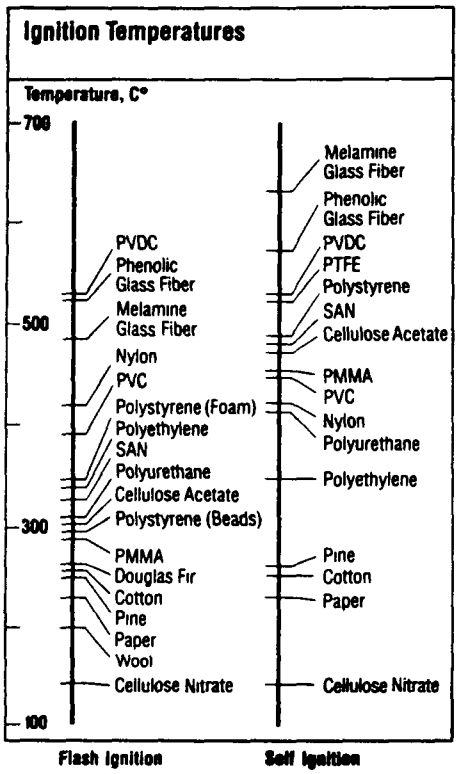
The Vinyl Institute

TECHNICAL INFORMATION

Fire Properties of Polyvinyl Chloride

Figure 1



Polyvinyl chloride (PVC, or vinyl) possesses excellent fire performance properties. In particular, it will not burn once the source of heat or flame is removed. This results from PVC having 56.8% chlorine in its base polymer weight. It is well known that chlorine is one of the few elements that confers good fire properties to a polymer.[1,2]

Samples of unplasticized (rigid) vinyl, such as those found in pipe, siding or vertical blinds, have higher ignition temperature, lower flame spread and lower heat released in a fire than similar samples of wood. When PVC is plasticized to make it into flexible products such as wire coatings, upholstery, medical blood bags or wall coverings, the fire properties become less favorable, depending on the amount and kind of plasticizer and other additives used. However, most plasticized PVC products in use will not continue to burn once the flame source is removed, even if not additionally fire-retarded.

The actual fire properties of PVC have been calculated from the results of small-scale and full-scale tests, and interpreted in terms of overall fire hazard.

FIRE HAZARD

The fire hazard of a product is determined by a combination of factors including its ignitability and flammability, the amount 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.

Ignitability

If a material does not ignite, it will not contribute to fire hazard and thereby cannot endanger lives. Most organic materials do, however, ignite and the lower the ignition temperature, the greater the hazard.

Figure 1 presents the self-ignition and flash-ignition temperatures of a variety of common materials, as measured by a standard test (ASTM D1929). With a flash ignition temperature of 346°C, PVC is among the least easily ignited polymers.

Flammability

Once ignited, the greater the flammability of a material, the greater the hazard associated with it. One of the most reliable quantitative small-scale flammability tests is the limited oxygen index test (LOI; ASTM D2863), which gives the limiting concentration of oxygen in the atmosphere necessary for sustained combustion. In general, a material with LOI of more than 21 should not burn in air at room temperature, and, one with LOI of more than 25-27 will only burn under extreme conditions. Table 1 shows that very few common materials have an LOI higher than PVC.

When PVC is plasticized in order to achieve flexibility, its LOI is lower than that of rigid PVC; the exact value will depend on the formulation. Phthalate plasticizer affects the LOI of PVC as shown in Figure 2. Because typical wire and cable compounds contain only 15-35 percent plasticizer, most will not burn in air unless a source of heat or flame is applied.

Flame Spread

The tendency of a material to spread flame can be measured using the radiant panel test, ASTM E162. Results from this test (Table 2) show that PVC is one of the materials with the lowest flame spread rating; it will not spread flame on its own.

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Table 1[2-4]

Limiting Oxygen Indices of Various Materials

Material	LOI
Polyacetal	14 9
Polyoxymethylene	15 7
Cotton	16-17
Natural rubber	17.2
PMMA	17 4
Polyethylene	17.4
Polypropylene	17.4
Polystyrene	17.6-18.3
Polyacrylonitrile	18.0
SAN	18.0
ABS	18.3-18.8
Rayon	18.7-18.9
Cellulose	19.0
PET	20.0
PVF	22.6
Nylon 6,6	24-29
Wool	25.2
Polycarbonate	26-28
Neoprene rubber	26 3
Modacrylic	26 8
Nomex	28.5
Polysulphone	30-32
Leather (FR)	34 8
Polyimide	36.5
PVDF	43.7
PVC (rigid)	45-49
Carbon black rod	59-63
PVDC	60 0
Chlorinated PVC	60-70
PTFE	95.0

Note: The fire performance for this test improves as the LOI becomes higher.

Heat Release

A burning object will spread a fire to nearby products only if it gives off enough heat to ignite them. Moreover, the heat has to be released fast enough not to be dissipated or lost while traveling through the cold air surrounding anything not on fire. Therefore, the most important flammability property, in terms of fire hazard, is the heat released. Figures 3 and 4 present normalized results for total heat released and maximum rate of heat released for a variety of materials, as measured by an Ohio State University rate of heat release calorimeter (OSU-RHR, ASTM E906).[6] They show that most materials are more prone to ignite other products than PVC.

Smoke

The amount of smoke that materials produce when they burn also is important because smoke obscures light and hinders escape from a fire.

The most common method for measuring smoke from burning products is the U. S. National Bureau of Standards (NBS) smoke chamber in the vertical mode (ASTM E662), and results from it are shown in Figure 5. This test is now known, however, to be seriously flawed; the principal deficiencies identified are shown in Table 3. The most important of the problems with the NBS smoke chamber is that its results misrepresent the smoke found in real fires.

One example of this is the effect of sample orientation. Some materials melt or drip when exposed to flame. When samples of such materials are exposed vertically in the NBS smoke chamber test, the molten portions will have escaped the effect of the radiant heat source. This means that some of the material does not burn during the test. If these dripping products are exposed horizontally, the entire sample will be consumed. The test, therefore, measures an amount of smoke artificially lower than what would be formed in a realistic scenario (see Table 4). PVC, however, does not melt or drip and the test, thus, gives the same smoke production results in the vertical or horizontal orientations. Therefore, when the smoke results of other materials are corrected for the melting effect by changing the orientation, the relative ranking of PVC in terms of smoke production changes. In fact, its smoke production figures become very similar to those of other materials regarded as low smoke producing, such as polyethylene or polypropylene (Table 5).

Table 2[4]

Surface flammability of some materials

Material	Thickness (mm)	Flame spread index
Chlorinated PVC	3	4
Polyether sulphone	3	5
PVC	4	10
Polyester	3	30-56
FR polystyrene	3	59
FR polycarbonate	6	73
Polycarbonate	3	88
Red oak	19	99
Phenolic resin	2	114
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

Note The fire performance for this test improves as the flame spread ratings become lower

Figure 2[5]

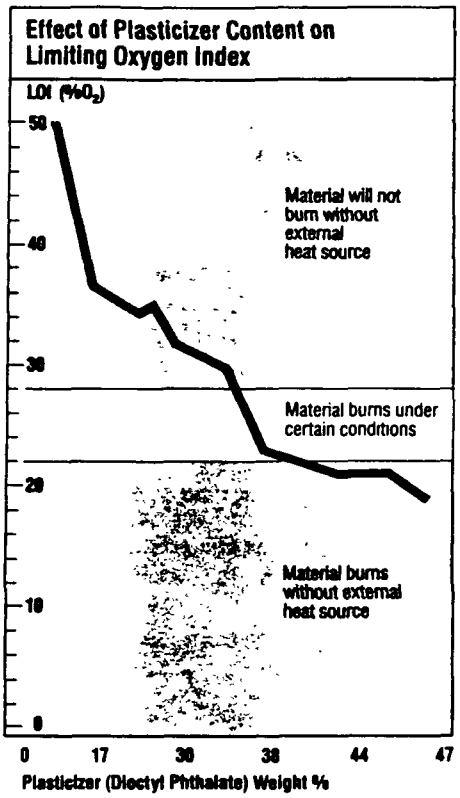
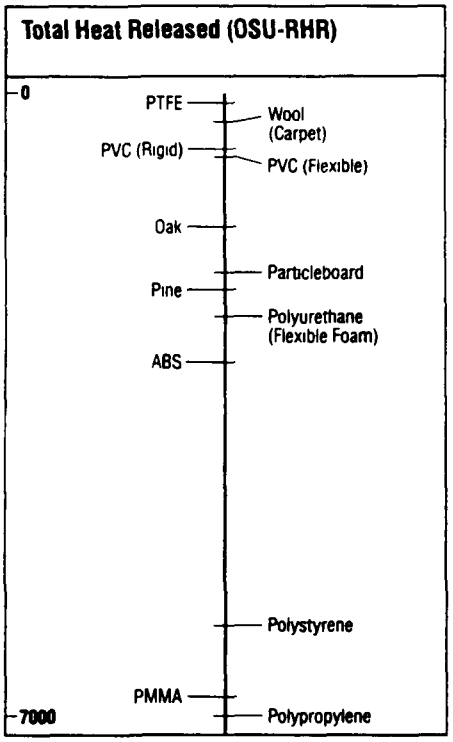
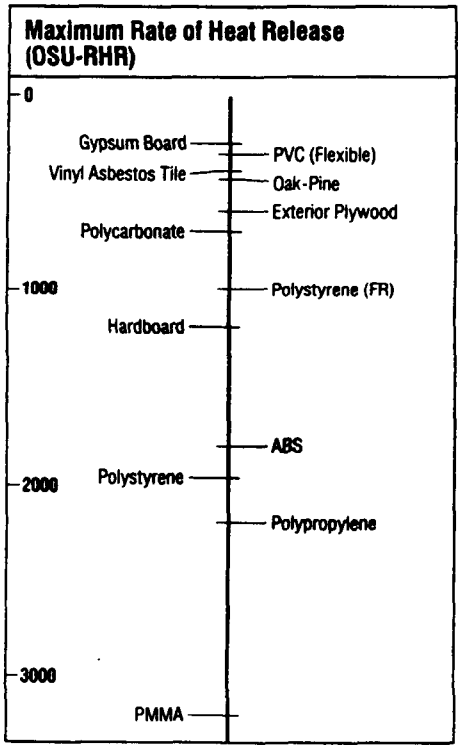


Figure 3



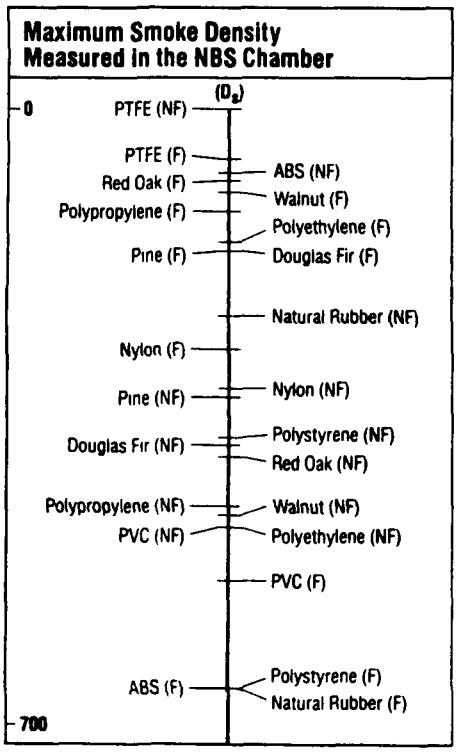
At 10 Min, per Unit Surface, at the Limiting Incident Heat Flux, per Unit Incident Heat Flux, (in BTU ft^{-2}/W cm^{-2})

Figure 4



At an Incident Heat Flux of 2 W cm^{-2} (in BTU min^{-1} ft^{-2})

Figure 5



F = flaming mode, NF = nonflaming mode

Even when corrections are made, however, the NBS smoke chamber cannot address the fact that fire hazard from smoke depends on how much product burns and how much heat is associated with it. This can be done by measuring smoke production from materials using a smoke parameter.[8] This is a test, developed by NBS, which measures the amount of smoke produced in the form most relevant to fire hazard by combining the light obscuration with the rate of heat released. It has been measured[4,11] on another, newer rate of heat release instrument: the NBS Cone calorimeter (ASTM E5- Proposal P-190).[12] Results from this instrument correlate with full-scale fires.[13-15] Table 6 indicates that standard rigid PVC has a smoke parameter less than one tenth of that of other plastic materials such as polyester, polyethylene, or polypropylene, with low smoke production numbers in the NBS smoke chamber test (Figure 5). Flexible PVC compounds have higher smoke parameters than rigid ones, due to the effect of the plasticizer.

Mass Loss

In addition to heat and smoke release, fire hazard also depends heavily on the release of toxic combustion products into the atmosphere – that is, on the mass loss rate of a material. If a product loses mass very rapidly, a hazardous accumulation of dangerous smoke will develop more easily. The rate of mass loss for most flame retarded materials is relatively similar. The other results shown in Table 6 – rates of mass loss and of heat release – also measured with the NBS Cone calorimeter, indicate that PVC has both a very low maximum rate of heat release and a low rate of mass loss.

Toxicity

Finally, fire hazard also is associated with the toxicity of the smoke itself. Figure 6 presents some results on the toxic potency of the smoke of a variety of common materials, as measured by the NBS cup furnace toxicity test,[18] and compares them with the intrinsic toxic potency of other poisons and toxic gases, as well as with textbook toxicity categories.[19]

This figure shows that toxicity is a relatively minor factor in fire hazard since the intrinsic toxic potency of the smoke of the majority of common materials is very similar, with very few exceptions. This is because the most important toxic product in any fire is carbon monoxide (CO), which is produced by all organic materials when they burn. Furthermore, there is wide agreement today that small-scale smoke toxicity tests can only show broad toxicity categories and cannot really distinguish between most materials.

This indicates that the toxicity of the smoke of most materials, including PVC, is simply a consequence of the amount of smoke produced. The only exceptions are those very few materials which have an exceptionally high toxic potency. That is why a low mass loss rate will generally mean a low toxic fire hazard, almost irrespective of the toxic potency of the smoke itself.

Table 3[7-10]

Deficiencies in the NBS smoke chamber

- Results do not correlate with full-scale fires.
- Vertical orientation leads to melt and drip.
- Time dependency of results cannot be established.
- No means of weighing sample during test.
- Maximum incident radiant flux is 25 kW/m^2
- Fire self-extinguishes if oxygen level becomes <14%.
- Therefore, composites often give misleading results.
- Wall losses are significant.
- Soot gets deposited on optics.
- Light source is polychromatic.
- Rational units of m^2/kg are not available.

Table 4

Effect of Orientation on Smoke Density (NBS Chamber)[7]
(maximum smoke density; flaming mode)

	Horizontal	Vertical
Polypropylene	398	57
Polyethylene	286	35
Nylon	264	48
Paraffin Wax	228	83

HEALTH EFFECTS OF HYDROGEN CHLORIDE

The majority of combustion products given off by PVC are the same as those produced by wood or most other common materials, both natural and synthetic.[1,3] The one product given off by PVC that is not given off by natural materials is hydrogen chloride (HCl).

Studies have been made on the susceptibility of different animals to various toxic gases. These studies have found that rats are reasonable models for primates as far as incapacitation and exposure dose for post-exposure lethality of irritants (like HCl) is concerned.[20-21] The rat is also a good model for asphyxiants such as CO.[21-22] On the other hand, the mouse has been shown to be much more sensitive to irritants (particularly HCl) than rats[23-25] or baboons.[25]

Table 7 shows the lethal doses of some of the most important toxic gases present in fires, as measured in those animal species with responses most similar to those of humans – namely, rats and baboons.[21, 22, 26, 27] These data show that although the mechanisms of action of CO and HCl are totally different, their lethal doses are very similar. However, HCl has an important feature related to fire hazard: a very pungent odor, detectable at a level of less than 1 ppm,[28] while CO is odorless and narcotic. Therefore, HCl will signal people in a fire atmosphere to escape, while CO will narcotize them.

Table 7 also shows the highest concentration of these gases found in two studies involving fire fighters equipped with monitoring devices. Interestingly, the peak CO concentration found when they entered burning buildings was higher than that known to cause lethality at 30 minutes. Similarly, the peak acrolein concentration found is equivalent, after a 30 minute exposure, to a dose in the range of the 5 minute lethal dose for baboons. On the other hand, the peak HCl concentration found was less than one tenth of the corresponding 30 minute lethal value. This data supports, again, the observation that CO is the prime toxic hazard in a fire.

Table 5

Smoke Density (NBS Chamber) Corrected for Melting Effect[7]

	maximum optical density (cm^2/g)
Polystyrene	14,300
Polypropylene	5,250
PVC	3,400
Polyethylene	2,900
Paraffin wax	2,300

Table 6[4,11,17]

Heat, Smoke and Mass Release Parameters from NBS Cone RHR Calorimeter (Horizontal exposure[a])

Material	Maximum Rate Heat Release kW/m^2	Average Specific Extinction Area at 5 min m^2/kg	Maximum Mass Loss Rate $g/(s\ m^2)$	Smoke Parameter $kW\ kg \times 10^{-5}$
1. Polycarbonate	22	0	5.0	0
2. Aircraft panel[b,d]	40	–	5.6	–
3. Low smoke rigid PVC	89	47	8.0	0 04
4. PVC	91	380	13.7	0.35
5. Low smoke FR PVC wire cpd	92	159	19.3	0 15
6. Carpet[b]	100	–	5.5	–
7. PVC (extrusion)	115	340	12.7	0 38
8. Rigid PU foam[b,d]	160	–	7.3	–
9. Particle Board[b,c]	180	–	12.6	–
10. PPO/PS with fiberglass	184	903	9.1	1 66
11. Standard PVC wire cpd	204	1099	14 0	2.23
12. FR ABS	250	1874	17.7	4 68
13. PPO/Polystyrene alloy	263	1561	11.3	4 10
14. FR Polystyrene	315	1747	21.5	5 50
15. FR ABS (with PVC)	445	1312	11 6	5 84
16. FR polyurethane TPU	509	606	12.6	3 08
17. PMMA[b,c]	650	–	25.0	–
18. Flexible PU foam[b,d]	650	–	28.5	–
19. ABS	746	863	24.2	6 44
20. Polystyrene	859	1027	26.5	8 82
21. EPDM/SAN	883	1016	24.8	8.97
22. Polyester	1216	460	59.4	5.59
23. Polyethylene	1325	337	24.7	4.46
24. Polypropylene	1335	461	26.7	6.15

[a] *Incident Flux: 20 kW/m^2; thickness: 0.63 cm*
[b] *Incident Flux: 25 kW/m^2*
[c] *Thickness: 1.28 cm*
[d] *Thickness: 2.54 cm*

Materials: 1,6,8,9,17,18 – Reference 17; 5,11 – BFGoodrich compounds; others – References 4,11. Lexan 141-111 polycarbonate; composite with phenolic-polyamide honeycomb and tedlar coating; low smoke PVC sheet extrusion compound; general purpose PVC custom injection moulding compound; PVC fire retarded flexible wire compound designed for low smoke; wool-nylon carpet with rubberized backing; weatherable PVC extrusion compound; GM31 rigid polyurethane foam[18]; 0 5 inch particle board; Noryl GFN-3-70 PPO/PS with fiberglas, standard flexible PVC wire and cable compound (non fire-retarded) Cycolac KJT ABS; Noryl N-190 polyphenylene oxide/polystyrene, Huntsman 351 FR polystyrene, ABS fire-retarded with PVC, FR thermoplastic polyurethane; 0.5 inch Rohm and Haas black poly (methyl methacrylate), 0.5 inch low density flexible polyurethane foam; Cycolac CTB ABS; Huntsman 333 polystyrene; Rovel 701 EPDM SAN copolymer; Celanex 2000-2 polyester, Marlex HXM 50100 polyethylene, Durro 8938 polypropylene

Table 7

Lethal Exposure Doses for Common Gases

Gas	LED ppm min	Animals	ODL[a] ppm[28]	Peak in Fire ppm[29,30]
CO	192,000[b]	rats	–	7,450
Acrolein	2,500-5,000[c]	baboons	0.16	98
HCl	112,000-169,000[d]	rats	0 77	280
HCl	ca. 150,000[e]	baboons	0.77	280
HCN	4,800[f]	rats	0 58	9

[a]Odor detection level
[b]30 min exposure; within exposure deaths; Reference 27
[c]5 min exposure; post-exposure deaths; Reference 21
[d]30-60 min exposure; post-exposure deaths; Reference 20
[e]5-15 min exposures, with no deaths; Reference 20
[f]30 min exposure; within exposure deaths; Reference 26

Table 8[35]

Results of Corner Burn Room Fire Test[a]

Material	Temp. at door (°C)	Heat generated at 13 minutes (MJ)	Peak smoke at door (OD/m)[b]	Smoke yield (g)	NBS Smoke Dm[c]
Crib only	171	32.6	1.6	106	–
Low smoke rigid PVC	178	25.6	4.6	187	94
Chlorinated PVC	169	30.2	1.5	93	53
Rigid PVC	188	31.7	8.3	384	780
FR Acrylic	322	36 6	>15.1	398	435
FR ABS	748	70.2	>15.1	>900	900
Wood (oak)	558	89.8	9.6	746	106
Polycarbonate	382	133.7	>15 1	>2500	247

[a]A 6.3 kg wood crib was used in all experiments.
[b]OD/m: optical density per meter.
[c]Dm: maximum smoke density.

HYDROGEN CHLORIDE DECAY

A series of studies was done to investigate the "lifetime" of HCl in a fire atmosphere.[31-34] These studies showed that HCl reacts very rapidly with most common construction surfaces (cement block, ceiling tile, gypsum board, etc.). Therefore, the peak HCl concentration found in a fire is much lower than would be predicted from the chlorine content of the burning material. Moreover, this peak concentration soon decreases and HCl disappears completely from the air. Figure 7 shows the HCl concentration-time pattern for several identical experiments where PVC wire insulation (containing the chlorine equivalent of 8,700 ppm of HCl) was electrically decomposed in the presence of sorptive surfaces. The peak concentration of HCl found in this simulated plenum was only 10% of the theoretical concentration.

One of the consequences of these studies is that toxicity tests carried out in glass or plastic exposure chambers may exaggerate the toxicity of PVC smoke. On these surfaces, HCl does not decay as fast as on real-use surfaces, so that toxic gases are present longer than in real fires.

PVC PERFORMANCE IN LARGE SCALE TESTS

It is probably of much greater importance to understand how PVC behaves in a real full-scale fire than to understand the results of small-scale tests, some of which are of questionable validity. A series of tests was conducted in which a corner, floor to ceiling, was paneled with different materials including wood and rigid PVC. Table 8 shows that the PVC panels added nothing whatsoever to the total heat generated and next to nothing to the temperature measured at the door of the room, as compared to the ignition source itself (a wood crib).[35] The smoke emitted by the burning PVC caused the room to become somewhat darker than when the crib burned alone, however, the darkness was much less than that generated when the wood panels were burned. The wood also gave off a very considerable amount of additional heat, much hotter temperatures at the door, and a large mass of smoke particulates. Other materials, with the exception of chlorinated PVC (CPVC), similarly generated much more smoke and heat than the PVC panels.

It is also interesting to note that the smoke yield in the full-scale tests did not correlate with that in the NBS smoke chamber. The reason for this lack of correlation is that the largest smoke yield in the NBS smoke chamber was given by those materials burning least extensively in the large-scale test.

Figure 6

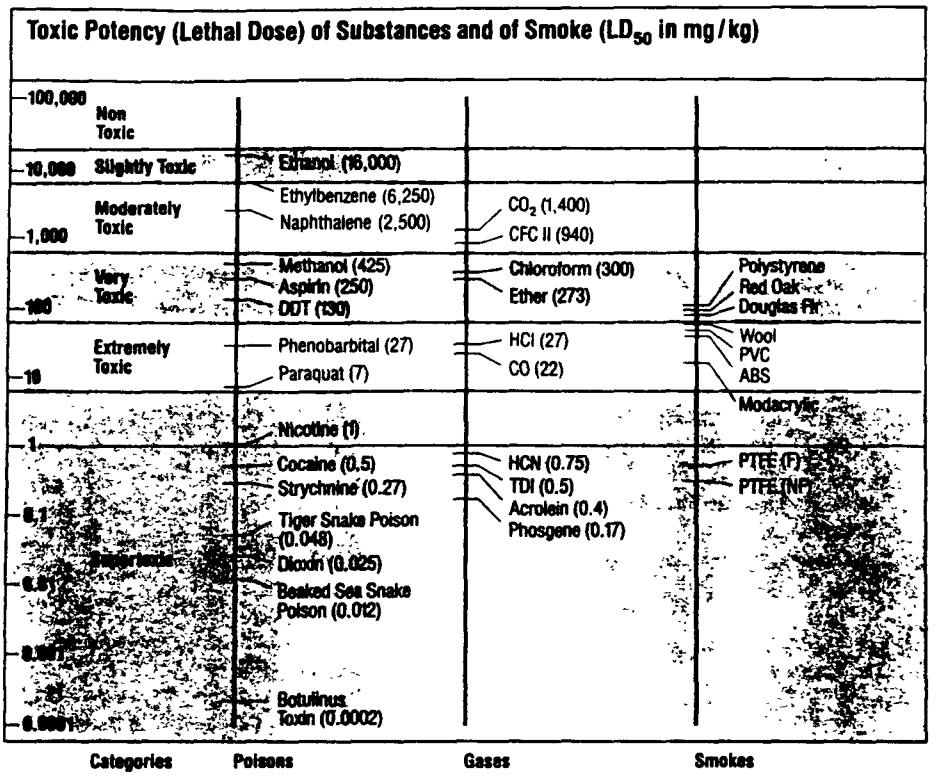
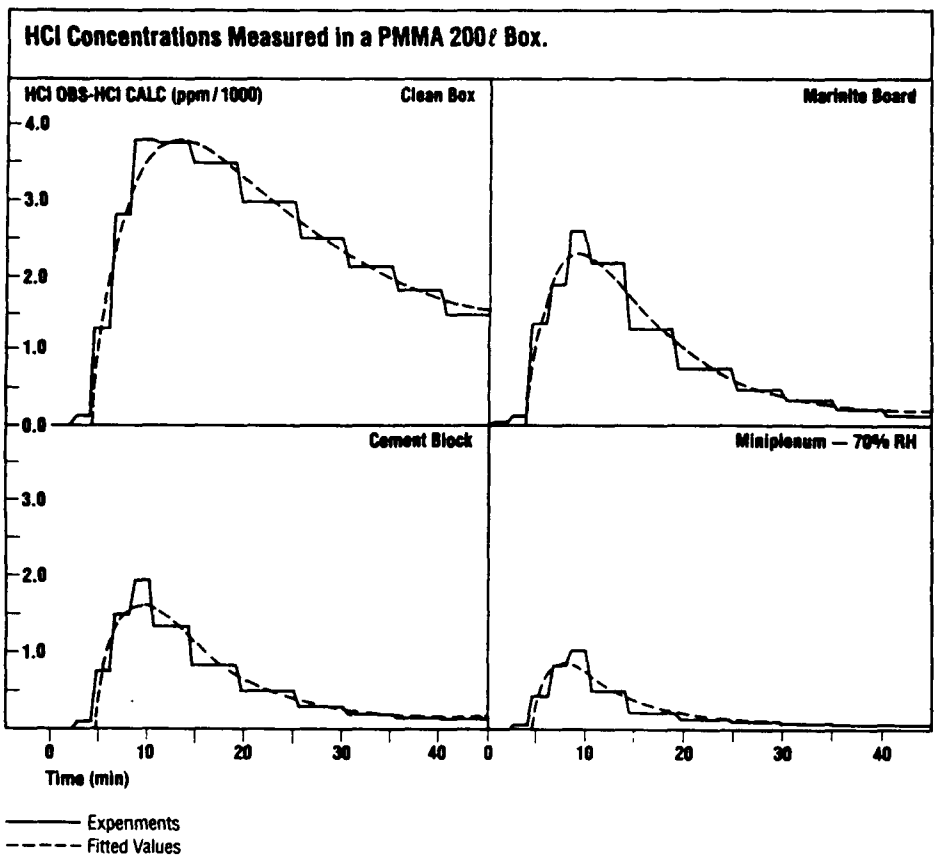


Figure 7



Large-scale experiments have also been carried out to investigate HCl decay. These show that, even if massive amounts of PVC are decomposed in a plenum space above a room, no HCl filters down into the room below unless driven by an air conditioning system, while other gases do accumulate in the room.[31, 34] Even with an air conditioning system, the concentrations in the room were found to be of virtually no toxicological concern. Consequently, high concentrations of HCl are unlikely to reach rooms other than that of origin and unlikely to affect victims in the post-flashover period.

Two other interesting studies have investigated the effects of burning PVC electrical products behind a wall (non-metallic tubing)[36] or a ceiling (conduit, non-metallic tubing, wire coating).[37] It was found, in both cases, that the temperatures and concentrations of toxic gases in the room would be lethal long before there would be any effect resulting from the combustion of the PVC products.

SUMMARY

1) The most important cause of fire deaths is CO, produced when all organic materials burn.
2) PVC is less flammable than most organic materials and it will not continue burning unless there is a powerful external source of heat.
3) When PVC eventually burns, it gives off less heat and does so more slowly than most materials.
4) The smoke produced by burning PVC is within the same range as that of many other materials.
5) The toxicity of PVC combustion products is comparable to that of most organic materials.
6) PVC is unusual in that, when it burns, it releases HCl, which is irritating. However, HCl odor is easily detectable (at less than 1 ppm) and HCl does not incapacitate or become dangerous until it reaches concentrations much higher than those measured in real fires.
7) HCl is unique among common fire gases in that it decays by reacting very rapidly with most construction surfaces and consequently, is not transported easily to other rooms.

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