

Combustion Gases of Various Building Materials

Organic materials are those which contain carbon. These include many natural products such as wood, wool, cotton, silk, rubber, leather and many synthetic products such as vinyl (polyvinyl chloride or PVC), nylon, rayon, acrylic, Teflon[®], Styrofoam[®], polyurethane, polyethylene and many more. All organic materials will burn (that is, undergo combustion), although the conditions required for each material to do so may differ.

When any material is involved in a fire, it releases smoke, which contains many different combustion products, mainly gases, virtually all of which are toxic. Among these fire gases, two are always present in a fire, irrespective of the material which is burning because they are the end products of combustion of all organic materials^{1,2}. These are carbon monoxide and carbon dioxide. Wood is a common construction material of natural origin which will, of course, burn. When it does, it can release up to 175 different fire gases. These gases include not only carbon monoxide and carbon dioxide, but also benzene and acrolein and numerous other irritating, corrosive and carcinogenic chemicals³⁻⁵.

The nature and concentration of toxic combustion products in a real fire will depend on many variables and not only on the material which is burning. Typically the ventilation to a fire (that is, the size and number of doors and windows) is the factor which most strongly controls the type of burning (that is, flaming, smoldering or flashover) and thus the toxic gases present in the fire atmosphere^{6,7}. Two studies have been carried out in which leading research organizations equipped fire fighters with devices to obtain samples of smoke from actual fires for laboratory analysis: the Harvard University School of Public Health (with the Boston Fire Department) in 1979⁸ and the Southwest Research Institute (with the San Antonio Fire Department) in 1981⁹. Both studies concluded that the most hazardous air contaminants in real fires were carbon monoxide and acrolein.

Carbon Monoxide

Carbon monoxide (CO) is present in all fires and, because of its abundance, CO is universally recognized as the greatest toxic hazard in real fires¹⁰⁻¹². Many studies have been carried out on the effects of CO on

man and of its toxicity in and out of fires. They all show that CO is toxic due to its fast (200 times faster than oxygen) reaction with hemoglobin in blood to form carboxyhemoglobin (COHb)^{13,14}. This leads to lack of oxygen, resulting in a feeling of drowsiness (narcosis) and eventually in death. The hazard of CO is particularly enhanced by the fact that it is a colorless and odorless gas which provides no warning of its presence. Furthermore, relatively low levels of CO are encountered in all smoky atmospheres (a bar, for example) and they produce no immediate symptoms of toxicity.

The amount of CO which is lethal depends on the age, general health (particularly the presence of heart disease) and on the level of activity of the person involved, as well as on other factors such as the presence of alcohol or the existence of thermal injury. The lethal dose of CO in the atmosphere is estimated to be 138,000 ppm min (that is 4,600 ppm for a 30 min exposure)¹⁵. A level of COHb in blood lower than 20% will not lead to death, but any level above this can be lethal¹². CO is the most dangerous combustion product present in a fire atmosphere.

Carbon Dioxide CTL028693

Carbon dioxide (CO₂) is also present in all fires¹. It is generally considered to be non-

toxic, but it will, however, increase breathing rates so that it may allow higher concentrations of other, more toxic, gases to be breathed in than would normally be the case¹⁵. Furthermore, it will displace equal amounts of oxygen. Therefore, CO₂ also is dangerous in a fire.

Acrolein

Acrolein is an extremely irritating gas which results mainly from the combustion of wood, cotton or paper (cellulosics), although some other materials such as polyethylene, polystyrene and oils and fats may also produce it⁸. Acrolein is frequently present in a fire^{8,9} and is detectable owing to its odor (odor detection level of 0.2 ppm¹⁶). The NIOSH Registry of Toxic Effects¹⁷ lists 153 ppm as the dose lethal to man in 10 min (1530 ppm min). The original reference for this entry states "a concentration of 0.35 mg per liter is lethal on 10 minutes' exposure"¹⁸. It is difficult, however, to attach any confidence to this statement because there is no associated data or information. Kaplan et al. have studied the effects of 5 min exposures of baboons to acrolein¹⁹. No deaths occurred for exposures of less than 1025 ppm. These data show that the lethal dose for acrolein is between 2525 and 5125 ppm min. Acrolein is thus one of the most dangerous gases present in a fire.

Hydrogen Chloride

Hydrogen chloride (HCl) is an irritating gas which results from the combustion of vinyl and from that of many other flame-retarded materials. It is generally best known as "stomach acid." It dissolves readily in water and it is also eliminated from the atmosphere (air) by virtually all common construction materials (dry-wall, cement, paint, ceiling tile, wood, metal and others)²⁰. It has a sharp, pungent odor (similar to ammonia) which is detectable at very low concentrations (odor detection level 0.8 ppm¹⁶).

Recent studies by the Federal Aviation Administration and by the Southwest Research Institute have shown that baboons are not incapacitated after exposure to levels of up to 30,000 ppm of HCl (3% in air) for 5 min^{19,21}. Additional research conducted by the Vinyl Institute on baboons at the Southwest Research Institute has shown that baboons exposed to 5,000 ppm of HCl (0.5% in air) for 15 min have received no long-term lung function effects. Furthermore only minimal long-term effects on lung function were observed after exposures to 10,000 ppm for 15 min. This means that the lethal dose of HCl is above 150,000 ppm min, and that exceedingly high levels of HCl are required to cause incapacitation or death. In the

Harvard University study of over 200 real fires in Boston, the maximum level of HCl found was 280 ppm⁸, while in the Southwest Research Institute study of real fires in San Antonio, the maximum level of HCl found was 232 ppm⁹. This indicates that the concentrations of HCl found in real fires are much lower than those which could generate fire deaths.

Combustion Products of Vinyl

Burning vinyl (PVC) produces numerous by-products, many of which are exactly the same as those produced by wood or by most other common organic, natural or synthetic materials^{1,3,5}. Carbon dioxide, carbon monoxide and hydrogen chloride account for 97% of the total volume of gases produced by burning vinyl. The remaining 3% consists of benzene and of an assortment of other gases, the composition of which is similar to that of wood smoke²².

Neither chlorine nor phosgene are combustion products of vinyl. The National Bureau of Standards investigated this problem and found that only traces of phosgene were produced from vinyl wire insulation by any of three methods: thermal decomposition in a red-hot furnace, flaming combustion and electrical overload²³. However, the application of a 10,000 volt arc to a chamber overloaded with vinyl did generate some phosgene (an average of 26 ppm). This is of no consequence in terms of hazard because, at the same time, such an arc will generate, on its own (even without any wire insulation), 15,000 to 30,000 ppm of the toxic gas nitrogen dioxide²⁴. This level of toxic gas is 100–200 times more hazardous than the phosgene and will not permit human survival.

Thermal decomposition of vinyl can, under certain conditions, generate trace amounts of vinyl chloride monomer (VCM)²⁵, but a flame environment will destroy it completely during combustion. VCM can be formed at temperatures above 527°F, with maximum levels of 15–30 ppm (compared to 6,000 ppm required to produce dizziness²⁶) at temperatures between 617 and 842°F, and is destroyed at higher temperatures. The critical temperature for human survival in a fire environment is 150°F for 1 min²⁷.

Conclusions

In conclusion, the typical combustion products of vinyl, that is carbon dioxide, carbon monoxide and hydrogen chloride, are either common to all organic materials (CO and CO₂) or of very limited hazard in a fire (HCl). Although there have recently been claims that hydrogen chloride incapacitates people

in a fire by "knocking victims down" and making escape impossible, such claims are inaccurate and are totally unsupported by laboratory testing or real fire experience. In fact, the Federal Aviation Administration has recently stated that "ultraconservative guesses" proposed for incapacitation by HCl hindered their research by forcing them to expose animals to concentrations 50–100 times lower than those which were eventually found not to be incapacitating²⁸. It is clear, therefore, that vinyl is at least as safe as most other materials in a fire.

References

1. C.F. Cullis and M.M. Hirschler, "The Combustion of Organic Polymers," Oxford University Press, Oxford, 1981.
2. H.L. Kaplan, A.F. Grand and G.E. Hartzell, "Combustion Toxicology," Technomic, Lancaster, PA, 1983.
3. N.W. Hurst and T.A. Jones, "A Review of Products from Heated Coal, Wood and PVC," *Fire Mats* 2, 1 (1985).
4. P.J. Fardell, J.M. Baldwin, J.V. Murrell and S.P. Rogers, "Chemical Fingerprints of Fire Atmospheres. Some Results from Full-Scale Fires in a Compartment/Corridor Rig," *Fire Research Station BRE Note N 12/81* (1981).
5. P.J. Fardell and Z.W. Rogowski, "Report of the Performance of the Pittsburgh/Alarie Combustion Model," *Fire Research Station, BRE CR21/85* (1985).
6. D. Drysdale, "An Introduction to Fire Dynamics," Wiley, Chichester, 1985.
7. P.H. Thomas, "Fire Modeling and Fire Behavior in Rooms," 18th Symp. (Int.) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 503, 1981.
8. W.A. Burgess, R.D. Treitman and A. Gold, "Air Contaminants in Structural Firefighting," Harvard School of Public Health, NFPCA Grant 7X008, 1979.
9. A.F. Grand, H.L. Kaplan and G.H. Lee, "Investigation of Combustion Atmospheres in Real Fires," Southwest Research Institute, USFA Grant 80027, SwRI Project 01-6067, 1981.
10. M.M. Birky, B.M. Halpin, Y.H. Caplan, R.S. Fisher, J.M. McAllister and A.M. Dixon, "Fire Fatality Study," *Fire Mats* 3, 211 (1979).
11. R.A. Anderson, P. Willetts, K.N. Cheng and W.A. Harland, "Fire Deaths in the United Kingdom 1976-82," *Fire Mats*, 7, 67 (1983).
12. G.L. Nelson, D.V. Canfield and J.B. Larsen, "Carbon Monoxide - Study of Toxicity in Man," 11th Int. Conf. on Fire Safety, San Francisco, CA 13-17 Jan., 1986.
13. R.D. Stewart, J.E. Peterson, E.D. Baretta, H.C. Dodd and A.A. Herrmann, "Experimental Human Exposure to Carbon Monoxide," *Arch. Environ. Hlth* 34, 154 (1970).
14. D.A. Purser and W.D. Woolley, "Biological Studies of Combustion Atmospheres," *J. Fire Sci.* 1, 118 (1983).
15. B.C. Levin, "Toxicological Interactions of the Primary Gases Found in Fire Atmospheres," A.C.S. Symp. on "Fire and Toxicity. What's New?" Miami, FL, Apr. 29, 1985.
16. J.D. Amooore and E. Hautala, "Odor as an Aid to Chemical Safety: Odor Thresholds for Industrial Chemicals," *J. Appl. Toxicol.* 3, 272 (1983).
17. R.J. Lewis and R.L. Tatken (Eds.), "Registry of Toxic Effects of Chemical Substances," N.I.O.S.H., 1979 Edn, Vol. 1.1, p. 61, 1980.
18. A.M. Prentiss, "Chemicals in War" (1st Edn), McGraw-Hill, New York, 1937.
19. H.L. Kaplan, A.F. Grand, W.G. Switzer, D.S. Mitchell, W.R. Rogers and G.E. Hartzell, "Effects of Combustion Gases on Escape Performance of the Baboon and the Rat," *J. Fire Sci.* 3, 228 (1985).
20. C.A. Bertelo, W.F. Carroll, M.M. Hirschler and G.F. Smith, "Hydrogen Chloride Generation and Decay from the Thermal Decomposition of Poly(Vinyl Chloride) Wire Insulation," 11th Int. Conf. on Fire Safety, San Francisco, CA, 13-17 Jan., 1986.
21. G.E. Hartzell, S.C. Packham, A.F. Grand and W.G. Switzer, "Modeling of Toxicological Effects of Fire Gases: III Quantification of Post-Exposure Lethality of Rats from Exposure to HCl Atmospheres," *J. Fire Sci.* 3, 195 (1985).
22. M.M. O'Mara, "Combustion of PVC," *Pure Appl. Chem.* 49, 649 (1977).
23. J.E. Brown and M.M. Birky, "Phosgene in the Thermal Decomposition Products of Poly(Vinyl Chloride): Generation, Detection and Measurement," *J. Anal. Toxicol.* 4, 166 (1980).
24. E.M. Carlson, P.G. LeFevre and R.C. Williams, "Insidious Vapors. Infrared Determination of NO₂ Generated in a High-Voltage Electric Arc," *Anal. Chem.* 56, 1454A (1984).
25. I.B. Wakeman and H.R. Johnson, "Vinyl Chloride Formation from the Thermal Degradation of Poly(Vinyl Chloride)," *Poly. Eng. Sci.* 18, 404 (1978).
26. F.A. Patty (Ed.), "Industrial Hygiene and Toxicology," 2nd Edn, Wiley, New York, Vol. II, p. 1304, 1963.
27. A.E. Cote "Highlights of a Field Test of a Retrofit Sprinkler System," *Fire J.* (May) p. 93, 1983.
28. C.R. Crane, "Human Tolerance to Toxic Components of Smoke," *Proc. Cabin Safety Conf. Workshop, DOT/FAA/ASF 100-85/01*, p. 127, 1985.