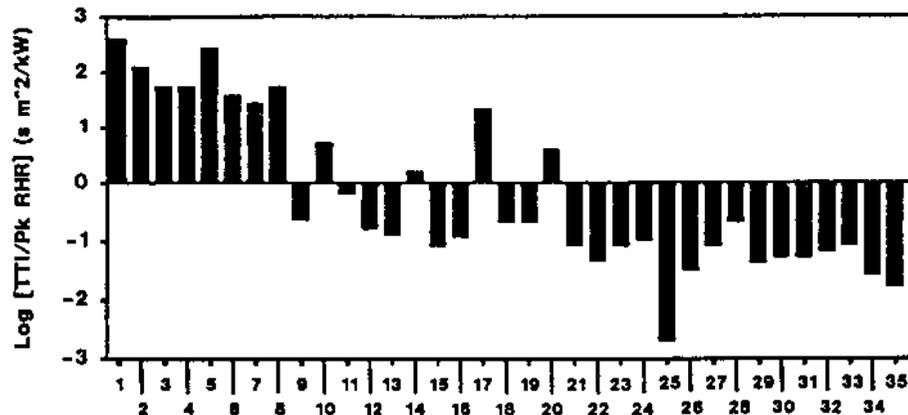


Figure 39. Weighted average of the propensity to flashover of all materials tested, at the three incident fluxes used, in terms of the log of TTI/RHR (in s m<sup>2</sup>/kW).

## 1) PEAK HEAT RELEASE RATE

Pk RHR > 60(kW/m<sup>2</sup>):

PTFE, VTE 3, VTE 2, VTE 4, VTE 1, CPVC, PVC CIM, PVC WC FR, PVC LS, PVC WC SM, PVC EXT.

60 > Pk RHR > 100(kW/m<sup>2</sup>):

XLPE, PVC WC, KYDEX, PPO/PS, FL PVC, DFIR.

100 > Pk RHR > 200 (kW/m<sup>2</sup>):  
FR, PS FR, ACET, THM FU.

P CARB, P CARB B, PPO GLAS, ABS FV, ABS

200 > Pk RHR > 300 (kW/m<sup>2</sup>):

PMMA, PET.

300 > Pk RHR (kW/m<sup>2</sup>):

FU, NYLON, ABS, PS, EPDM, PBT, PE, PP.

## 2) IGNITABILITY

2.5 &lt; Log (TTI)(s):

PTFE, VTE 3, VTE 2, VTE 4, PCARB, VTE 1, CPVC, P CARB B.

1.5 &lt; Log (TTI) &lt; 2.5(s):

PVC CIM, PVC LS, XLPE, PVC EXT, PPO GLAS, ABS FV, NYLON, PS, PPO/PS, PBT, PET, PE, EPDM.

1.0 &lt; Log (TTI) &lt; 1.5(s):

PVC WC FR, PVC WC SM, PVC WC, KYDEX, ABS FR, FL PVC, DFIR, PS FR, ACET, PMMA, THM FU, ABS, PP.

0.5 &lt; Log (TTI) &lt; 1.0(s):

-

Log (TTI) &lt; 0.5(s):

FU.

## 3) PROPENSITY TO FLASHOVER (TTI/RHR)

1.0 < Log (TTI/RHR)(s m<sup>2</sup>/kW):

PTFE, VTE 3, VTE 2, VTE 4, PCARB, VTE 1, CPVC, PVC CIM, PCARB B.

0.0 < Log (TTI/RHR) < 1.0(s m<sup>2</sup>/kW):

PVC LS, PVC EXT, ABS FV

-1.0 < Log (TTI/RHR) < 0.0 (s m <sup>2</sup> /kW):	PVC WC FR, XLPE, PVC WC SM, KYDEX, NYLON.
-2.0 < Log (TTI/RHR) < -1.0 (s m <sup>2</sup> /kW):	PVC WC, ABS FR, FL PVC, DFIR, PS FR, ACET, PMMA, THM PU, ABS, PS, EPDM, PBT, PET, PE, PP.
Log (TTI/RHR) < -2.0 (s m <sup>2</sup> /kW):	FU.

#### 4) SMOKE (Smoke Factor)

1.5 > Log (SmkFct) (MW/m <sup>2</sup> ):	PTFE, VTE 3, VTE 2, VTE 4, CPVC, XLPE, DFIR, ACET.
2.0 > Log (SmkFct) > 1.5 (MW/m <sup>2</sup> ):	VTE 1, PVC WC FR, PVC LS, FU.
2.5 > Log (SmkFct) > 2.0 (MW/m <sup>2</sup> ):	PCARB, PVC CIM, PVC WC SM, PVC EXT, PVC WC, PCAR B, PMMA, THM PU.
3.0 > Log (SmkFct) > 2.5 (MW/m <sup>2</sup> ):	KYDEX, PPO GLAS, PPO/PS, ABS FV, FL PVC, NYLON, PET, PE.
Log (SmkFct) > 3.0 (MW/m <sup>2</sup> ):	ABS FR, PS FR, ABS, PS, EPDM, PBT, PP.

Five materials appear in the top category in all four classifications: (PTFE, VTE 3, VTE 2, VTE 4, CPVC,) but no material appears in the lowest category in all four classifications.

#### Product Fire Performance

Setting fire performance of materials in these ranges can be an interesting tool in order to choose materials for their advantages in specific areas. It has to be remembered, however, that fire performance is a combination of a number of fire properties and good results for a specific property may not be a sufficient indicator of overall fire performance.

Moreover, it has been shown extensively that the fire performance of products is a result of the interaction between the different materials that are contained in the product. These interactions are often...

that of any of its component materials.

There are two sets of products that have been analysed more extensively than many others: upholstered furniture and electrical cables. In both cases it appears that, all else being equal, the outer layer of combustibles is more important than the inner layer.

In the case of upholstered furniture fabric/foam combinations, it has become apparent that the fire performance of the fabric (first line of attack of the fire) is more important than that of the foam. This statement depends, of course, on maintaining the initial integrity of the fabric (i.e. not exposing the foam directly to the fire) and on the use of foams of some degree of adequacy in fire performance.

In the case of electrical cables it has been shown that, if the fire performance of the jacket or sheath (the layer that surrounds the individually coated conductors) is adequate, the fire performance of the insulation (the layer that coats the conductors directly) is of secondary importance.

The main consequence to be drawn from these discussions is that fire performance of materials is important but that choices should be made following testing of products, or of systems simulating the final product by containing all the materials involved, in relevant combinations. Predictions of product fire performance from fire test results of individual materials should only be used if it has previously been shown that the products perform in a way that can be predicted from a combination of the fire performance of the materials.

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