Fire Properties of Polyvinyl Chloride

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Polyvinyl chloride (PVC, or vinyl) possesses excellent fire performance properties. All organic polymers (whether they are plastics or natural materials like wood, cotton or rubber) are combustible: when sufficient heat is supplied to any organic polymer, it will thermally decompose, and its thermal decomposition products will burn. However, PVC will typically not burn once the source of heat or flame is removed. This results from PVC having 56.8% chlorine in its base polymer weight and it is well known that chlorine is one of the few elements that confers good fire properties to a polymer[1,2].

When polymers burn they give off gaseous products, which usually generate flames (most likely with light emission and soot).[3-6]

Polymer + Heat →→→ Thermal Decomposition Products
Decomposition Products + Oxygenated Radicals →→→ Combustion Products + Heat

A few polymers break down completely so that virtually no solid residue remains and all decomposition products become gaseous (and can burn). Most polymers, however, leave behind some solid residues, typically as char. Thermal decomposition of PVC occurs mostly by chain stripping, whereby hydrogen chloride (HCl) species are given off, followed by some cross-linking. Therefore, PVC is an example of a charring material that leaves much of the original carbon content as a solid residue, meaning that less of it can burn in the gas phase. The presence of chlorine in PVC exerts its influence in two ways: causing an increase in char formation (meaning that less flammable decomposition products are formed) and generating HCl, which then acts as a gas phase scavenger slowing down further reactions of flammable products in the gas phase[1, 7].

The actual fire properties of PVC have been assessed based on the results of small-scale and full-scale tests, and interpreted in terms of overall fire hazard, and this document summarizes some of the multiple studies conducted.

Samples of unplasticized (rigid) vinyl, such as those found in pipe, siding or vertical blinds, have better fire performance, especially in terms of having lower flame spread and lower heat released in a fire than similar samples of many other combustible materials, including wood. However, the fire properties of PVC typically deteriorate when PVC is plasticized, which is necessary to make it into flexible products such as wire coatings, upholstery, medical blood bags or wall coverings, depending on the amount and kind of plasticizer and other additives used. However, in fact many of the plasticized PVC products in use will not continue to burn once the flame source is removed, even if not additionally fire-retarded. Moreover, technologies were developed in the 1980's and 1990's, using combinations of plasticizers and other additives, which resulted in plasticized PVC materials with fire (and smoke) properties better than those of unplasticized PVC[8]. This allowed the use of PVC materials in applications, such as plenum cables, for which PVC materials were previously not suitable.

FIRE HAZARD

Overall fire safety is generally achieved by deciding if materials meet certain pre-set safety objectives. However, it is usually necessary to combine various properties and calculate results based on certain fire models. The fire hazard of a product is determined by a combination of factors including its ignitability and flammability, the amount (and rate) of heat released from it when it burns, the rate at which this heat is released, the flame spread, the smoke production and the toxicity of the smoke. It has now been determined that the rate of heat release (which determines the intensity of a fire[9-12]) is the key property controlling fire hazard. Analyses of the various fire properties of PVC materials, and comparisons with those of alternate materials, follow. Some examples of fire hazard assessments performed on PVC materials and products will also be discussed later.

IGNITABILITY

If a material does not ignite, it will not contribute to fire hazard and thereby cannot endanger lives. All organic materials do, however, ignite. The danger of ignition was formerly assessed based on ignition temperature (the lower the ignition temperature, the greater the hazard), using tests such as ASTM D1929 (or ISO 871). It is now accepted that ease of ignition is better assessed based on either the time to ignition at a specific incident heat flux or the critical heat flux for ignition to occur, for example using the cone calorimeter (ASTM E1354 or ISO 5660)[13]. Table 1 indicates that PVC materials are among the least easily ignitable polymers, using either of these criteria, at various incident heat fluxes (ranging from low to high). Ignition temperature data and further information on ignition of other materials can be found in a chapter on PVC flammability[2] and a further discussion of ignition sources has also been published[14]. Table 2 describes the materials assessed in Table 1, many of which are also used in several other tables.

EASE OF EXTINCTION

The oxygen index test (also known as OI or LOI, ASTM D2863 or ISO 4589-2) is a reliable measure of the limiting concentration of oxygen in the atmosphere needed for sustained combustion. Since normal atmospheres have about 21% oxygen the higher the LOI the less likely it is that the material will continue burning in air (so that the test is occasionally considered an ignition test). In fact, materials with high LOI (e.g. above 30) will tend to burn only when a source of flame is present and extinguish otherwise. The test is not a reliable predictor of fire hazard but is frequently used in material data sheets to indicate fire properties. Table 3 shows some results and PVC materials are usually among the very best performers.

SMALL-SCALE FLAMMABILITY

Once ignited, the greater the flammability of a material, higher will be the hazard associated with it. Small-scale flammability tests extensively used for plastic materials are the family of UL 94 tests (also standardized in ASTM, ISO and IEC, but most widely known from the UL standard). In this test, a small sample of material is exposed vertically to a small Bunsen-burner type flame from underneath and the results show a rating, ranging from V-0 (best), through V-1, V-2 to "B" (for Burn). One aspect that this test assesses is whether the material produces, on burning, flaming particles capable of igniting a combustible product found underneath (surgical cotton is used in the test). Materials that produce flaming particles will be assessed V-2 or B, depending on whether they continue to burn. Materials with a "B" rating on the UL 94 Vertical test can also be tested in the less severe UL 94 HB (for horizontal burning), which measures simply a flame spread rate. The UL 94 test is the most widely used fire test for plastic materials, especially fire retarded ones, and the results are almost always found in specifications and in data sheets. PVC materials will typically not produce flaming particles unless they have been heavily plasticized and have not been fire retarded. Table 4 presents some UL 94 fire test results for wire and cable materials; it shows that PVC materials usually present a UL 94 V-0 rating down to the least thickness usually measured, typically 1 mm, while many other materials will fail (or "Burn").

FLAME SPREAD

The tendency of a material to spread a flame away from the fire source is critical to understand the potential fire hazard. Flame spread tests are used with the materials themselves or with the products in diverse applications (such as textiles or electrical insulation), preferably with all components of an assembly. Sample sizes range widely and range up to the large Steiner tunnel samples (7.3 m × 0.56 m, or 24 ft × 22 in, ASTM E84, a test widely used in building applications).

Two other test apparatuses are used to assess flame spread: ASTM E162 (radiant panel) and ASTM E1321 (Lateral Ignition and Flame Spread Test, or LIFT). Because of its wide use, a number of applications tests were developed from it, primarily for products to be used in plenums. They include NFPA 262 (for electrical and optical fiber cables), UL 1820 (for pneumatic tubing, UL 1887 (for sprinkler piping), UL 2024 (for communications raceways) and UL 2846 (for water distribution pipe). The fire source, two gas burners, ignites the sample from below with an 89 kW fire source. The results are presented in terms of flame spread index (FSI), calculated based on the area under the flame spread distance vs. time curve and, for smoke obscuration, smoke developed index (SDI). The alternate product tests described above use classifications based on flame spread and optical density (see Table 5). Table 6 displays FSI value ranges for a variety of products and it is clear that rigid PVC will exhibit an FSI less than 25 and that flexible PVC materials tend to range in FSI up to 40. With regard to plenum cables, multiple formulations exist using PVC jackets and even some formulations use both PVC jackets and PVC insulations; all of them meet the NFPA 262 requirements of the National Electrical Code. Note that the National Electrical Code (NEC, NFPA 70) regulates the fire performance requirements for electrical materials (especially cables) throughout the US.

ASTM E162 is used to assess flame spread via a radiant panel index. This test method is frequently used in regulations, particularly for transportation environments and large appliances, and results are quoted in data sheets.

Results from this test for some materials are shown in Table 7. In general results for rigid PVC range from 10 to 25 (which usually meets the needed requirements) while flexible PVC materials can have higher radiant panel index results, typically ranging up to 50.

The LIFT apparatus, which is an improvement on the radiant panel apparatus in ASTM E162, is extensively used for regulation in marine applications. PVC materials are shown to perform very well. The test method determines the critical flux for flame spread and is useful as a predictor of full-scale flame spread performance[15].

HEAT RELEASE

The key question to ask in a fire is: "How big is the fire?" The single fire property that answers that question is the maximum rate of heat release. A burning product will spread a fire to nearby products only if it gives off enough heat to ignite them. Moreover, in order for fire to propagate heat has to be released sufficiently quickly that it is not dissipated or lost while traversing the “cold” air surrounding anything that is not on fire. Thus, fire hazard is dominated by the rate of heat release, which has been shown to be much more important than either ease of ignition, smoke toxicity, or flame spread in controlling time available for escape or rescue[16].

The first bench-scale (meaning that it uses small test samples) heat release test instrument was developed in the late 1960s, the Ohio State University (OSU) calorimeter (ASTM E906)[17]. This instrument is still important primarily because it forms the basis for regulation of major aircraft materials by the US Federal Aviation Administration (FAA) in conjunction with the regulatory authorities of most other developed countries; the regulations are contained in the regularly-updated FAA Aircraft Materials Fire Test Handbook[18]. In heat release testing, fire performance improves when the heat release rate is lower. Table 8 contains peak heat release rate results for a variety of materials at an incident heat flux of 20 kW/m2 measured in the OSU calorimeter. Note that the PVC materials exhibit very low heat release rates.

In the early 1980s, the National Institute of Standards and Technology (NIST, then National Bureau of Standards) developed a more advanced bench-scale test method to measure heat release rate: the cone calorimeter (ASTM E1354, ISO 5660). It was discussed earlier that this fire test can also be used to assess ignitability (see Table 1) but its primary goal is to conduct measurements of heat release, while at the same time assessing smoke release and mass loss. Moreover, cone calorimeter test results have been shown to predict full scale fire test results for many products, including upholstered furniture, mattresses, electrical cables, wall linings and aircraft panels among them (highlighted because they are the products most likely to contribute heavily to real fires)[19-25]. In order to obtain a good overall understanding of the fire performance of materials, it is important to test the materials under a variety of conditions, which means a variety of incident heat fluxes in the cone calorimeter. The peak heat release rates (and total heat released) of the materials in Table 2 at three incident heat fluxes are shown in Table 9[13]. It is again clear that PVC materials tend to outperform many of the alternate materials. The table also contains another important parameter, namely the fire performance index (FPI) for the same materials at all three fluxes. The fire performance index (which is the ratio between the time to ignition and the peak heat release rate) has been shown to be a reasonable first-order indicator of propensity to flashover[23-24]. Just like the time to ignition, better results in the fire performance index correspond to those materials with higher numbers and PVC materials invariably appear among the best performers.

It has been found of interest to assess the fire performance of minute specimens of materials (in the mg range), using a technique called the micro-calorimeter (or the pyrolysis combustion flow calorimeter, standardized as ASTM D7309). This instrument[26] measures (among other parameters) the heat release capacity of materials (a fundamental property that is well correlated to the heat release rate). Table 10 contains data for heat release capacity of a variety of polymeric materials and PVC is one of the best performers.

The heat release tests discussed above use small-scale samples of materials. In order to confirm that these test results are meaningful, it is often necessary to assess materials (or products) at a larger scale. A number of modern full-scale fire test methods have been developed for products, and they rely mainly on heat release rate measurements. They address wall lining products (via room-corner tests such as NFPA 265 and NFPA 286), upholstered furniture, mattresses, stacking chairs, display stands and other decorative products and electrical cables. In fact, room-corner tests are being used in codes as preferred alternatives to replace the ASTM E84 Steiner tunnel test, thus generating more useful results. Table 11 contains information from one of the relatively few studies[2] of the same materials in a room corner test and the cone calorimeter. It shows cone calorimeter data at four incident heat fluxes for seven wall lining materials (peak heat release rate and fire performance index) and includes comparisons to room-corner test results (using a 6.3 kg wood crib as ignition source) in terms of heat and smoke release. It is clear that all rigid vinyl materials give very low heat release and none of them causes flashover. The table also contains total smoke yield in the full scale tests as well as additional small scale smoke obscuration data, to be discussed later.

Table 12 contains data from a series of tests in which various halogenated (PVC and fluorinated ethylene propylene, FEP) materials intended for wire and cable insulation and jacket applications were compared with materials that were non halogenated (LDPE, EVA and other polyolefins)[27]. In this series both large-scale and small-scale tests were conducted. However, the data presented shows results from large scale (2.4-3.0 m high) cable tray tests, namely CSA FT4 (or UL 1685/FT4, used in North America) and IEC 60332-3 (used in Europe). It is clear that the PVC materials perform much better than the halogen-free cable materials.

Although it is not possible to give easy summaries of heat release data for vinyl materials, the data shown makes it clear that PVC materials exhibit extremely low heat release, and tend to have low propensity to flashover (as shown by high fire performance indices).

SMOKE OBSCURATION

Smoke obscuration is a serious concern in fires, because when visibility decreases it hinders both escape from the fire and rescue by safety personnel. The main way in which visibility decreases in a fire is through smoke emission. A decrease in visibility is the result of a combination of two factors: how much material is burnt in the real fire (which will be less if the material has better fire performance) and how much smoke is released per unit material burnt.

In spite of the fact that it is clear that smoke obscuration needs to be measured in large scale tests, or by a method which can predict large scale smoke release, the most common small scale test used to measure smoke from burning products is the traditional smoke chamber in the vertical mode (ASTM E662). The test results are expressed in terms of the "specific optical density", something which has now been shown not to be representative of real smoke release. For example, when melting materials, which melt or drip when exposed to flame, are exposed vertically in the test, the molten portions will have escaped the effect of the heat source and will not burn (or give off smoke) during the test, while in a real fire, all the molten material will burn and generate smoke. Moreover, the ASTM E662 smoke chamber is a static system, in which smoke accumulates, in contrast with real fires, where smoke flows from one compartment to another. Smoke chamber test results for several materials[2] are shown in Table 13.

As discussed above, the cone calorimeter, a dynamic flow-through fire test, can also be used to assess smoke obscuration. The results in terms of the relative rankings of materials tend to be very different from those found in the static smoke chamber. Table 14 contains obscuration data from the cone calorimeter for the materials in Table 2[13]. Empirical parameters have been proposed to compensate for incomplete sample consumption in small scale tests. A key one is the smoke factor (SmkFct), determined in the cone calorimeter[28]; it combines light obscuration (as total smoke released) and the peak heat release rate. The results shown in Table 14 are presented in terms of the average specific extinction area (SEA, ratio of the extinction coefficient of smoke to the mass loss, at each measurement point), the total smoke released in the test (TSR) and the smoke factor. The results show that PVC materials, when assessed properly, can release smoke in the same range as most other materials, or even less in some cases, when properly formulated.

Studies of room-corner tests have shown that the majority of materials with low flame spread (or low heat release, like PVC materials) tend to also exhibit low smoke release. In a series of studies only some 10% of the materials tested (8 out of 84) exhibited adequate heat release (or fire growth) characteristics, but very high smoke release[29, 30]. This needs to be taken into account when assessing PVC materials in products that occupy large surfaces, because PVC materials have intrinsically high smoke release, but only when the entire material is forced to burn.

SMOKE TOXICITY

The majority of fire fatalities result from the inhalation of smoke and combustion products, and not from burns. However, that does not mean that people die in fires because the smoke from some materials is much more toxic than the average. In fact, the following facts are now widely accepted by fire scientists31-38 and they are critical to understand how to assess fire hazard:

- Fire fatalities usually occur in fires that became very large; in the US such fires account for over six times more deaths than all other fires[39-40].

- Carbon monoxide concentrations in flashover fires (the fires most likely to cause fatalities) are virtually unaffected by chemical composition of fuels. The yields of CO in full-scale flashover fires are roughly 0.2 g/g, which corresponds to a toxicity of 25 mg/l[41-42]. This consistent yield of CO results from compiling 24 studies[43]. A comprehensive study of fatalities (fire and non-fire) associated with CO[37] showed that the CO found in blood statistically tracks fire fatalities, without needing to include other factors, normally.

- Toxic potency values from the most suitable small-scale smoke toxicity test (NIST radiant test, using rats as the animal model, but only for confirmatory purposes, standardized in ASTM E 1678 and NFPA 269) have been well validated with regard to toxicity in full-scale fires. However, toxicity comparisons between small-scale and full-scale cannot be done to better than a factor of 3. This is illustrated by the fact that the range of the toxic potency of the smoke of almost all materials (including PVC) is so small that it pales in comparison with the ranges of toxic potencies of typical poisons. All smoke is extremely toxic, irrespective of what is burning. Figure 1 compares the toxic potency of the smoke of plastics with those of categories and individual chemicals.

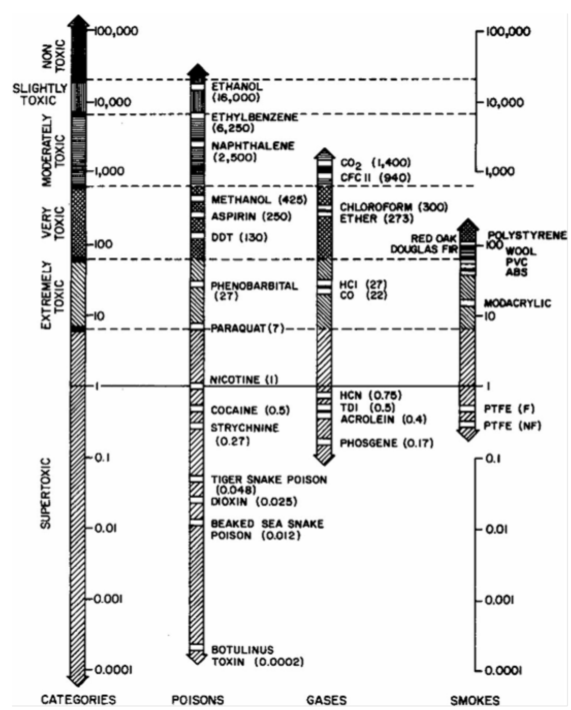

Figure 1.
Levels of smoke toxicity (in orders of magnitude)

- The consequence of this is that any toxic potency (which is usually expressed as an LC50) higher than 8 mg/l (meaning a value lower than that number) will become of no consequence because of the toxicity of the atmosphere. Thus, common materials have virtually the same smoke toxicity and their associated fire hazard will not be a function of smoke toxic potency but of how much they burn and how high their heat release rate is.

Neither PVC nor any of the products into which it decomposes (by burning or by simple thermal action) is included in any list of substances of concern. Note that PVC does not depolymerize to form vinyl chloride monomer and that commercial PVC materials do not contain such monomer. In the past, PVC compounds contained some traditional plasticizers that have since found their ways into such lists; they are no longer in use, at least in the US or in developed countries.

Chlorinated dioxins and furans can be formed when PVC materials are thermally decomposed at relatively low temperatures. However, studies of incineration of municipal solid waste, with and without added PVC, showed that the use of efficient incinerators (i.e. ones operating at high enough temperatures) ensures that PVC in such waste has very little, if any, effect on dioxin emissions[44]. Moreover, studies have also demonstrated that the amount of dioxins generated from PVC in dwelling fires is negligible compared to the overall emissions of dioxins[45].

HYDROGEN CHLORIDE DECAY

During the 1980's a series of 23 studies were conducted to investigate the "lifetime" of HCl in a fire atmosphere. These studies were summarized more recently[38]; they showed that HCl reacts very rapidly with most common construction surfaces (cement block, ceiling tile, gypsum board, etc.) and that, therefore, the peak HCl concentration found in a fire is much lower than would be predicted from the chlorine content of the burning PVC. Moreover, this peak HCl concentration soon decreases and HCl disappears almost completely from the fire atmosphere. Figure 2 shows the HCl concentration-time pattern for several identical experiments where PVC cables (containing the chlorine equivalent of 8,700 ppm of HCl) was electrically decomposed in the presence of sorptive surfaces (which represent construction surfaces). In one case, with a simulated plenum, the peak HCl concentration found was only 10% of the expected value[46-47]. A consequence of this HCl decay is that toxicity tests carried out in typical (non-sorptive) glass or plastic exposure chambers will exaggerate the toxicity of PVC smoke, because HCl does not decay as fast as on construction surfaces, so that HCl is present longer than in real fires.

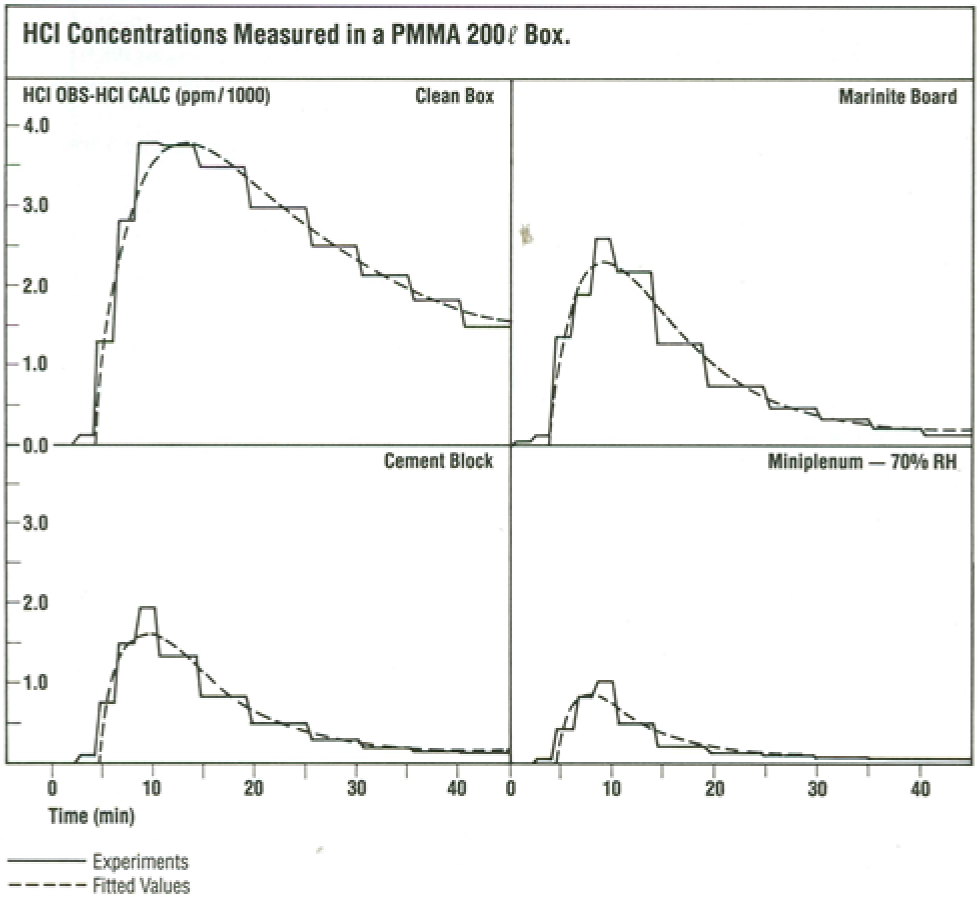

Figure 2.

HCl from Thermal Decomposition of PVC Cables in a Lined PMMA Box

Additionally, full-scale experiments were conducted in a real plenum and in a long corridor, among others. The plenum tests[48] showed that even if massive amounts of PVC are thermally decomposed in a plenum space above a room, no detectable HCl filters down into the room below (unless driven by an air conditioning system) while other gases (such as CO) do accumulate in the room. Even when driven by the air conditioning system, the HCl concentrations measured were found to have no toxicological concern. Thus, HCl from PVC is unlikely to affect victims outside the room of fire origin (meaning that they won't affect victims in the post-flashover period).

FIRE HAZARD, FIRE RISK AND PVC PERFORMANCE IN REAL FIRES

Overall fire safety is generally achieved by deciding if materials meet certain pre-set safety objectives. Many of the prescriptive techniques used most often for fire safety requirements (standard fire tests) were developed many years ago, and tend to have some deficiencies when applied to materials not commonly used when the test was developed.

As PVC does not normally melt away from flames, it often appears to perform less well in traditional tests than typical melting thermoplastics, when the test involves vertical or ceiling mounting, both of which can generate misleading results with melting materials. This has resulted in the development of techniques where all relevant fire properties and the entire fire scenario are considered, instead of pass/fail criteria based on individual tests. Such a process is called a fire hazard assessment. Fire hazard needs to be differentiated from fire risk. Fire hazard is the potential for harm to result when a fire occurs and fire risk is the combination of fire hazard and the probability that a fire will occur. PVC products have been shown to perform very well when both fire hazard and fire risk assessments are made. Four fire hazard assessments and one fire risk assessment were conducted in the 1980's and 1990's addressing burning of PVC electrical products in concealed spaces. The fire hazard assessment studies, as shown below, indicated that such PVC products exhibit low fire hazard. In all cases, it was found that the temperatures and concentrations of toxic gases in the room would have been lethal long before there would be any effect resulting from burning the PVC products, and that the materials involved were safe for the corresponding applications. The studies involved PVC non-metallic tubing installed behind walls[49], PVC conduit, PVC non-metallic tubing, or PVC wire coating, installed in a plenum, with a fire starting in the room below[50], PVC wire coating installed in a plenum, with a fire starting in the plenum51 and PVC wall linings in a cafeteria[52]. The fire risk assessment study, conducted through an NFPA project by NIST[53], involved PVC cables installed in concealed spaces in hotels. It indicated that cables with the fire performance of PVC were unlikely to add significantly to the fire risk associated with the other materials present.

It is of interest to point out an interesting aspect of a study by NIST investigating smoke toxicity predictions but using products made of 3 materials: wood (Douglas fir planks), polyurethane rigid foam and rigid PVC sheets[33]. In the full-scale tests the authors found that both the wood and foam products were able to be ignited while using small cribs of the same material and ignited by adding heptane contained in a pan under the crib. On the other hand, neither the PVC cribs nor the PVC sheets ignited under those conditions and a 450 kW gas burner had to be used to get the toxicity information needed. This is another example to show the excellent fire performance of rigid PVC in real-scale fires.

SUMMARY

- PVC is less flammable than most polymeric materials, natural or synthetic and it will not normally continue to burn unless a source of a sizeable fire exposure remains present.
- The heat release rate of PVC is lower than that of most combustible materials and it has been demonstrated that heat release rate governs the intensity of a fire.
- That means that, when PVC eventually burns, it both gives off less heat than most materials and it gives off heat more slowly than others.
- The smoke produced by PVC in small-scale tests is in the same range as many other materials and the smoke generated in full scale fires is usually lower because PVC materials burn less than most others.
- The smoke toxicity of PVC materials is in the exact same range as that of most commercial materials.
- PVC is one of the safer materials when fire safety is an essential consideration.

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Table 1: Ignitability of Materials in the Cone Calorimeter					
	Time to ignition (in s) at heat flux			**Heat flux (in kW/m²) for a time to ignition of**	
	20 kW/m²	**40 kW/m²**	**70 kW/m²**	**600 s**	**100 s**
Vinyl Materials					
PVC PL 3	10,000	1,212	17	45	64
PVC PL 2	10,000	1,253	424	60	110
PVC PL 4	10,000	10,000	1,583	86	115
PVC PL 1	10,000	1,271	60	47	65
CPVC	10,000	621	372	42	90
PVC CIM	5,159	73	45	30	39
PVC WC FR	236	47	12	≤ 15	31
PVC LS	5171	187	43	33	44
PVC WC SM	176	36	14	≤ 15	27
PVC EXT	3591	85	48	30	39
PVC WC	117	27	11	≤ 15	22
FL PVC	102	21	15	≤ 15	20
Non Vinyl Materials					
PTFE	10,000	10,000	252	63	83
PCARB	10,000	182	75	34	43
ACR FR	200	38	12	≤ 15	28
PCARB B	6400	144	45	32	42
XLPE	750	105	35	22	40
PPO GLAS	465	45	35	18	33
PPO/PS	479	87	39	17	38
ABS FV	5198	61	39	30	38
ABS FR	212	66	39	≤ 15	33
DFIR	254	34	12	≤ 15	29
PS FR	244	90	51	≤ 15	38
ACET	259	74	24	≤ 15	35
PU	12	1	1	≤ 15	≤ 15
PMMA	176	36	11	≤ 15	27
THM PU	302	60	38	≤ 15	34
NYLON	1,923	65	31	27	37
ABS	236	69	48	≤ 15	34
PS	417	97	50	15	40
EPDM/SAN	486	68	36	18	36
PBT	609	113	59	20	41
PET	718	116	42	22	42
PE	403	159	47	≤ 15	50
PP	218	86	41	≤ 15	37

Table 2: Materials Used for Various Series of Experiments (*Samples are 6 mm thick unless noted differently*)

#	Abbreviation	Description and Source – including trade name
1	PTFE	Polytetrafluoroethylene sheet (samples were two sheets at 3 mm thickness each, Du Pont)
2	PVC PL 3	Flexible PVC thermoplastic elastomer alloy cable jacketing plenum compound
3	PVC PL 2	Flexible PVC thermoplastic elastomer alloy cable jacketing plenum compound
4	PVC PL 4	Semi flexible PVC thermoplastic elastomer alloy cable jacketing plenum compound, containing PVC and CPVC (BFGoodrich)
5	PCARB	Polycarbonate sheeting (Lexan 141-111, General Electric)
6	PVC PL 1	Flexible PVC thermoplastic elastomer alloy cable jacketing plenum compound
7	CPVC	Chlorinated PVC sheet compound (BFGoodrich)
8	PVC CIM	PVC custom injection molding compound with impact modifiers (BFGoodrich)
9	PVC WC FR	Flexible cable PVC compound (containing flame retardants) (BFGoodrich)
10	PVC LS	PVC rigid sheet extrusion compound with smoke suppressants (BFGoodrich)
11	XLPE	Black non-halogen flame retarded, irradiation cross-linkable, polyethylene copolymer cable jacketing compound (DEQD-1388, Union Carbide)
12	PVC WC SM	Flexible cable PVC compound (with minimal amounts of flame retardants) (BFGoodrich)
13	PVC EXT	PVC rigid weatherable extrusion compound with minimal additives (BFGoodrich)
14	PVC WC	Flexible cable PVC compound (not flame retarded) (BFGoodrich)
15	ACR FR	Kydex: flame retarded acrylic paneling, blue, (samples were 4 sheets at 1.5 mm thickness each, Kleerdex)
16	PCARB B	Commercial polycarbonate sheeting (Commercial Plastics)
17	PPO GLAS	Blend of polyphenylene oxide and polystyrene containing 30% fiberglass (Noryl GFN-3-70, General Electric)
18	PPO/PS	Blend of polyphenylene oxide and polystyrene (Noryl N190, General Electric)
19	ABS FV	Polymeric system containing ABS and some PVC as additive
20	ABS FR	Cycolac KJT ABS terpolymer flame retarded with Br compounds (Borg Warner)
21	FL PVC	Standard flexible PVC compound (non-commercial; similar to a cable compound) used for various sets of testing (contains PVC resin 100 phr; diisodecyl phthalate 65 phr; tribasic lead sulphate 5 phr; calcium carbonate 40 phr; stearic acid 0.25 phr)
22	DFIR	Douglas fir wood board
23	PS FR	Flame retarded polystyrene, Huntsman 351 (Huntsman)
24	ACET	Polyacetal: polyformaldehyde (Delrin, Commercial Plastics)
25	PU	Polyurethane flexible foam, non-flame retarded (Jo-Ann Fabrics)
26	PMMA	Poly(methyl methacrylate) (25 mm thick, lined with cardboard, standard HRR sample)
27	THM PU	Thermoplastic polyurethane containing flame retardants (estane, BFGoodrich)
28	NYLON	Nylon 6,6 compound (Zytel 103 HSL, Du Pont)
29	ABS	Cycolac CTB ABS terpolymer (Borg Warner)
30	PS	Polystyrene, Huntsman 333 (Huntsman)
31	EPDM	Copolymer of EPDM rubber and SAN (Rovel 701)
32	PBT	Polybutylene terephthalate sheet (Celanex 2000-2 polyester, Hoechst Celanese)
33	PET	Polyethylene terephthalate soft drink bottle compound
34	PE	Polyethylene (Marlex HXM 50100)
35	PP	Polypropylene (Dypro 8938)

Table 3: Oxygen Index of a Variety of Materials		
Material	**LOI**	**Vinyl or Non Vinyl**
PTFE	95.0	NV
CPVC	62.2	V
PVDC	60.0	NV
Carbon black rod	59.9	NV
PVC PL 4	49.4	V
PVC PL 2	48.0	V
PVC (rigid)	47.0	V
PVDF	43.7	NV
Polyimide	36.5	NV
Leather (FR)	34.8	NV
Polysulphone	31.1	NV
Nomex	28.5	NV
Modacrylic	26.8	NV
Neoprene rubber	26.3	NV
Polycarbonate	26.2	NV
Wool	25.2	NV
Nylon 6,6	25.1	NV
PVF	22.6	NV
PET	20.0	NV
Cellulose	19.0	NV
Rayon	18.8	NV
Polyacrylonitrile	18.0	NV
SAN	18.0	NV
PMMA	17.9	NV
Polystyrene	17.7	NV
ABS	17.6	NV
Natural Rubber	17.2	NV
Polypropylene	17.1	NV
Polyethylene	17.0	NV
Cotton	16.5	NV
Polyacetal	15.8	NV
Polyoxymethylene	15.7	NV

Table 4: UL 94 Test Results of Wire and Cable Materials				
Material #	**V-0 @ 1 mm**	**V-0 @ 2 mm**	**V-0 @ 3 mm**	**HB**
PVC Cable FR1	V-0	V-0	V-0	
PVC Cable FR2	V-0	V-0	V-0	
PVC Cable FR3	V-0	V-0	V-0	
PVC Cable FR4	V-0	V-0	V-0	
PVC Cable Non FR	V-1	V-2	V-0	
Chlorosulphonated PE	V-1	V-0	V-0	
PTFE	V-0	V-0	V-0	
LDPE Cable Non FR	B	B	B	2 in/min
EVA Cable FR1	B			
EPR Cable FR2	B			
EVA Cable FR3	V-1	V-0	V-0	
EVA Cable FR4	B	B	B	
EVA Cable FR5	V-0	V-0	V-0	
Polyphenylene Oxide	B	B	B	
EVA Cable FR6	B	B	V-0	
PVC PL2	V-0	V-0	V-0	

Table 5: Steiner Tunnel Test Classifications		
ASTM E84 Class	**FS**	**S**
A	≤ 25	≤ 450
B	> 25 & ≤ 75	≤ 450
Class	> 75 & ≤ 200	≤ 450
Plenum	≤ 25	≤ 50
Other tunnel standards: flame spread ≤ 5ft, peak optical density ≤ 0.50 and average optical density ≤ 0.15		

Table 6: Flame Spread Index from the ASTM E84 Test		
Material/Product	**Flame Spread Index Range**	
	Low	**High**
ABS	200	275
Douglas fir/cedar plywood	190	230
Ponderosa pine A	170	230
Acrylic plastic	220	
Northern white pine A	190	215
Southern yellow pine	130	195
Hemlock/cedar plywood	190	
Red oak flakeboard	70	190
Poplar	170	185
Particleboard	135	180
Northern white pine B	120	180
Modified polyphenyl oxide	170	
Lauan hardwood	150	170
Ponderosa pine B	105	170
Red Gum (25 mm)	140	155
Cypress (25 mm)	145	150
Plywood panelling over gypsum	130	150
Red pine	140	
Walnut	130	140
Douglas fir overlay	110	140
Vinyl faced plywood	110	130
Polycarbonate	80	120
Cottonwood (25 mm)	115	
Polyether imide	110	
Yellow birch (25 mm)	105	110
Maple flooring	105	
Western spruce	100	
Red oak flooring (20 mm)	100	100
Douglas fir (25 mm)	70	100
ABS FR	10	100
Lodgepole pine	95	
Eastern white pine	85	
Pacific yellow cedar (25 mm)	80	
Cellulose fiberboard ceiling tile	70	80
Western white pine	75	
Western red cedar (25 mm)	70	
Pacific silver fir (25 mm)	70	
Varnished pine (10 mm)	70	
Redwood	65	70
West coast hemlock (25 mm)	60	70

Table 6: Flame Spread Index from the ASTM E84 Test – *Continued*		
Fire retarded polycarbonate	10	65
FR Polyester B	35	45
FR Treated plywood (6 mm)	40	
Vinyl faced wallboard	20	35
FR Polyester A	20	30
PVC wallcovering on gypsum board	10	25
PVC rigid profile	15	20
Polypropylene scrim foil	15	20
Cellulosic ceiling tile (15 mm)	15	
Phenolic foam (38 mm)	15	
Gypsum wallboard	10	20
Polypropylene scrim kraft paper	10	15
PVC siding (1 mm)	10	15
PVC vapor barrier	10	15
PVC sheet (3 mm)	5	10
Polyimide foam (51 mm)	0	
Mineral wool unfaced (51 mm)	0	0
Asbestos cement board	0	0

Table 7: Radiant Panel Index Results from ASTM E162		
Material	**Thickness (mm)**	**Radiant Panel Index**
Chlorinated PVC	3	4
Polyether sulphone	3	5
PVC (rigid)	4	10
Polyester	3	43
FR polystyrene	3	59
FR polycarbonate	6	73
Modified polyphenylene oxide	6	84
Polycarbonate	3	88
Red oak	19	99
Phenolic resin	2	114
ABS	6	131
Plywood (fir)	6	143
Hardboard	6	185
GRP polyester (21%)	2	239
FR acrylic	3	316
Polystyrene	2	355
Acrylic	6	416
Polyurethane foam (flexible)		1490
Polyurethane foam (rigid)		2220

Table 8: Results from OSU Heat Release Testing	
Material (#)	**Pk HRR (kW/m²)**
PMMA	586.8
PE	476.9
PP	451.2
EPDM	402.8
PS (non FR)	398.9
ABS (non FR)	391.1
Polystyrene	376.7
ABS (non FR)	344.5
Polyester PBT	316
Hardboard	227.1
Polycarbonate	192.5
Polystyrene (FR)	189.3
PPO Glass	170.4
THM PU	158.1
ABS FV	152.4
PPO/PS	136.4
Polycarbonate	132.5
Plywood	113.6
PS (FR)	103.8
Pine (25 mm)	79.5
Oak (25 mm)	79.5
Vinyl tile	75.7
ABS (FR)	70.7
FL PVC	56.8
Gypsum board	47.3
PVC CIM	43
PVC EXT	40
LS PVC	39.3
PVC PL4	17.5

Table 9: Heat Release and Fire Performance Index Test Results in the Cone Calorimeter (*Materials in Table 2*)

	Flux 20 kW/m²			Flux 40 kW/m²			Flux 70 kW/m²		
Material	**Pk RHR**	**THR**	**FPI**	**Pk RHR**	**THR**	**FPI**	**Pk RHR**	**THR**	**FPI**
	(kW/m²)	**(MJ/m²)**	**(s m²/kW)**	**(kW/m²)**	**(MJ/m²)**	**(s m²/kW)**	**(kW/m²)**	**(MJ/m²)**	**(s m²/kW)**
PTFE	3	0.3	6780	13	11.7	839	161	69.1	1.56
PVC PL3	4	5.1	2850	43	31.5	36.4	70	48.8	0.24
PVC PL2	9	5.7	1301	64	66.1	21.4	100	39	6.01
PVC PL4	14	13.2	1027	87	25.9	115	66	57.4	24.3
PCARB	16	0.1	5173	429	119.2	0.43	342	121.7	0.22
PVC PL1	19	12.2	591	77	48.1	16.7	120	63.4	0.49
CPVC	25	14.7	392	84	37.4	7.44	93	44.9	4.06
PVC CIM	40	3	1343	175	24.3	0.42	191	93	0.24
PVC WC FR	72	36.5	3.49	92	51.7	0.5	134	65.5	0.09
PVC LS	75	6.6	72.4	111	73.6	1.65	126	75.5	0.34
XLPE	88	87.6	8.08	192	126.2	0.55	268	129.2	0.13
PVC WC SM	90	49	1.96	142	75.4	0.25	186	73.4	0.07
PVC EXT	102	2.9	31.4	183	90.8	0.46	190	96.5	0.25
PVC WC	116	47.3	1	167	95.7	0.16	232	94.4	0.05
ACR FR	117	20.5	1.7	176	86.7	0.22	242	77.2	0.05
PCARB B	144	35.4	474	420	134.7	0.34	535	143.5	0.08
PPO GLAS	154	111	3.03	276	125.8	0.16	386	125.7	0.09
PPO/PS	219	103.6	2.45	265	128.5	0.33	301	134.3	0.13
ABS FV	224	80.7	66.3	291	108.5	0.21	409	114.1	0.1
ABS FR	224	38.3	0.93	402	70.3	0.16	419	61	0.09
FL PVC	233	116.4	0.44	237	98.2	0.09	252	86.3	0.06
DFIR	237	46.5	1.1	221	64.1	0.15	196	50	0.06
PS FR	277	93	0.9	334	94.5	0.27	445	82	0.11
ACET	290	143.9	0.9	360	141.3	0.2	566	167.1	0.04
PU	290	9.4	0.04	710	13.2	0.0014	1221	13.3	0.0008
PMMA	409	691.5	0.43	665	827.9	0.05	988	757.1	0.01
THM PU	424	110	0.72	221	119.3	0.28	319	120.1	0.12
NYLON	517	188	3.85	1313	226.3	0.05	2019	233.8	0.02
ABS	614	160	0.38	944	162.5	0.07	1311	162.5	0.04
PS	723	202.6	0.58	1101	210.1	0.09	1555	197.8	0.03
EPDM	737	213.1	0.66	956	199.8	0.07	1215	215.7	0.03
PBT	850	96.7	0.75	1313	169.9	0.09	1984	197.4	0.09
PET	881	93.3	0.82	534	113.7	0.22	616	125.5	0.07
PE	913	161.9	0.44	1408	221	0.06	2735	227.5	0.02
PP	1170	231.3	0.19	1509	206.9	0.06	2421	231.1	0.02

Table 10: Heat Release Capacity of Polymeric Materials	
Polymer	**Heat Release Capacity**
-	(J/g K)
High density polyethylene	1450
Polypropylene	1106
Polystyrene	1088
High impact polystyrene	873
Acrylonitrile butadiene styrene	585
Polycarbonate	578
Polyamide 6,6	565
Poly(methyl methacrylate)	480
Polyethylene terephthalate	366
Poly ether ether ketone	345
Poly(vinylidene fluoride)	309
Polyphenylene sulfide	230
Polyphenyl sulfone	219
Polyoxymethylene	200
Polyether imide	197
PVC	157
Fluorinated ethylene propylene	82

Table 11: Fire Properties of Wall Lining Materials (Full scale and Small Scale)									
			Rigid PVC	**Wood Panel**	**Low Smoke PVC**	**CPVC**	**Polycarbonate**	**FR ABS**	**FR Acrylic Paneling**
Cone Calorimeter	**20 kW/m²**	**Pk HRR (kW/m²)**	109	385	62	17	363	158	62
		FPI (sm²/kW)	4.14	0.72	69.03	588.24	5.97	4.37	15.90
	25 kW/m²	**Pk HRR (kW/m²)**	105	367	54	42	351	165	124
		FPI (sm²/kW)	1.45	0.37	18.87	8.19	2.83	0.47	0.67
	40 kW/m²	**Pk HRR (kW/m²)**	224	435	91	54	233	264	109
		FPI (sm²/kW)	0.21	0.09	0.54	3.15	0.34	0.14	0.21
	70 kW/m²	**Pk HRR (kW/m²)**	270	661	95	94	297	341	183
		FPI (sm²/kW)	0.07	0.03	0.13	0.64	0.09	0.04	0.05
Room Corner Test (6.3 kg wood crib)	**Avg HRR**	**(kW)**	2.6	73.2	0	3	135.6	54	10.9
	THR	**(MJ)**	29.9	85.2	25.6	30.2	133.9	70.2	36.6
	Smoke Yield	**(g)**	368	868	202	26	4218	3432	483
ASTM E662	**Dm**	**(-)**	780	106	94	53	247	900	435

Table 12: CSA FT4 (UL 1685/CSA) and IEC 60332-3 Cable Tray Test Results on Various Electrical Cables												
Cable Materials		**CSA FT4 - UL 1685/CSA**									**IEC 60332-3**	
Insulation	Jacket	Pk HRR	Avg HRR	THR	Pk RSR	TSR	Mass loss	Ht Comb	Char	Flame Ht	Char	Flame Ht
		kW	kW	MJ	m^2/s	m^2	% combust	MJ/kg	m	m	m	m
PVC	PVC FR	59	33	10	0.74	187	16.54	13.6	1.11	1.25	1.02	1.20
PVC	PVC FR2	52	27	8	0.64	168	14.45	12.5	1.12	1.30	1.11	1.25
PVC	EVA FR	232	72	64	0.40	166	56.16	26.5	2.44	3.10	1.08	1.40
PVC FR	PVC	55	32	13	0.70	185	16.58	15.7	1.06	1.25	1.15	1.35
PVC FR	PVC FR2	38	25	5	0.67	179	12.49	8.3	0.91	1.00	0.90	1.10
PVC FR	PVC PL2	33	25	6	0.38	115	13.36	8.4	1.00	0.98	0.97	1.25
PVC FR	EVA FR2	52	30	12	0.14	54	15.33	16.0	0.99	1.23	0.96	1.25
PVC FR	Polyolef FR	46	30	12	0.20	61	13.37	16.6	0.97	1.10	0.86	1.25
LDPE	PVC	510	101	100	0.86	233	74.52	35.9	2.44	3.30	3.50	3.30
LDPE	PVC FR2	325	82	84	0.82	360	67.75	32.7	2.44	3.30	3.50	3.30
LDPE	PVC PL2	184	82	74	0.56	310	65.27	30.4	2.44	3.00	2.72	2.75
LDPE	EVA FR2	280	106	105	0.23	74	69.22	39.6	2.44	3.10	2.25	2.25
LDPE	Polyolef FR	368	117	115	0.22	87	67.12	45.4	2.44	3.30	3.50	3.30
EVA FR2	PVC FR	67	30	33	0.37	184	19.37	34.8	1.43	1.19	1.16	1.45
EVA FR2	PVC FR2	66	30	27	0.35	146	16.57	32.7	1.28	1.23	1.22	1.30
EVA FR2	EVA FR	206	31	105	0.13	77	48.69	42.4	2.44	3.00	1.35	1.65
FEP	PVC PL2	26	23	3	0.05	27	9.75	7.1	0.80	0.75	0.94	1.00
FEP	EVA FR2	66	34	13	0.14	36	15.80	22.6	1.14	1.28	0.91	0.90
PEEK	PVC PL2	29	22	2	0.08	27	8.84	8.5	0.77	0.80	0.92	1.00
PEEK	EVA FR2	54	33	15	0.06	27	10.25	42.6	1.02	1.13	0.92	0.95
FEP	FEP	28	25	5	0.02	10	5.89	23.5	0.76	0.75	0.52	0.80

Table 13: Maximum Specific Optical Density of Materials in ASTM E662 Test			
Material	**Flaming or Non Flaming**	**Dm**	**Thickness (mm)**
Acrylonitrile butadiene styrene	.F	780	6
Polystyrene	.F	780	6
Acrylonitrile butadiene styrene	NF	780	6
Polypropylene	NF	780	6
Natural rubber foam	.F	660	6
PVC rigid	.F	535	6
PVC rigid	NF	470	6
Polyethylene	NF	470	6
Black walnut	NF	460	6
Polystyrene	NF	395	6
Red oak	NF	395	6
Douglas fir	NF	380	6
Natural rubber foam	NF	372	6
White pine	NF	325	6
Nylon rug	NF	320	8
Nylon rug	.F	269	8
Douglas fir	.F	156	6
White pine	.F	155	6
Polyethylene	.F	150	6
Polypropylene	.F	119	6
Black walnut	.F	91	6
Red oak	.F	76	6
Polytetrafluoroethylene	.F	53	6
Polytetrafluoroethylene	NF	0	6

Table 14: Smoke Release Test Results in the Cone Calorimeter for Materials in Table 2									
	Flux 20 kW/m²			**Flux 40 kW/m²**			**Flux 70 kW/m²**		
Material	**SEA**	**TSR**	**SmkFct**	**SEA**	**TSR**	**SmkFct**	**SEA**	**TSR**	**SmkFct**
	(m^2/g)	**(-)**	**(MW/m^2)**	**(m^2/g)**	**(-)**	**(MW/m^2)**	**(m^2/g)**	**(-)**	**(MW/m^2)**
PTFE	0	200	0.4	673	376	0.3	33	764	4.4
PVC PL3	305	730	0.4	319	1571	13.5	302	2077	42.4
PVC PL2	94	422	0.6	358	2253	24.9	266	1725	80.3
PVC PL4	131	417	1.1	246	670	35.9	174	945	25.7
PCARB	3	15	0.1	993	3620	733.2	978	3900	728.4
PVC PL1	331	1249	4.3	547	3198	76.1	572	4888	239.1
CPVC	51	225	1.3	18	200	3.8	33	405	7.9
PVC CIM	96	934	13.7	569	6653	298.2	1041	6920	701.8
PVC WC FR	440	2149	27.7	566	2391	104.6	664	3754	283.9
PVC LS	54	465	9.3	591	1937	78.6	528	2285	148.6
XLPE	607	387	1.5	93	837	24	198	1427	133.8
PVC WC SM	645	4127	77.6	937	5880	473	1020	6512	872.6
PVC EXT	186	1227	24.3	3459	7027	459.6	1130	8917	1143.8
PVC WC	676	3608	100.4	939	5652	503.5	1046	6419	969.7
ACR FR	512	1409	65	839	6825	535	951	7786	1368.9
PCARB B	415	1033	2.7	814	3142	616	879	4784	1124.1
PPO GLAS	0	4145	1.8	1342	5550	853.8	1334	6160	1830.5
PPO/PS	0	7830	25.9	1731	8056	1143.3	1627	7830	1519
ABS FV	0	6650	22.3	1527	9692	1499.2	1243	8612	2561.8
ABS FR	0	9053	456.2	1772	9705	3740.9	1331	8222	3438.2
FL PVC	914	4912	481.6	1053	6075	914.5	1156	6809	1277
DFIR	114	318	30.4	65	287	42.9	96	307	59.7
PS FR	865	12090	290.1	1870	12799	3461.7	1445	10575	4490.1
ACET	74	249	13	10	198	17.5	25	477	103.3
PU	225	138	33.1	572	301	134.4	545	297	239.9
PMMA	67	2506	51.6	77	3646	429	97	3009	1012.1
THM PU	0	3970	216.3	566	3592	367.6	684	4037	746.1
NYLON	118	1966	2.7	217	3088	887.9	251	2130	4003.4
ABS	0	5520	793.3	885	4773	4457.4	666	3897	5035.5
PS	107	6653	44.6	1293	7738	6791.5	852	5906	9152.8
EPDM	0	7795	28.6	1014	7570	5785.4	1162	8586	10375.9
PBT	7	41362	1.4	466	3941	4711.2	660	4704	9656.5
PET	1	2308	2.8	286	2837	1207.9	503	4009	2355.9
PE	1982	892	29.9	299	1870	1822	275	4009	3975.8
PP	0	2700	536	475	2503	3416.5	429	2317	5509.4