LETTERS TO FORTUNE

International Barter

Writer John Dizard's point on the inefficiency of international barter is well taken ("The Explosion of International Barter," February 7). I tell my students that since the shoemaker wants bread more often than the baker wants shoes, in barter there is more often a want of coincidence than a coincidence of wants. The most infamous international barter incident was a swap that Hitler made, giving Yugoslavia aspirin for its copper. The Yugoslavs were left with carloads of aspirin, not one of which could solve the headache of how to get rid of them.

CHARLES COLLAZZO
Professor of Management, Northeastern University
Boston

We haven't begun to see the dimensions to which this form of international commerce will reach. It is not difficult to understand why. Given the high cost of financing international purchases, the Third World is starting to bypass lenders altogether by ignoring their money and offering goods in return. It is not inconceivable to imagine the day when the banks themselves, if they ever hope to recoup any of their huge international debt, will start accepting goods in payment.

The Third World has been squeezed dry, and it is now starting to squeeze back. Let's hope the developed nations are creative enough to accept the challenge and adapt to the ways in which world trade is changing.

ROBERT LINDER
Panagri Trading Corp.
Panama

Plastic Pipe

I am writing to express my disappointment and that of the other officers and employees of Allied Tube & Conduit Corp. in "The Dubious War on Plastic Pipe" (February 7). It failed even to attempt a balanced analysis of the serious issue of the toxicity of plastic materials.

FORTUNE need only have looked at its own files to learn that "the interiors of even fire-resistant structures are often veritable plastic bombs waiting to be ignited. When they are, clouds of toxic smoke—some of it invisible—are released, much denser and deadlier than smoke from natural substances" ("How to Manage Killer Smoke," January 26, 1981).

While you make much of the receipt by the Foundation for Fire Safety of grants from our company—something in which we take pride and have never concealed—you fail to inform your readers of the following comparable facts about the sources on whom you rely:

Dr. Irwin Benjamin, who is characterized in the article solely as "an eminent fire researcher and now a private consultant after many years at the Bureau of Standards," is a consultant for a major plastics manufacturer and has been proposed as a recipient of a research grant from the Society of the Plastics Industry.

Professor Irving Einhorn, described only as an adjunct professor at the University of Utah, has been affiliated with Springborn Laboratories, which has done substantial testing for a principal manufacturer of PVC, and has testified as a witness for Carlon at public hearings on toxicity.

The American Council on Science and Health, which you describe as a "consumer education group," is supported with contributions from at least three major plastics manufacturers and numerous other petrochemical companies that have a commercial stake in the issue.

You highlight the activities of Allied at the 1980 meeting of the National Fire Protection Association (NFPA) in opposing the efforts of plastics

"Despite the industry's attempts to intimidate Allied, we will continue our program."

manufacturers to include thin-walled PVC tubing in the National Electrical Code. But you omit any reference to the efforts of the plastics industry at that same meeting to actively lobby support for its position. Nor do you report the fact that the plastics industry appeal from the vote of the NFPA membership was rejected by the NFPA board of directors.

As for the views of firefighters, those on-the-line professionals who must deal with this problem daily, your article confines itself to the begrudging concession that, "conveniently for Allied, some professional firefighters have strong opinions against plastics and will state them publicly." Your notable failure to elaborate clearly reflects the "inconvenience" these views create for your argument.

The article's obvious prejudice carries over to your attempted portrayal of our company as a disingenuous purveyor of the same toxic material that we are seeking to combat. In doing so, you chose to ignore information repeatedly given to your reporter by me and other Allied officials. Among other omissions, you neglected to mention the warning notice we placed in the catalogue, which reads, "The PVC-coated items in this section are offered by Allied for these out-of-the-ordinary corrosive applications. PVC-COATED MATERIAL MUST BE USED WITH CAUTION! When smoldering or burning, PVC emits highly toxic hydrogen chloride gas (HCl). Even short-term exposure may be hazardous."

This article is particularly unfortunate not so much because it unfairly attacks Allied's motives, which it does, but because a magazine of FORTUNE's stature has fallen into the trap of contributing to the plastics industry's massive attempt to divert attention away from the real issue.

Despite the industry's attempts to intimidate Allied, we will continue our program of consideration of toxicity of building materials as a factor in code approval, and we will continue to help those who by experience and scientific background have knowledge of the fire-gas toxicity of plastics to speak out on this issue.

JOHN M. LISON
Vice President and General Counsel
Allied Tube & Conduit Corp.
Harvey, Illinois

The quotation attributed to me was taken out of context and is misleading. My point is simply this: the potential toxic hazard of a material depends on the specific fire situation in which it is involved and on additional factors. In many circumstances, the contribution of PVC conduit would be minimal. In some, it could be significant. Research on combustion toxicity at the Center for Fire Research is addressing the relative contribution of individual materials to the overall toxic hazards of fires.

JACK E. SNELL
Director, Center for Fire Research
National Bureau of Standards
U.S. Department of Commerce
Washington

"The Dubious War on Plastic Pipe" focused on Allied's campaign to portray PVC conduit as a major cause of fire deaths despite a lack of conclusive evidence that it is. The 1981 FORTUNE article, which dealt with ways of controlling smoke from all sources once a fire has begun, did not suggest that banning plastics in construction could reduce fire casualties. Dr. Benjamin and Professor Einhorn are recognized authorities in this area. Since leaving the government a year ago, Dr. Benjamin has done consulting work for Du Pont, but not on the PVC-conduit controversy. Professor Einhorn has done work for both the plastics industry and its opponents on matters of fire safety; the financing he has received from the plastics industry in the last five years has been minor. About 22% of the budget of the American Council on Science and Health is provided by plastics and petrochemical companies; the remainder comes from foundations and companies with no stake in the plastic pipe debate. At the 1980 NFPA meeting, Carlon, the leading maker of plastic conduit, bought no new voting memberships. Allied and others in the metals industry bought scores of new memberships, vot-

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ing these against the plastics industry position.

The quotation from Mr. Snell was checked with him for accuracy in the course of his interview with FORTUNE. *The quotation and its immediate context were subsequently checked with a spokesman for the Center for Fire Research authorized to speak for Mr. Snell. The spokesman said that the quotation in context accurately reflected Mr. Snell's views.*

**FORTUNE stands by its story.*

Representatives of the Foundation for Fire Safety have at various public forums challenged members of the plastics industry to enter a room of burning PVC while they enter a room of burning Douglas fir. The implication is that a wood fire is safe. Of course, this is completely false, as virtually any burning material, natural or synthetic, would emit carbon monoxide, a potent killer. You correctly quoted a government study as concluding that polyvinyl chloride and Douglas fir have similar combustion toxicity characteristics.

BUD HALL
Conoco Chemicals Co.
Houston

Foxy Little Lisa

My, my. That foxy little Lisa ("Apple's Bid to Stay in the Big Time," February 7). "She" sure sounds like a saucy wench. "Seductive," says writer Peter Nulty. "Disarming." Up to a "lady's tricks." It's a crying shame such a cutie had to be given a Neanderthal brow.

I'd be interested in knowing *why* Apple chose a woman's name for its new computer. Apple surely should have expected such cliché-ridden forays into the realm of insipid journalism. But I'd be even more interested in knowing how Nulty would have described this same computer had it been named Ralph.

Next time, FORTUNE, get a Lisa and use its mouse to put such writing in the garbage can, where it belongs.

LUANA HELLMANN HILL
Canby, Oregon

Beautiful Persons in Fur

It is obscene that people still get rich killing animals or selling their dead bodies ("The Fur Trade," February 7). Those who *wear* furs are no better.

I have never seen a truly "beautiful person" in a fur—except the original owner.

ED SIMPSON
South Pasadena, California

Burning Wood vs. Fission

Can FORTUNE really be so easily taken in by a myth promoted by the split-wood-not-atoms crowd: "Wood burning produced more heat than nuclear energy" (The Washington Connection, February 7)? This superficial comparison ignores a critical difference: wood is generally a simple heat source, and nuclear energy is converted to electricity.

About two-thirds of all electricity is used by the commercial/industrial sector and is critical to the national economy. On the other hand, the most efficient use for wood is not burning, but in pulp and paper and construction. Wood is an eminently energy-sensible construction material: a steel rafter requires seven times as much energy to make as a wood one; aluminum siding five times as much as plywood.

MARK P. MILLS
Vienna, Virginia

Firings and Stockholders

Professor Michael Levin missed a large and important point in his review of my new book, *Do It My Way Or You're Fired!* (Books and Ideas, February 7).

In every account I described of competent, conscientious employee objectors, the owners would have benefited if a manager had not answered the employee with a pink slip. A faulty new product would not have been launched, an illegal practice would have been nipped in the bud before becoming an operational tragedy, a neurotic dingbat in managerial clothing would have been exposed before doing more harm.

This is not a theoretical argument. Every company that has instituted a due process procedure for resolving boss-subordinate conflicts—from Bank of America to Pitney Bowes—will testify to its practical values. What is more, the direct costs of corporate due process are peanuts. I can think of at least two companies now tied up in the courts by employee objectors that could have paid several times over for the cost of due process by avoiding the litigation.

DAVID W. EWING
Managing Editor, Harvard Business Review
Boston

Mind-Probe Logic

Writer Walter Kiechel's scathing indictment of the psychological testing industry, "The Managerial Mind Probe" (Office Hours, February 7), was premised on some very faulty logic. To insinuate that, because some tests are invalid, all tests are is as ridiculous as asserting that since some medicines are ineffective, all medicines are ineffective.

HERBERT M. GREENBERG
President, Personality Dynamics Inc.
Princeton, New Jersey

Buoyant Transportation Ideas

"Calling All Cars" (Keeping Up, February 7) reminds me of an equally good idea—one I proposed to the Air Force when I was a flight instructor:

Fire Hazards of Plastics Spark Heated Debate

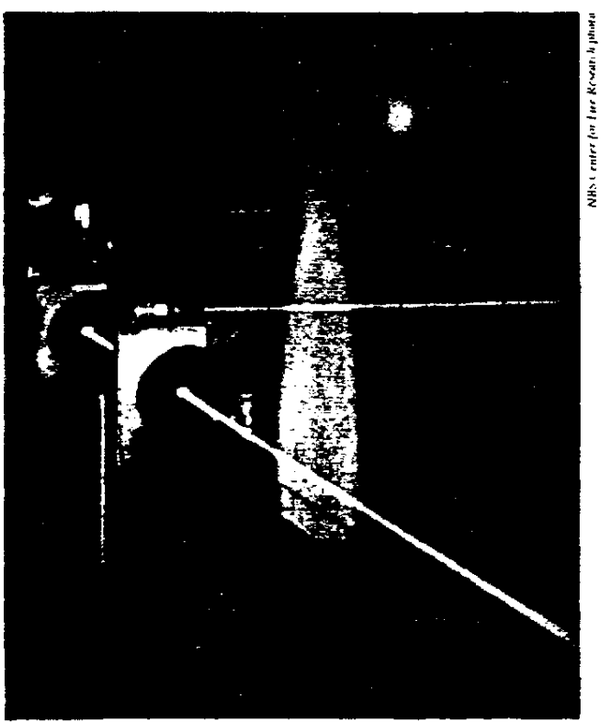
Researchers are studying the effects of toxic gases produced in fires by the combustion of plastics and other synthetic materials

Rebecca L. Rawls, C&EN Washington

Americans are afraid of fires. And with good reason. If trends continue, some 7500 people will die in fires in the U.S. this year, and four times that number will be injured. That's a fire death rate per capita that is almost twice the international average, and one that is surpassed by only one other country—Canada. And as for fire incidence, the U.S. rate per capita is the highest in the world.

The fires Americans seem most afraid of are those in public buildings like hotels, night clubs, and even jails, where a single incident can lead to scores of deaths. Although these public fires focus attention on fire hazards, by far the largest number of fire deaths in the U.S. occur in homes.

On average, about 25 people per day in the U.S. die in fires. But when 119 people died between November 1980 and May 1981 in three highly publicized hotel fires in the U.S. and, more recently, 27 died in one incident in the Harrison County Jail in Mississippi, public concern quickly focuses on the problems of fire safety. And that is when legislators and other public officials are called upon to do something about fire risks.



NBS Center for Fire Research photo

A laminar hydrocarbon flame is probed by a laser at the Center for Fire Research in a study to determine what chemical species are formed

In a real sense, these deaths, more than the thousands of other fire deaths during the same period, have led several state legislatures and a number of national bodies concerned with fire safety issues to begin a major reexamination of what happens to people in fires and what can be done to prevent deaths and injuries. This examination already has stirred up controversies and is raising serious questions about available methods for assessing fire risks and damage. Eventually, researchers expect that sophisticated computer-based models will improve matters considerably and perhaps lay to rest many disagreements.

Meanwhile, the current examination focuses largely on the effects of toxic gases produced when buildings burn. According to the Center for Fire Research, the federal government's principal organization for conducting research in laboratories on fires, and a part of the National Bureau of Standards, 80% of fire deaths are due to the inhalation of smoke or hot gases and are not the result of burns. Furthermore, the character of smoke seems to have changed in recent years. As the U.S. National Fire Protection Association's recent report on the toxicity of combustion products points out, fire fighters are reporting that fires appear

to develop faster now than in years past and that smoke apparently develops more rapidly and is more obscuring and more irritating to the respiratory tract than it used to be. "There appears to be an increase in fire fighter casualties from smoke inhalation," the report states. "The smoke in today's fires . . . may be producing increased risk of inhalation injury to fire fighters as well as to building occupants."

In the Mississippi jail fire late last year, the fire itself was confined to one room containing only one person who was not seriously injured. Yet 27 people were killed in the fire and 61 others injured, almost all from inhalation of gases and smoke. Toxic gases spread from the burning cell to others through the jail's ventilation system. Gases caused the jailer to lose consciousness before he could unlock some of the occupied cells, thereby trapping many of the inmates who died.

A jail, of course, is not a typical building; it is intended to be difficult to leave. But this pattern of toxic gases traveling through ventilation systems and by other routes to areas far from the actual fire, there to trap and kill people, is a common one in building fires. When the MGM Grand Hotel burned in Las Vegas on Nov. 21, 1980, for example, 85 people died—three from burns, one from a skull fracture when a portion of the building collapsed, and the rest from inhalation of smoke and toxic gases. Sixty-one of the victims were in a different part of the hotel from the fire, most of them 20 stories or more away from the fire itself.

Whether it is the increased use of plastics in buildings and furnishings that is changing the character of combustion products and causing many of these fire deaths is at the heart of much of the current examination of the causes of fire deaths.

There is little question that the amount of plastics used in buildings is rising rapidly. In the mid-1960s plastics represented only 2% of total building materials consumed, according to Predicasts, a Cleveland-based market research firm. By 1981 plastics' share of the building material market was 10%, or 6.5 billion lb valued at $5.7 billion. And gains may be even more rapid through the rest of the 1980s because of increasing cost differences between plastics and metals, the materials plastics most often replace in buildings.

One of the leading voices contending that this increased use of plastics bears a large part of the blame for the lethal gases produced in modern building fires is that of the Foundation for Fire Safety, an Arlington, Va.-based organization headed by Gordon F. Vickery, former head of the U.S. Fire Administration and a former Seattle fire chief.

"When materials burn, they release certain toxic gases," states a recent publication of the foundation. "Almost any material, man-made or natural, will give off carbon monoxide. But synthetic materials, namely plastics, burn twice as fast, twice as hot, and can give off up to 500 times as much toxic gases as more conventional materials."

These are fighting words, and one of the most persistent groups to fight them, not surprisingly, is the Society of the Plastics Industry, that industry's main trade association. "The metal electrical conduit industry has embarked on a 'fear and smear' campaign against plastics products in order to improve its position in the marketplace," SPI claims in a recent news release. This campaign is "based on a total distortion of scientific fact," says SPI. "The metal conduit industry would have the public believe that toxic gases in a fire didn't exist before plastics; that is patently ridiculous," says SPI spokesman E. S. Nuspliger. "As long as 50 years ago, fire journals were lamenting the high number of fatalities from smoke and toxic gases."

"We feel that plastics, where properly used, do not present any increased hazard in the fire environment," sums up John R. Lawrence, the society's technical director.

If SPI can be regarded as the spokesman for plastics makers in this dispute, many would consider the Foundation for Fire Safety to be the spokesman for steel pipe and metal conduit forces. Indeed, the organization,

NBS Center for Fire Research photos

Full-scale tests of how rooms burn, like this one conducted at the National Bureau of Standards' Center for Fire Research in Gaithersburg, Md., dramatically illustrate the hazards of fires in buildings. In this time sequence, smoke and gases accumulate near the ceiling of a mock living room until the gases become hot enough to burn themselves. This phenomenon, called flashover, makes the fire spread furiously to all combustible objects in the room. This entire sequence took place in less than three minutes (see clock in foreground). In a real fire, the room's occupants would have only that amount of time to escape

which considers itself a private, nonprofit research and educational foundation, receives almost all its funding from the steel pipe and conduit industries. "We have tried to get more balance in our funding sources by getting the plastics people to fund some of our research, but so far they haven't seemed interested," says Merritt M. Birky, former head of the Center for Fire Research's program for toxicology of combustion products and current director of research for the Foundation for Fire Safety. Despite the heavy funding from an industry that competes with plastics in the building trades, Birky says the foundation has been able to maintain its independence and chart its own course of action. "On the one hand, we think it is commendable for the steel people to support this kind of research," Birky says, "but we do realize that they have an economic interest in it."

Indeed they do. Pipes and fittings have been the fastest growth area for plastics in U.S. building construction, rising from an annual use of 230 million lb in the mid-1960s to 2.27 billion lb in 1981. Another 738 million lb of plastics go into electrical applications, including use as an alternative for metal electrical conduits.

One of the strongest arguments of those who think plastics are not increasing fire hazards is that fire deaths have been decreasing steadily in the U.S., probably since World War II, despite increased use of plastics in buildings. Methods of counting such deaths have changed over the period, so trends are difficult to pin down, explains Frederic B. Clarke, a private consultant on fire safety issues and former director of the Center for Fire Research at the National Bureau of Standards. However, using adjusted figures, total fire deaths in the U.S. have fallen in the past decade from about 9000 in 1971 to 7600 in 1981. On a per capita basis the drop is even more dramatic—a 25% decrease from 44 deaths per million population in 1971 to 33 per million in 1981.

"There has definitely been a big shift in the fuels present in buildings over this period," Clarke says, referring to the kinds of combustible materials present in a building, so that "if there were a direct correspondence between plastics use and toxic gases, you'd expect to see a big increase in fire deaths, but you don't."

Not everyone agrees that the falling fire death rate necessarily means that plastics are not increasing fire hazards in buildings. "We really have no statistics on whether the risk in building fires is increasing," says Yves Alarie, professor of respiratory physiology and toxicology at the University of Pittsburgh's school of public health and a leading researcher in the area of fire toxicity. The buildings that are burned down now are the old ones, he says, and we will have to wait 10 to 20 years before any change in fire hazard associated with greater use of plastics will start to show up in fire death statistics.

Clarke, however, disagrees. "The causes of fires are far more related to the things that are brought into buildings—like lighted cigarettes—than to the buildings themselves," he says. "The age of the building has nothing to do with it."

Another claim that is often made by supporters of plastics use, and contested by those who oppose them, is that by far the most important toxic gas in fires is carbon monoxide, which is produced in large amounts by any burning organic material, including wood and other natural products. Among the evidence cited to support this claim are a pair of studies sponsored by the U.S. Fire Administration and SPI in which firefighters carried gas sampling equipment into real fires to find out what gases were present.

The first study, conducted by Harvard's school of public health and published in 1979, examined the gases produced when older, multistory dwellings burned in the city of Boston. The second study, done by Southwest Research Institute in 1981, looked at the fire products of more modern, single-story, single-family houses in San Antonio. "The results of [both studies] are consistent with the universal view that carbon monoxide is the most prevalent and potentially toxic combustion product in fire environments," says the San Antonio study.

"Firefighters may encounter atmospheres in which carbon monoxide is present in sufficient quantities to incapacitate and cause death within a few minutes. More frequently, they are likely to be exposed to carbon monoxide concentrations below these levels but sufficient to produce toxic effects that may markedly impair their performance and, possibly, disable them. Even the lower concentrations of this gas, which were detected in the majority of the fire samples, will diminish the supply of oxygen to the brain, and, possibly, disorient the individual and compromise his performance and safety," the study concludes.

Other toxic gases, also commonly found in fires, include acrolein, hydrogen cyanide, and hydrogen chloride. These gases can be produced by certain natural materials, but hydrogen cyanide and hydrogen chloride, in particular, are produced much more abundantly by many synthetic polymers than by wood.

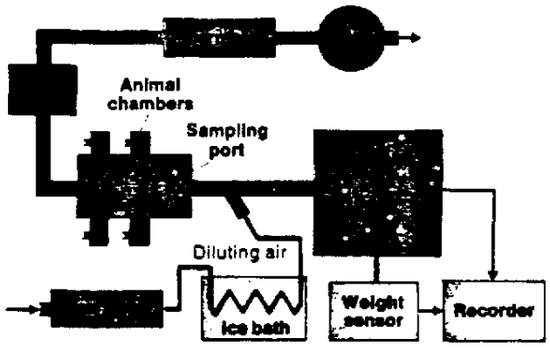
Determining which gases actually are responsible for deaths in fires requires finding out what gases have been inhaled by fire victims. Several studies of this type have been done, including several by the Foundation for Fire Safety's Birky. "It's correct that almost all fire victims in the past few years have had elevated carboxyhemoglobin levels in their blood [an indication that they have inhaled carbon monoxide], but that does not explain all fire deaths," Birky says. He estimates that carbon monoxide poisoning can account for no more than 50% of these fire deaths. Blood hydrogen cyanide levels are often high, too, he says, and hydrogen chloride also may be a contributing factor in fire fatalities, although its role is harder to document because of its natural presence in the body.

Birky cites a study he conducted of the victims of a fire at the West Chase Hilton Hotel in Houston on March 6, 1982. All 10 of the people who died during the fire had elevated but sublethal blood levels of carboxyhemoglobin, he finds. All 10 victims also had elevated blood cyanide levels and in two cases the levels were high enough to have been responsible, by themselves, for death. In addition, the 10 who died in the fire and two who died afterwards all had severe respiratory tract damage, which Birky says was consistent with exposure to hydrogen chloride. The hydrogen cyanide, he says, came from flexible polyurethane carpet padding, nylon carpet and blankets, and a flexible polyurethane cushion found on an upholstered chair. The hydrogen chloride, he says, came from a polyvinyl chloride wall covering.

"Based on the findings of this study, it is doubtful that carbon monoxide and the obstructive nature of soot alone were the causes of the deaths in the rooms that had little evidence of soot deposits," Birky says. "It must be concluded that hydrogen cyanide and hydrogen chloride contributed to most, if not all, of these deaths. Synthetics in the fire room produced these two deadly gases during combustion, contributing to the ultimate deaths of 12 persons."

As is often the case, SPI's Lawrence views things differently: "There were a lot of synthetic materials in the room where the fire occurred, but there were a lot of burnable nonplastics, too," he says. The medical examiner found carbon monoxide poisoning the cause of death in every case except for the people in one room, who had lethal blood levels of hydrogen cyanide, says Lawrence. However, it takes very careful handling of blood after death to get an accurate measurement of the hydrogen cyanide present when the person died, Lawrence points out, because the body itself will produce a certain amount of hydrogen cyanide.

Test method carefully controls animal exposure to combustion gases



In the University of Pittsburgh method for measuring toxicity of combustion gases, four mice can be exposed to gases flowing past them from a furnace where the sample material is burned. Other test methods involve placing the furnace underneath the exposure chamber to allow the gases to flow upward, and burning the sample material in a flame rather than a furnace. Each method duplicates some of the conditions found in real fires; the differences reflect which fire conditions are thought to be the most life threatening

To make the question still more complicated, it is worth considering whether, if the cyanide had not been present, the people would have lived, says Richard G. Gann, who heads the fire measurement and research division at the Center for Fire Research. "There is no good basis for saying that just because people died from a specific cause in a fire that they would not have died anyway," he says. "We need to find out when a particular measureable factor is the cause of toxicity," and fight the real hazard. It may be, he suggests, that increased use of plastics in buildings is making bad fires worse—even a lot worse.

It is not only the combustion products of plastics that cause worry, but that some of them burn much faster and hotter than wood and other natural materials. Most of the heats of combustion of synthetic polymers are much higher than those for natural materials, Birky says. The heats of combustion of polyurethane, polystyrene, and polyethylene, for example, are similar to that of No. 1 fuel oil, he points out. "That means that once those materials are ignited, the heat produced is going to be much higher [than from wood]. The fire will develop faster and there will be less time to escape."

Many plastics, however, don't have very high heats of combustion compared to wood. But other factors, such as ignition temperature, are also important in deter-

mining how a material will contribute to the growth and spread of a fire, Lawrence says. Polyvinyl chloride has largely replaced cotton as an insulating material for electrical wires, in part because its higher ignition temperature makes it less likely to burn. "We think that's an example of increased fire safety from using plastics," Lawrence says.

"A lot depends on how materials are used," he continues. "When properly used, plastics do not constitute an unusual hazard."

The connection between the fire safety issue and the inroads of plastics into markets that were once held by conventional materials came up in recent debates in the California legislature. That state, along with New York, has passed legislation calling for an investigation of existing methods to test the toxicity of combustion products with an eye toward changing the state's building codes to exclude particularly hazardous materials from use in buildings if such materials can be identified.

The California legislation, passed in August 1982, evolved from an earlier battle in that legislature over whether use of polyvinyl chloride pipe in buildings should be restricted because of possible risk to occupants of cancer caused by substances leaching from the pipe or from the adhesives used to connect pipe segments. A coalition of metal pipe manufacturers and a plumbers' union worked for several years, without success, to restrict the use of plastic pipes in buildings on this basis.

"When the metal-pipe people realized that they were not winning on the carcinogen issue, they brought up the flammability question, but they were only interested in the flammability of [plastic] pipes," says one California state official who has watched the debate in the state legislature. The legislature, under pressure from the plastics industry, expanded its study to consider the combustion toxicity of all materials that are used in high-density occupancy buildings.

Focusing on the fire hazards of pipes may not be so parochial as it seems at first glance. "Plastic pipes burn; metal pipes don't," says Pittsburgh's Alarie. Because of stringent codes, most public buildings are made largely of noncombustible materials like concrete, glass, and metal. Thus, the major fire hazard is not the structure itself, but its furnishings and what Alarie calls the services of the building: its plumbing, electrical wiring, and air conditioning. "Whenever a combustible material is used to replace a noncombustible one, we need to ask an awful lot of questions," Alarie says. "We are raising the fuel load everywhere in our buildings, and the fire implications of that can be tremendous."

The California study, set to get under way this week, has two parts. The state's department of industrial relations will assess the test methods currently available to measure combustion toxicity and "adopt or adapt the most appropriate existing test method to rate the relative toxicity of all materials intended for use in or as part of high-density occupancy buildings." These tests are expected to measure not only the lethality of a material but also the time it takes to cause death. Meanwhile, the state fire marshal's office will assess tests of combustibility and adopt or adapt the most appropriate existing test methods to rate materials on their ignitability, flame spread, rate of heat release, and rate and extent of smoke generation. "It is the intent of the legislature that the tests adopted . . . be used to ultimately develop a hazard rating index," the resolution says.

Lawrence: no increased hazard from plastics

Though most observers praise the intent of the California legislation, many critics question whether the proposed study is likely to turn up anything useful. For one thing, no money was allocated for the project. For

Birky: hydrogen cyanide a factor in fatalities

another, the department of industrial relations has no experience with combustion studies, although it has done toxicological testing in occupational settings. Another difficulty is that the two studies are to be completed by April 30, which is considered by some critics too soon to do a thorough study.

The legislature's demands may be "unrealistic to a degree," admits California fire marshal Philip Favro, whose own position may change with the new administration. However, he thinks it possible in four months to determine what tests have been developed and whether any are ready to serve as the basis of a combustibility hazard rating. And he supports the concept of trying to set up a performance index of materials based on both their combustibility and the toxicity of their combustion products.

"I feel that to look at toxicity in isolation is naive," he says, citing as an example polytetrafluoroethylene, more commonly known by its tradename, Teflon. "In some tests, this material is highly toxic when it burns, but it won't burn under ordinary conditions . . . Our feeling is that the real problem with synthetic materials is their ability to burn rapidly. Perhaps in an infrastructure that includes flame-retardant systems, sprinklers, smoke detectors, and other devices, they can be used safely." But, he adds, "any of these judgments are premature until we get a real rating of hazard.

"I'm not confident that we'll be able to solve anything by April," Favro says, "but this is a question that needs a good airing, and what we are doing gets it out of the closet."

Another airing is taking place in New York, where the state legislature has called for an outside evaluation of available test methods to determine the toxicity of various materials under heat conditions. The New York study will look at the gaseous products of materials at different temperatures including just below the ignition temperature (when pyrolysis, rather than combustion, products are given off) and just above ignition. The study is to review existing test methods, recommend improvements that can be made in them, develop a scale for rating the combustion hazard of materials based on the tests, and recommend additions to the state's building code on the basis of what toxicity tests can show.

The contract for the New York study has been awarded to Arthur D. Little Inc., a Cambridge, Mass., research firm. The principal investigator is Rosalind C. Anderson, a former associate of Alarie's at the University of Pittsburgh. Data from a literature search and an indication of the feasibility of developing a rating scale are expected in an interim report around Feb. 1. The entire report is scheduled to be completed by May 31, and the secretary of state is to report back to the legislature concerning possible changes in the building code by June 30.

Clearly, legislators in New York and California are hopeful that existing tests can identify the materials that pose the most serious hazards in building fires. But a number of scientists doubt whether this is the case.

For example, in a study for SPI published last summer, Southwest Research Institute reviewed the state-of-the-art of combustion toxicology testing. "Materials

Alarie: plastic pipes burn; metal pipes don't

should not be regulated on the basis of data from laboratory smoke toxicity tests," the study concludes, in part because "fire technologists and toxicologists do not yet know how to incorporate data from smoke toxicity tests into a hazard assessment." But there are other problems, too, such as variations in test results from lab to lab and even within the same lab. These variations can produce significantly different orders in rank among materials, the study says. "Even gross differences in smoke toxicity should be interpreted with caution, since other flammability properties are involved in assessing hazard."

Available laboratory toxicity tests can serve useful purposes, the study suggests. They can, for example, be of value to producers developing new products by suggesting potential toxicity problems. "Some investigators have identified a few materials producing smoke claimed to be 'unusually toxic' in comparison with most other materials. Such a finding does, indeed, place a burden on the manufacturer to further assess hazard," the Southwest Research Institute report says.

Gann, of the Center for Fire Research, basically agrees with the study's conclusions. He thinks that it's premature for states to regulate materials use based on the combustion toxicity tests now available. There's an "outside chance that they may be able to screen out bad actors" with current test procedures, he says, but current tests may be putting materials through conditions that they never would encounter in a real fire.

Animal test procedures also have been developing at the same time that fire science has, he explains, so that combustion toxicity tests are based on assumptions about the nature of fires that now are known to be not really correct. Several newer test methods have been developed, including one by researchers at the Center for Fire Research, based on what the developers expect the

Gann: are plastics making bad fires even worse?

life-threatening fire situation to be. But their choices were made before science could determine what the real health threats in fires are. In some respects, Gann says, we still do not know what fire conditions need to be duplicated to produce a meaningful test.

Though it may be possible to design tests now that can provide useful information about the risks of using certain materials in particular situations, Clarke suggests, it is not possible to take existing tests designed for other purposes and apply them broadly to assess fire hazards under many different conditions. This is what he thinks California is trying to do.

Snell: existing fire tests have deficiencies

The combustion toxicity test developed at the Center for Fire Research was intended as a screening test to be applied to plastics during their development. "We were concerned," says Clarke, "that some new materials might be unexpectedly toxic even against the background of carbon monoxide and other things that were already present in fires and toxic." The test method they came up with was published last June, and it is one of a half dozen or so that California and New York will be examining.

Though researchers at the Center for Fire Research are proud of their test method, it is not ideal in several ways. For one thing, the method of exposure used in the test—samples of material are burned in a furnace and the combustion gases diffuse into the test chamber—is not that of a real fire, explains center director Jack E. Snell. The test evaluates materials one at a time, so that synergistic effects, which do exist, are not taken into account. And the test can turn up hazards that would not be present in a real fire; whether the test also misses some real fire hazards has yet to be determined. Finally, the center's tests, and all of the others currently available, are animal tests. "We need good models of incapacitation and of human response to irritants present in fires," Snell says. "It's very unlikely we'll get this information from tests on mice or rats."

Alarie, who has developed another animal test for the toxicity of combustion products, thinks the tests are ready to be used carefully to regulate materials used in buildings. "There's no question that the existing tests can separate materials on the basis of their toxicity," he says. "We're not going to regulate materials on the basis of small differences in test results—that would be stupid—but we can use the tests to look for materials that are tremendously more hazardous."

But even the tremendously more hazardous materials don't always perform the same way when test conditions are changed slightly. For example, when the Center for Fire Research evaluated its method, it ran tests on 12 materials, some synthetic and some natural. Toxicity ratings for 11 of the materials generally grouped together, Gann explains, but one material, polytetrafluoroethylene, came out 1000 times more toxic than the others. Alarie also tested polytetrafluoroethylene in his test, and here, too, its combustion products were much more toxic than those of most other materials. However, when Clarke and Du Pont toxicologist Stephen J. Williams retested the polymer using flame rather than a furnace to heat the sample, its toxicity value dropped back into the range common for other tested materials. Alarie also retested the material in his system using a flame, but he got the same high value he found when the sample was heated in a furnace.

Such discrepancies "cut to some very fundamental issues in toxicity testing," Gann says. If relatively slight changes in the way samples are tested make such large differences in test results, and particularly if they make those differences only in some tests and not in others, then "there's an awful lot that still needs to be figured out to know what's going on," he says.

Several explanations have been suggested for the test discrepancies. Alarie thinks the flame used by Clarke

and Williams was much hotter than the one he uses or than the furnace temperatures used in his test and the Center for Fire Research's. Higher temperature would mean more complete oxidation of the sample and would bypass formation of intermediate combustion products including short-chain fluorinated hydrocarbons, some of which might be highly toxic. But Clarke says the temperature of his flame was the same as that of the furnace in the Center for Fire Research test. He thinks that polytetrafluoroethylene is a fairly unusual polymer in that it contains no hydrogen atoms. When it is burned alone, as in a furnace, it produces highly toxic by-products; but when it burns along with other materials that can supply hydrogen to the combustion mixture, as in a flame, further reactions occur and the highly toxic products are not formed.

"This is the first case we've seen where a relatively small change in test conditions makes a big difference in results," Clarke says. "The real concern is, what if there are materials in which the change goes the other way?"

Although researchers may disagree about just how useful current combustion toxicity tests are, they do agree about what needs to be done to really understand the hazards of fires in buildings and to control them. "What I'd like to see is a system that would take account of all the properties of fires and interrelate them so that I could tell you whether a particular material would be more hazardous than another material," Clarke says. Such a system would involve sophisticated modeling of fire situations and not fixed codes of the sort now used in regulation. Many researchers think it will take some time to win over regulators to such an approach to fire safety, even when the system exists.

Research to build such models is already well under way. Some of the more optimistic—like the Center for Fire Research's Gann—predict useful models that take into account not just combustion toxicity but other important properties of fires will be developed in three to five years.

The current test methods are, in a sense, a form of modeling, says James Quintiere, head of fire modeling at the center. They are based on their developer's idea of which aspects of a fire are particularly important. What needs to be done now is to incorporate more key variables into models, on the one hand, and to find out which fire variables are really the life threatening ones, on the other.

Research into the mathematical modeling of fires is helping to do both of these things, says Howard W. Emmons, professor of engineering at Harvard. Not only do present models begin to pull together different aspects of a fire so that the problem can be considered as a whole, but the models also point to key data that are missing and suggest how to conduct experiments to get the data.

Emmons and Quintiere are two of about a half dozen researchers worldwide who are trying to develop large-scale, compartmental models of what happens in a whole building as it burns. Many others are using modeling to look at particular components of a building fire—flame spread along a vertical wall, for example. But

Quintiere: modeling the burning of a building

it is these compartmental models that address the question of combustion toxicity most directly.

Emmons, for example, has developed a computer model of a hypothetical building. In the model, he can start a fire in one of the building's rooms and follow how heat and combustion gases will flow from that room through the rest of the building. So far, the model considers only movement caused by convection from the fire and not the effect of the building's ventilation system on gas and heat movement. But the model begins to look at where potentially dangerous gases will be found when a building burns.

Such a model cannot determine whether the nature of the burning materials makes a difference in the amount and toxicity of the gases produced, Quintiere points out, but the model does re-emphasize the need for better data on these points.

However long it takes to achieve, the picture Emmons paints of what models one day will do is a very attractive one. Someday, Emmons says, an architect will take the plan for a new building to a city's computer, which mathematically will burn the building down perhaps a dozen times or more, each time under different circumstances—fires starting in different rooms, critical doors opened or closed, and so forth. The model will predict when smoke detectors and other fire alarms will detect the fire, which parts of the building will become hazardous to occupants, how long escape routes will remain safe to travel in, and other factors key to the fire safety of the building. To do this, the computer will need to know not just what the building is made of, but how it is furnished. "The computer is not going to solve a problem, if there is one," Emmons says, "but it will find it and turn it back to the architect or some other person to solve." □

NEW PRINCIPLES OF FIRE HAZARD ASSESSMENT FOR FLUID-FILLED ELECTRICAL EQUIPMENT

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Dow Corning Corporation

Presented At

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I. INTRODUCTION

The fire hazards associated with dielectric fluids in electrical power systems depend on the fire safety properties of the fluid, use of the fluid in an electrical system and installation of the system in a building. Electrical insulating fluids are widely used in such equipment as transformers, capacitors, switchgear cables and bushings. The potential for a fire in these devices is related to service conditions and the electrical and fire safety protection of the equipment [1,2,3].

In order for a liquid-filled electrical device to become a fire hazard, it is necessary that a rupture of the tank or cooling tubes and ignition/combustion of the fluid occur. Previous fire hazard analysis for fluid-filled electrical equipment was focused primarily on the catastrophic failure mode caused by instantaneous high current internal arcing and the risk for ignition and combustion of flammable electrical insulating material. However, recent fire incidents [4,5,6] have shown that under adverse conditions even the so-called nonflammable products such as fire-retardant resins and halogen-containing fluids can burn and produce hazardous fire products. Therefore, a total fire hazard assessment for electrical equipment requires technical information on all the fire products of the insulating material used in the system, including evolution of heat, smoke and fire gases.

There are three basic types of fire risks for electrical equipment:

A. Ignition and combustion of insulating materials caused by an external arc or any external fire source [5,6].

B. Internal electrical insulation breakdown resulting in rupture of the fluid-containing device. The ignition of the fluid may be caused by the arcing which initiated the rupture.

C. Nonviolent rupture of the tank or cooling tubes could occur as a result of either internal pressure caused by a low current electrical breakdown or external mechanical damage to the electrical device during transportation and installation. The probability of ignition under these circumstances is very low.

The electrical power transformer is a typical high voltage, high energy device and the author has selected this type of equipment for an analysis of the fire hazards of fluid-filled electrical apparatus.

The end-user of electrical transformers has many different transformer alternatives:

A. Liquid-filled transformers with fluids of three different fire hazard classifications:

   1. Nonflammable halogen-containing fluids which do not have a measurable flash and fire point.

   2. Less-flammable fluids that have a defined high fire point and a listed Heat Release Rate (HRR) value.

   3. Conventional mineral oils with specified flash and fire points.

B. Dry-type transformers insulated with:

   1. Cast resin systems.

   2. Resin-impregnated systems.

These different types of transformers should be installed and and protected in accordance with the 1984 National Electric Code.

Article 450-21, Dry-Type Installed Indoors
" 450-22, Dry-Type Installed Outdoors
" 450-23, Less-Flammable Liquid Insulated Transformer
" 450-24, Nonflammable Fluid-Insulated Transformer
" 450-25, Askarel-Insulated Transformer Installed Indoors
" 450-26, Oil-Insulated Transformer Installed Indoors
" 450-27, Oil-Insulated Transformer Installed Outdoors
" 450-28, Modification of Transformers

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The conventional liquid-cooled transformers have a series of performance and safety advantages that make them attractive and useful in electrical systems:

Outstanding reliability and safety record [7,8].
High overload capability.
High operating efficiency and low operating costs.
Sealed system operational in all environments.
Compact design requiring less space and weight.
Low sound level.
Use less expensive surge protection.

Historically, the selection of dielectric fluids for indoor transformers was an easy matter. There were two classes of fluids -- mineral oils and polychlorinated biphenyls (PCBs or askarels). Use of the former fluid required auxiliary fire protection, such as a vault. In both cases installation was deemed fire safe and indeed the record is admirable. For example, 1978 National Fire Reporting System (NFIRS) shows only seven fires (out of 230,000 in the data base) beginning with indoor transformers. There were no reported injuries or deaths and the maximum reported damage was $2,000.

In the late 1970s, the manufacture and distribution of the PCB's were banned. This reflected their potential biological hazards in the environment. The impact of the ban on the electrical systems was serious. The simplicity of the previous fire code ended, for a variety of fluids were developed and used to replace the PCBs. There has been considerable discussion and test development to produce fire safety criteria that will preserve the fine record of performance and safety of the fluid-filled transformer.

This report describes some of the new principles of fire hazard analysis and gives data presently available for some transformer fluids.

II. PROTECTION OF TRANSFORMER INSTALLATIONS

Newly developed concepts of fire hazards of systems are replacing the narrower concept of flammability of materials. Most valid fire hazard tests are those that evaluate the system or a product under conditions closely simulating the potential fire-failure mode and fire-failure condition in the equipment installation.

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Transformer fluid fires are rare because much fire protection is already built into the system. The severity of a transformer fire is not only dependent on the fire safety properties of the fluid, but is directly dependent of the external safeguards such as control of power into the device, separation of the transformer from other flammable materials, containment of the fluids and use of fire detection and suppression systems. The installation of indoor small power transformers is covered by the National Electric Code and these requirements are listed in the next section.

Transformer Fire Safety Protection Requirements

The Appendix A shows the text of Section B of Article 450 of the National Electric Code (NEC) for 1984. The protection requirements can be summarized as follows:

A. All transformers must be electrically protected by over-current device to limit arc currents.

B. All transformers must be guarded against physical damage and ventilated to reduce thermal damage.

C. All transformers rated over 35,000 volts must be placed in a vault or at least have a three-hour fire-resistant wall.

D. All oil-filled transformers must be installed in a vault regardless of the rating.

E. Transformers filled with nonflammable fluids, that have no specific flash or fire point, require no vault.

F. Transformers rated at 35,000 volts or less and insulated with less-flammable liquids can be installed without the vault in noncombustible occupancy areas in noncombustible buildings provided there is a liquid confinement area.

G. Transformers with less-flammable fluid installed in combustible buildings or combustible occupancy areas must be provided with automatic fire-extinguishing systems or installed in a vault.

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The essence of the National Electric Code is that the fire can be limited to a transformer itself by its fire containment and external protection.

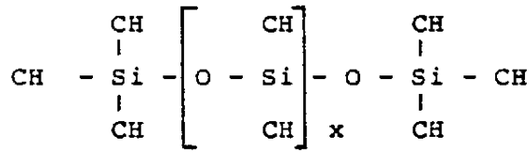
The Factory Mutual Engineering Corp. (FM) has established a Loss Prevention Data Sheet 5-4/14-8 and 5-4S/14-8S that makes detailed recommendations for the electrical and mechanical protection of the transformer installation. FM has a listing of less-flammable fluids (Class 6933) that requires a minimum of 300 degrees fire point and a specific value of the HRR of the fluid. The HRRs are analyzed relative to the building's ability to withstand such a fire. A graph showing how the HRR value is related to requirements for a safe transformer installation is shown in Figure 1.

Fire hazards are associated with all existing transformer systems which will develop fire products that constitute fire hazards. Unfortunately, very limited data and information exists on the fire products of the halogen-containing fluids [9,10,11] and the fire-retardant resin systems [12]. Data and information do exist for the oil and less flammable liquids, and discussion of fire safety properties is limited to fluids of known characteristics.

III. FIRE SAFETY PROPERTIES OF LESS-FLAMMABLE INSULATING LIQUIDS

More than 90% of all transformers use mineral oil or less-flammable insulating liquids as the dielectric coolant. The two most used less-flammable fluids are silicone fluid and high molecular weight (HMW) hydrocarbon liquids. The reliability and safety record of transformer installations with the new less-flammable fluids has been exceptionally good [8], and technical information about the fire safety properties of these fluids is readily available.

The silicone transformer fluid is polydimethylsiloxane having the following general formula.



x = 0 to greater than 2000.

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The fluid is characterized by a narrower molecular weight distribution than mineral oil or askarels. It has very low total volatile content, less than 0.5%, which permits operation at high temperatures with low vapor pressure. Silicone transformer fluids are stable at maximum operating temperatures whereas mineral oil and askarels may show some degradation.

The HMW hydrocarbon liquids are mineral oils with properties similar to those of conventional transformer mineral oil. However, the HMW fluids are subjected to a special hydrogenation and stripping process to reduce the volatile content of the fluid, thereby increasing the viscosity and the fire point of the fluid. The properties of the silicone fluid and the HMW hydrocarbon fluids are compared to regular mineral oil in Table I.

The fire safety properties of these three types of transformer fluid can be discussed in six points:

A. Gases developed under sustained arcing conditions.

B. Ignition and flame spread.

C. Heat release rates.

D. Smoke and fire gases developed under fire conditions.

E. Oxygen depletion.

F. Extinguishment behavior.

A. <u>Gases Developed Under Sustained Arcing Conditions</u>

Both silicone fluid and hydrocarbon fluids evolve flammable gases under high current arcing and, therefore, can produce a flash or a fire ball under catastrophic failure conditions [13,14,15]. However, testing has shown that even a "nonflammable liquid" can develop a fire ball under high current arcing conditions [13,16]. The major arcing gases from the hydrocarbon and silicone liquids are hydrogen and lesser amounts of acetylene, methane, ethylene, and other gaseous hydrocarbons (see Tables II and III from reference 15).

Considerable effort has been done to study the formation of arc gases and the potential hazard of a violent catastrophic rupture of the transformer tank. These studies are complicated by the many variables leading to

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a variety of different failure modes, dependent on the design, construction, and protection of the transformer system. While this aspect of the transformer fire hazard is recognized, it has been up to this point impossible to establish a meaningful, reproducible test that related to the actual fire hazard of the transformer installation rather than to the arc behavior of the fluid itself [2].

A very interesting phenomenon observed during the arc studies has been the propensity of the silicone fluids to build a bridge of solid matter between the electrodes if one of the electrodes is not rotated continuously [15]. If the electrodes are kept stationary after arcing commences, solid matter immediately begins to accumulate in the electrode gap. Within a few seconds, a solid bridge forms across the electrode gap. The arc is extinguished and the generation of gas ceases completely. The behavior of silicone fluids in arcs is unique. When arcing begins, the silicone fluid that is very near the arc (but not in it) does not vaporize or decompose as hydrocarbon or askarel liquids would; instead, it gels. In the arc plasma itself, decomposition of the silicone fluid forms a large amount of silicon dioxide, silicon carbide, carbon, and probably silicon. By contrast, arc decomposition of hydrocarbons and askarels produce a much smaller amount of solid matter consisting almost entirely of carbon. The solids formed in a silicone fluid do not disperse immediately. Instead they coalesce with gelled silicone fluid to bridge the electrodes gap. The resistance of the bridge has been measured at between 10^5 and 10^8 ohms, although this will vary considerably with arc conditions.

The possible implications of the bridging phenomenon can be seen in A. M. Lockie's explanation of how most catastrophic transformer faults begin:

> Whatever the cause, the great majority of transformer failures start as faults between turns, or layers of turns, in the windings. Since most of the winding impedance remains in the circuit, the initial fault current is relatively small. Arcing at the initial failure point, however, causes the failure to spread to adjacent turns and layers, reducing the residual impedance and increasing the fault current [26].

If it can be shown that a silicone fluid will form a solid high impedance bridge in that initial small turn-to-turn fault, preventing the arc from spreading and generating more gas, it could have tremendous implications from the safety standpoint.

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Although we know that resins and halogen liquids give off substantial smoke and gases under conditions of arcing, the author has not been able to find technical information permitting a meaningful comparison of hazards associated with arcing in fire retardant and less-flammable materials.

B. Ignition and Surface Flame Spread

Flash and fire points are measured in accordance with ASTM D92. Table IV shows the flash and fire points for mineral oil, HMW hydrocarbon and silicone fluid. There is a substantial difference in the flash and fire points of the three liquids and the higher values for the silicone fluid indicate its reluctance to ignite.

Ignition is defined as a process of generation and maintenance of a flammable fuel vapor/air mixture at the surface. Flame spread is defined as a series of consecutive ignitions at the surface. Ignition and flame spread are sustained at the surface when there is a balance between the energy supplied to the surface and the energy required to generate and maintain the flammable fuel vapor/air mixture near the surface.

The ignition and the flame spread of the hydrocarbon and the silicone liquids have been studied in more detail in FM's flammability apparatus report. The FM tests were done in a small scale combustibility apparatus developed by Dr. A. Tewarson [17]. Figure 1 (from the FM report) shows a plot of the energy required for ignition as a function of the external heat flux for the silicone and a HMW hydrocarbon fluid.

The FM flammability apparatus is designed to obtain generalized parameters to describe the fire behavior of liquids and solids under wide variation of fire conditions. The external energy is supplied to the fuel surface by radiant heaters. The air flow to the sample can be controlled. The fire parameters from the sample are continuously monitored and recorded. Thus, as the heat flux is increased, the ignition and surface flame spread are expected to be faster in the large scale fire. Under natural or forced air flow condition, the value of the ignition energy for silicone fluid is higher than for high molecular hydrocarbon fluid. Thus, in accordance with Tewarson [17] ignition and surface flame spread in larger scale fires are expected to be faster for the hydrocarbon fluids than for the silicone fluid.

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Comparison of the resistance to ignition of mineral oil and silicone liquid under arcing conditions has been established by H. Kuwahara [15], and these results are summarized in Table V. The silicone fluid again shows great resistance to ignition under arcing conditions. It is recognized that the halogen transformer liquids will only burn with a pilot flame or with a sustained arc condition [5].

C. Heat Release Rates (HRR)

HRR is defined as a product of vaporization rate and the heat of combustion of the fluid. The higher rate of HRR in a large scale fire, the higher the degree of the fire hazard. Table VI (from FM report) lists the HRR values obtained in the small scale and large scale FM combustibility apparatus for methanol, heptane, HMW hydrocarbon and silicone fluids. Figure III shows curves of the HRR of fluids as a function of the energy flux. The comparison to the HRR's of an askarel is obtained by the use of a pilot flame.

A good agreement can be noted between small-scale and large-scale data for the radiative heat release rates for heptane and HMW hydrocarbon. The radiative heat release rate for silicone fluid obtained from external heat flux value in the range of 60-71 kw/m^2 is higher than the rate measured in the larger scale fires. This suggests that the actual vaporization rate for dimethylsiloxane fluid for external heat flux values in the range of 60-71 kw/m^2 is higher than the actual rate in the larger scale fire.

Using the HRR data for higher luminous flame region from the degree of fire hazard expected for heptane is about two times the fire hazard expected from hydrocarbon fluid, about four times the hazard expected from methanol, and about twenty times the hazard expected for dimethylsiloxane. The fire hazard expected for HMW hydrocarbon fluids is about ten times the hazard expected for dimethylsiloxane under large-scale pool fire conditions. The lower degree of a fire hazard of dimethylsiloxane is due to its ability to form a solid crust at the surface in combustion reducing the fuel vaporization rate considerably.

Since the NEC requires confinement of the liquid by curbs around the transformer, the hazards of heat release from burning liquid must be related to the total heat from the surface of the curbed area and the potential damaging effects on the building structure.

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D. Smoke and Fire Gases Developed Under Fire Conditions

Smoke includes both particulate matter and liquid aerosols. Fire gases include products of combustion and pyrolysis (smoldering conditions). Smoke and gases produced on burning contribute to hazard in three ways:

1. Smoke and fire gases may be highly toxic, irritating and/or hot enough to cause damage to the respiratory system.

2. They may cause eye irritation and/or obscuration of light which substantially reduces the probabability of escape from enclosures.

3. Smoke and fire gases may corrode and damage equipment.

Statistics show that inhalation of smoke and fire gases causes far more deaths and injuries in fires in enclosures than does actual flame contact [18]. Complete combustion of hydrocarbons produces carbon dioxide and water vapor. Complete combustion of silicones produces carbon dioxide, water vapor and amorphous (noncrystalline) silica [19]. Complete combustion does not occur in large pool fires as mixing of air and fuel is inefficient and the turbulent flames are often oxygen-deficient. Carbon monoxide, smoke (carbon and liquid aerosols), hydrogen, gaseous hydrocarbons, and particularly oxidized products as well as carbon dioxide and water are produced in such hydrocarbon fires.

Production of these products of incomplete combustion will increase for fires which are more oxygen-deficient (e.g. very large fires and fires in enclosures which restrict access of air).

Data and information exists for the less flammable liquids such as HMW hydrocarbon and silicone fluids. Southwest Research Institute (SWRI) data [20] for fires in the small Ohio State University calorimeter and the room size calorimeter gives comparative rates of oxygen consumption and production of common fire gases. Smoke release rates, using a method similar to the National Bureau of Standards (NBS) smoke chamber test, were also measured (Table VII).

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Lower rates of oxygen consumption and smoke and fire gas production for the silicone fluid is a consequence of its much lower rate or burning. Note that data for the silicone are peak rates of short duration whereas hydrocarbon data are steady-state rates.

The column labeled CH_x represents total gaseous hydrocarbons and partial oxidation products. In assessing toxicity of combustion products, the possibility always exists that an unsuspected or trace component of the smoke or fire gases will prove highly toxic. Animal exposure studies are often performed for this reason. The obvious causes of animal injury or death (oxygen depletion, carbon monoxide concentration, and test chamber temperature) should be closely monitored and maintained within nonlethal limits.

HMW and silicone liquid were evaluated for toxicity of pyrolysis gases (Table VIII) using a screening method developed by Hilado [21,22]. Pyrolysis, or smoldering conditions, is often found to produce more highly toxic products. A 1 gram sample is placed in a quartz tube and heated from 200 to 800°C at 40°C/minute. The quartz tube is connected to a 4.2 liter transparent chamber containing four mice. The apparatus is sealed during the heating stage. An experiment is performed at least twice and results are averaged. Animals are observed during a 30 minute test period in a sealed chamber and for 14 days thereafter. The average time to various stages of incapacitation and death (for at least eight mice) is considered a measure of relative hazard. Chamber temperatures and oxygen levels were nonlethal. Maximum carbon monoxide concentrations reached were high enough to cause death in 3 to 6 min.

Burning silicone liquid exhibits significantly longer times than does HMW oil to produce all stages of incapacity, and ultimately death, of test animals. The time to the first signs of smoke is longer for PDMS than for HMW. Furthermore, levels of carbon monoxide and gaseous hydrocarbons (CH_x) are significantly lower for silicone liquid.

A complete comparison of the smoke and gas evolution of less flammable fluids with fire products from halogen comparison of the smoke and gas evolution of less-flammable fluids with fire products from halogen fluids and resins is not possible because of lack of data. One report [25] shows a table (see Table IX) of the optical density of epoxy, polyester and silicone resin. The epoxy resin does show a considerable evolution of smoke. Another gives some information about the toxic gases from combustion of epoxy resins, but these data do not provide enough information to establish a fire hazard assessment.

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Standardized test methods which will involve far more accurate, elaborate and time consuming methods, generating classifiable dose-response curves, are presently under development at NBS and elsewhere. These tests should be used to evaluate all the products used in transformer systems including resins and halogenated liquids.

The fire hazards of smoke and fire gases of liquid must be reviewed with respect to transformer installation and potential hazards to people and damage to buildings or contents of buildings. In addition to the toxicity hazards, it is known that transformer fires can cause substantial smoke contamination [4].

E. Oxygen Depletion

Oxygen concentration may be reduced to life-threatening values for large fires in enclosures with limited access to air [23,24]. An oxygen concentration of 10% is considered the minimum required for survival. Values below 10% have been found in large fires.

The much lower burning rate of silicone fluids as compared to the hydrocarbons leads to a lower rate of oxygen depletion. However, no information is available on oxygen levels reached in large pool fires.

F. Extinguishment Behavior

There are two basic types of fire detection, one using the principles of ionization and and the other using photoelectricity. Based on the information given in this paper on generation of fire products, it is obvious that these detections can be effectively used both for protection of HMW hydrocarbon and silicone liquid-filled electrical equipment.

The silicone and hydrocarbon fires are readily extinguished using water sprays [19,24], carbon dioxide [19], or dry-powder extinguishers [19,24]. Tests using a calibrated overhead sprinkler system show that water delivery rates of 0.3 gal/min-ft^2 will extinguish such fully developed 4 ft. pool fires within 15 seconds [19].

IV. CONCLUSIONS

A. Fire Hazards exist for all forms of electrical power equipment regardless of the insulating material used. Even nonflammable liquids and fire retardant resins have burned.

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B. While considerable information and data exist for the less-flammable liquids such as HMW hydrocarbons and silicone, the author has been unable to find data for the combustion and arc products from the resin and solids used in dry-type and molded transformers and for the halogen fluids used in transformers. A meaningful safety comparison of all transformer alternatives is not possible before data is available for all major insulating materials used in transformers.

C. A total fire hazard analysis of an electrical device requires complete understanding of code requirements and the protection systems used for the equipment. The fire safety properties of an electrical insulating product are only meaningful when reviewed in relationship to the installation of the equipment and its external safeguards.

D. The fire safety properties of electrical insulating products can be defined as: evolution of arc gases, ignition, flame spread, and evolution of fire products such as heat, smoke, and toxic gases.

E. The application of modern principles for fire hazard assessment for liquid-filled electrical transformers using less-flammable fluids shows that a silicone-filled transformer installed in accordance with the National Electric Code provides a high degree of safety because of its resistance to ignition and its low evolution of fire products under burning conditions.

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APPENDIX A

NATIONAL ELECTRIC CODE ARTICLE 450

TRANSFORMERS AND TRANSFORMER VAULTS

Section B: Specific Provisions Applicable to Different Types of Transformers

450-21, Dry-Type Transformers Installed Indoors

(a) Not Over 112½ kVA. Transformers installed indoors and rated 112½ kVA or less shall have a separation of at least 12 inches (305 mm) from combustible material unless separated therefrom by a fire-resistant heat-insulating barrier, or unless of a rating not over 600 volts and completely enclosed except for ventilating openings.

(b) Over 112½ kVA. Individual transformers of more than 112½ kVA rating shall be installed in a transformer room of fire-resistant construction.

Exception No. 1 to (b): Transformers constructed with Class 80°C rise or higher insulation and separated from combustible material by a fire-resistant, heat-insulating barrier or by not less than 6 feet (1.83 m) horizontally and 12 feet (3.66 m) vertically.

Exception No. 2 to (b): Transformers constructed with Class 80°C rise or higher insulation and of completely enclosed and ventilated-type construction.

(c) Over 35,000 Volts. Transformers rated over 35,000 volts shall be installed in a vault complying with Part C of this article.

450-22, Dry-Type Transformers Installed Outdoors

Dry-type transformers installed outdoors shall have a weatherproof enclosure.

Transformers exceeding 112½ kVA shall not be located within 12 inches (305 mm) of combustible materials of buildings.

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450-23, Less-Flammable Liquid-Insulated Transformers.

Transformers insulated with listed less-flammable liquids shall be permitted to be installed without a vault in Type I and Type II buildings in areas in which no combustible materials are stored, provided there is a liquid confinement area, the liquid has a fire point of not less than 300°C, and the installation complies with all restrictions provided for in the listing of the liquid.

Such indoor transformer installations not meeting the restrictions of the listing listing, or installed in other than Type I or Type II buildings, or in areas where combustible materials are stored, shall (1) be provided with an automatic fire extinguishing system and a liquid confinement area, or (2) be installed in a vault complying with Part C of this article.

Transformers installed indoors and rated over 35,000 volts shall be installed in a vault.

Transformers installed outdoors shall comply with the safeguards of Section 450-27.

(FNP):As used in this Section "Noncombustible" refers to Type I and Type II building construction and noncombustible materials as defined in Types of Building Construction, NFPA 220-1979.

(FNP):See definition of "Listed" in Article 100.

450-24, Nonflammable Fluid-Insulated Transformers.

Transformers insulated with a dielectric fluid identified as nonflammable shall be permitted to be installed indoors or outdoors. Such transformers installed indoors and rated over 35,000 volts shall be installed in a vault.

For the purpose of this section, a nonflammable dielectric fluid is one which does not have a flash point or fire point, and is not flammable in air.

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450-25, Askarel-Insulated Transformers Installed Indoors.

Askarel-insulated transformers installed indoors and rated over 25 kVA shall be furnished with a pressure-relief vent. Where installed in a poorly ventilated place, they shall be furnished with a means for absorbing any gases generated by arcing inside the case, or the pressure-relief vent shall be connected to a chimney or flue that will carry such gases outside the building. Askarel-insulated transformers rated over 35,000 volts shall be installed in a vault.

450-26, Oil-Insulated Transformers Installed Indoors.

Oil-Insulated transformers installed indoors shall be installed in a vault constructed as specified in Part C of this article.

Exception No. 1: Where the total capacity does not exceed 112½ kVA, the vault specified in Part C of this article shall be permitted to be constructed of reinforced concrete not less than 4 inches (102 mm) thick.

Exception No. 2: Where the nominal voltage does not exceed 600, a vault shall not be required if suitable arrangements are made to prevent a transformer oil fire from igniting other materials, and the total capacity in one location does not exceed 10 kVA in a section of the building classified as combustible, or 75 kVA where the surrounding structure is classified as fire-resistant construction.

Exception No. 3: Electric furnace transformers having a total rating not exceeding 75 kVA shall be permitted to be installed without a vault in a building or room of fire-resistant construction, provided suitable arrangements are made to prevent a transformer oil fire from spreading to other combustible material.

Exception No. 4: Transformers shall be permitted to be installed in a detached building that does not comply with Part C of this article if neither the building nor its contents presents a fire hazard to any other building or property, and if the building is used only in supplying electric service and the interior is accessible only to qualified persons.

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Exception No. 5: Oil-insulated transformers shall be permitted to be used without a vault in portable and mobile surface mining equipment (such as electric excavators) if each of the following conditions is met:

a. Provision is made for draining leaking fluid to the ground.

b. Safe egress is provided for personnel.

c. A minimum ¼ inch (6.35 mm) steel barrier is provided for personnel protection.

450-27, Oil-Insulated Transformers Installed Outdoors.

Combustible material, combustible buildings, and parts of buildings, fire escapes, and door and window openings shall be safeguarded from fires originating in oil-insulated transformers installed on roofs, attached to, or adjacent to a building or combustible material.

Space separations, fire-resistant barriers, automatic water spray systems, and enclosures that confine the oil of a ruptured transformer tank are recognized safeguards. One or more of these safeguards shall be applied according to the degree of hazard involved in cases where the transformer installation presents a fire hazard.

Oil enclosures shall be permitted to consist of fire-resistant dikes, curbed areas or basins, or trenches filled with coarse crushed stone. Oil enclosures shall be provided with trapped drains where the exposure and the quality of oil involved are such that removal of oil is important. Transformers installed on poles or structures or underground shall conform to the National Electrical Safety Code, ANSI C2-1981.

450-28, Modification of Transformers.

When modifications are made to a transformer in an existing installation which changes the type of the transformer with respect to Part B of this article, such transformer shall be marked to show the type of insulating liquid installed and the modified transformer installation shall comply with the applicable requirements for that type of transformer.

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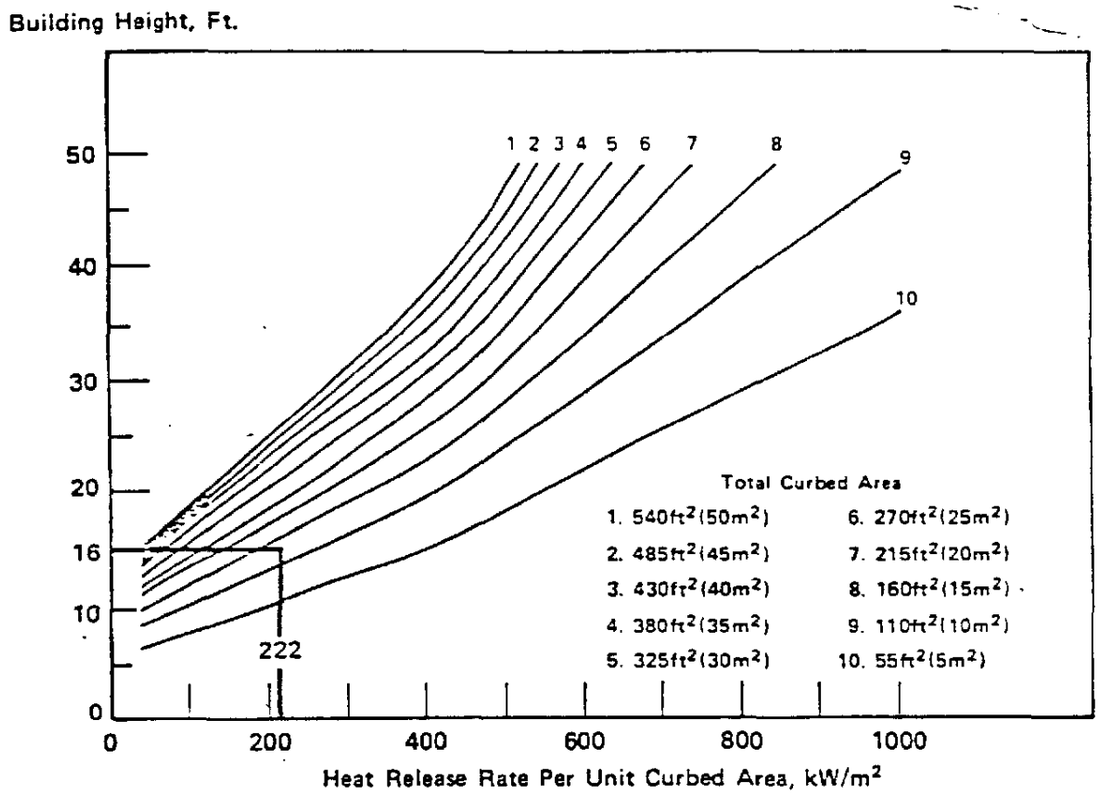
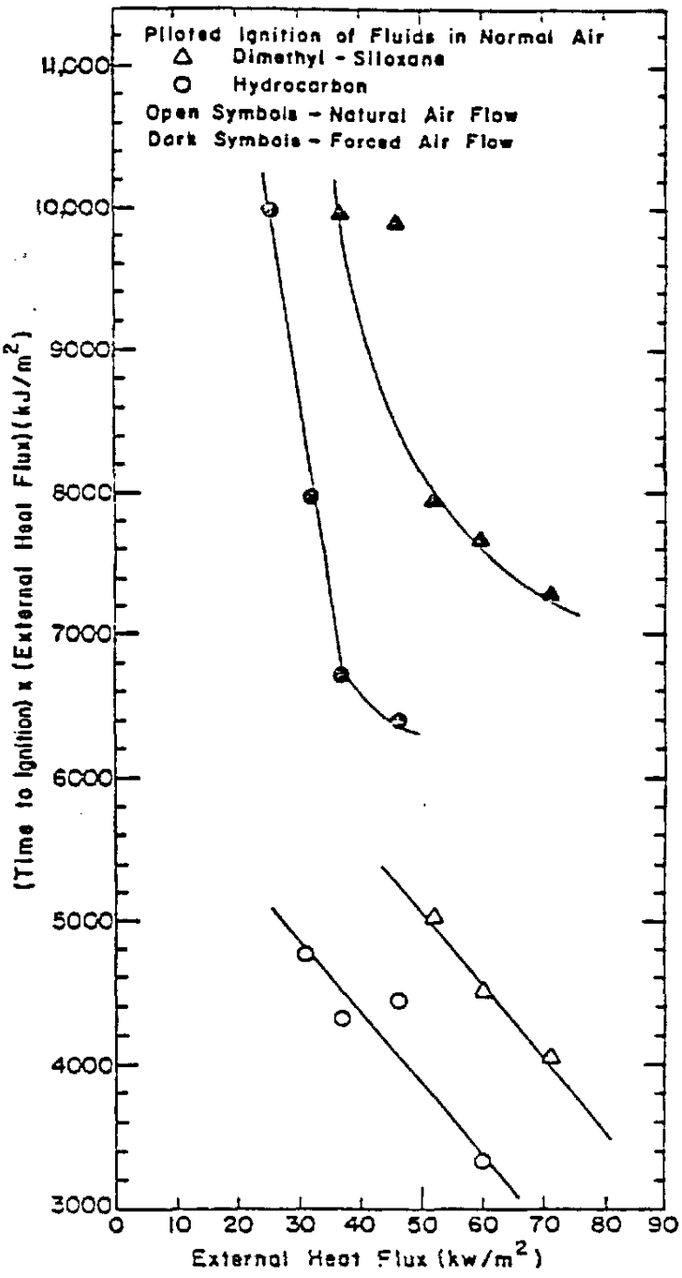


STEEL FRAME ROOF

FIGURE 1



IGNITION FLAME SPREAD FOR PURE DIMETHYLSILOXANE AND HMW HYDROCARBON FLUIDS AS A FUNCTION OF EXTERNAL HEAT FLUX UNDER FORCED AND NATURAL AIR FLOW CONDITIONS.

FIGURE 2

FACTORY MUTUAL RESEARCH CORPORATION

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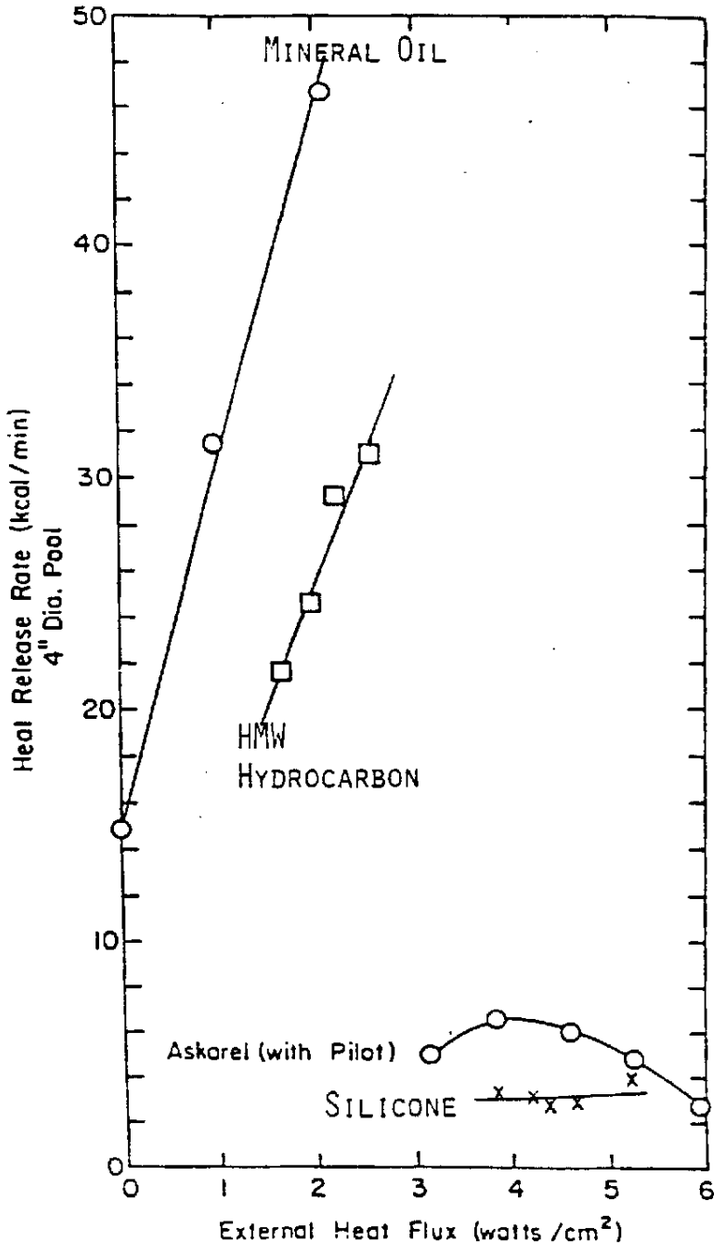

FIGURE 3 CONVECTIVE HEAT RELEASE RATES OF TRANSFORMER FLUIDS.
LABORATORY SCALE APPARATUS

TABLE I

TYPICAL PROPERTIES OF INSULATING LIQUIDS

Properties	Transformer Oil	HMW Hydrocarbon	Silicone Liquid		
	Initial Values	Initial Values	Initial Values	After 3 Yr Of Service	After 5,000 Hr In Test Model
Dielectric Strength, kv (ASTM D 877)	40	40	40	45.0	-
Dielectric Constant, 35°C (ASTM D 877)	2.2	2.4	2.7	-	2.7
Dissipation Factor, 25°C (ASTM D 924)	0.02	0.00001	0.00002	-	0.0005
Volume Resistivity, 25°C (OHM/cm $1x10^{15}$)	$8.5x10^{15}$	$8x10^{12}$	$1x10^{15}$	-	$3.6x10^{13}$
Viscosity, 25°C, cSt (ASTM D 88)	16	350	50	50	50
Specific Gravity, 25°C (ASTM D 1298)	0.88	0.87	0.96	-	-
Pour Point, °C (ASTM D 92)	-40	-15	-60	-	-
Water Content,ppm* Modified K. Fischer	<25	<25	<50	47	53

*Specified levels to obtain satisfactory dielectric properties.

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TABLE II

TYPICAL EXAMPLES OF GAS-COMPONENT ANALYSIS OF EVOLVED GAS UNDER ARC CONDITIONS

Liquid		Silicone Liquid			Mineral Oil		
Current		810 mA	715 mA	26.2 A	345 mA	1,050 mA	15.9 A
Electrode		Rotating 24 rpm.	Rotating 120 rpm.	Fixed	Rotating 24 rpm.	Rotating 120 rpm.	Fixed
Gas Component, percent							
H_2		74.6	75.6	77.1	65.0	68.28	73.44
CO		19.0	17.2	14.0	-	-	-
CH_4		1.7	1.2	4.02	1.2	2.02	3.45
C_2H_2		4.3	5.7	3.76	32.8	26.59	20.74
C_2H_4		0.4	0.3	1.13	0.8	1.40	2.12
C_2H_6		trace	trace	-	trace	trace	0.03
C_3H_6		trace	-	-	0.2	0.17	0.21
C_3H_8		-	-	-	trace	trace	trace
Evolved Gas	Measured	22	35	43	45	45	48
Vol.(mℓ/kWs)	Calculated	88	89	82	65	57	47

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TABLE III

EVOLVED GAS VOLUMES UNDER ARC CONDITIONS IN LIQUIDS

Current Level	Silicone Liquid		Mineral Oil	
	Measured (mℓ/kWs)	Calculated (mℓ/kWs)	Measured (mℓ/kWs)	Calculated (mℓ/kWs)
Lower	35-40	85-95	42-46	55-75
Medium	40-45	75-85	45-55	45-50
Higher	100	-	100	-

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TABLE IV

FLASH AND FIRE POINT OF FLUIDS

	Transformer Oil	HMW	Silicone
Flash Point, °C (ASTM D 92)	150	284	300
Fire Point, °C (ASTM D92)	165	312	343

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TABLE V

TEST RESULTS OF FLAMMABILITY

No.	Liquid	Current A	Arc Location From Liquid Surface mm	Current Duration Min.	Final Liquid Temp.	Resulting Conditions
1	Mineral	6.1	10	4	140	Fire
2	"	"	20	7	150	Fire
3	"	"	30	12	120	Arc in liquid did not reach to a surface. No fire.
4	Silicone	"	10	25	260	Fire
5	"	"	20	27	212	Gap was bridged with solids. No fire.
6	Mineral	13	10	-	-	Arc was sustained in air.
7	"	"	20	3	140	Fire
8	"	"	30	2.75	140	Fire
9	Silicone	"	20	13	230	Fire
10	"	"	10	8.5	243	Fire

(1) Applied Voltage: 6.9 kV
(2) Distance between electrodes: 2 mm
(3) Liquid Volume: 1,350 m
(4) Initial Liquid Temperature: 30

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TABLE VI

LABORATORY-SCALE AND LARGE-SCALE DATA FOR HEAT RELEASE RATES[a]

	Methanol		Heptane		BMW Hydrocarbon		Dimethylsiloxane	
	Lab-Scale	Large-Scale[c]	Lab-Scale	Large-Scale[c]	Lab-Scale	Large-Scale[c]	Lab-Scale	Large-Scale[c]
Heat of Combustion[b] (kJ/g)								
Convective	15.5	-	21.6	-	18.2	-		
Radiative	2.1	3.4	17.4	14.4	20.4	16.3		
Actual	17.6	-	39.0	-	38.6	-		
Complete Combustion	20.0	-	44.6	-	46.3	-	26.9	-
Heat Release Rate (kW/m^2)								
a) Luminous Flame Region								
Convective	-372	315[d]	-	-			84[e]	58
Radiative	-50	69	-	-			48[e]	24
Actual	-422	384[d]	-	-			132[e]	
b) Highly Luminous Flame								
Convective	574	-	1512	1514[d]	728	534		
Radiative	78	-	1218	1009	816	415		
Actual	651	-	2730	2523[d]	1544	-		

[a] Average steady state (maximum) values under natural air flow condition.
[b] Heat of combustion = heat release rate/vaporization rate.
[c] Fuel surface areas: 1.17, 2.37, and $4.67 m^2$
[d] Estimated from laboratory scale data; larger scale data are not available as yet.
[e] Average for external heat flux values 60 to 71.3 kW/m^2 under forced air flow condition.

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TABLE VII

RATES OF SMOKE AND COMBUSTION PRODUCTS OUTPUT

Fluid	Pan Size	SRR[1]	O_2 Depletion Rate (liters/min)	Generation Rates (liters/min) CO_2	CO	CH_{x3}
HMW	3" Dia.	246	19.5	6.75	0.021	0.07
	6" Dia.	196	36.7	23.0	0.30	0.30
	12" Dia.	-	1700	330	23	2.9
	24" Dia.	-	4012	1700	230	16
PDMS[2]	3" Dia.	38.5	2.0	1.5	-	-
	6" Dia.	67.0	20.0	3.5	-	-
	12" Dia.	-	60.0	56	3.3	1.5
	24" Dia.	-	-	100	3.3	0.1
	36" Dia.	-	300	80	7.0	0.5
	48" Dia.	-	600	300	8.0	2.1

[1]SRR = Smoke Release Rate = $v/AL\ (\log_{10})$

where v = Air Flow Rate in OSU Apparatus, 85 cfm
A = Area of Pan - sq. ft.
L = Light Path Length - 0.4375 ft.
%T = % Light Transmission

[2]Release Rates are Peak Values.

[3]Total hydrocarbon Equivalent of Methane.

TABLE VIII

TOXICITY TEST DATA, USF METHOD B
(200-800°C Rising Temperature, 40°C/Min., No Forced Air Flow)

Time In Minutes

Sample	Incapacitation	Staggering	Collapse	Convulsions	Death
PDMS	20.51±0.27	21.39±0.63	23.12±1.23	24.43±1.84	27.03±0.35
HMW	10.31±0.25	12.44±2.04	18.57±1.08	19.62±0.57	21.43±0.82

Times are mean ± standard deviation, for at least 8 mice.

Sample	Time to First Sign of Smoke (min.)	Highest Chamber Temperature Recorded	Maximum Gas Concentration Oxygen (%)*	CO (ppm)	CH_4 (ppm)
PDMS	5.28	27°C	15.9	7,750	1,600
HMW	4.39	26°C	17.5	11,050	4,150

*minimum concentration

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PCBs, PCDFs, and PCDDs Resulting from Transformer/Capacitor Fires: An Overview

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Abstract

The purpose of this paper is to give an overview of what the author considers to be current information concerning PCB transformer/capacitor fires in the U.S. On December 15, 1983, the Environmental Protection Agency issued a national dioxin strategy for investigating, identifying, and cleaning up sites contaminated by dioxin. Within the framework of this strategy is a plan that calls for research to be conducted on PCB transformer/capacitor fires. This research will entail an investigation into the characterization of sources of PCDFs and PCDDs, that is, the chemistry of PCB fires and theoretical products of thermal stress based on composition of askarel used; emergency response protocols for firemen, including protective clothing; and practical remedial measures for building cleanup.

The author also feels that only through the sharing of information and full cooperation among electrical utilities, chemical manufacturers, firemen, insurers, EPRI, EPA, and NIOSH can "preventive maintenance" be performed to minimize or preclude future impacts of PCB transformer/capacitor fires.

PREFACE

On January 10, 1979, a railroad tank car carrying 75,000 liters of crude o-chlorophenol ruptured near Sturgeon, Missouri. Forty-seven workers from the Norfolk & Western Railway Company were employed to clean up the spill and in the process were exposed to a variety of toxic chemicals, including chlorinated phenols, phenol, and the toxic artifact, 2,3,7,8-TCDD (1). In fact, the concentration of this dioxin isomer amounted to only 22 ug/kg (ppb) (2). As a result of alleged exposure and the manifestation of certain perceived health effects and physiological symptoms, e.g., rashes, dizziness, loss of memory, extreme fatigue, impotence, upper respiratory difficulties, and in one case, cancer of the testicles and the skin, the workers brought suit in an Illinois court against the railroad company and the manufacturers of the tank car and the faulty coupling, including Monsanto, the manufacturer of the orthochlorophenol. On August 26, 1982, the Edwardsville, Illinois jury awarded the highest monetary judgments ever made as a result of a

Presented at the EPRI PCB Seminar, Atlanta, GA, December 6-8, 1983.

single tankcar spill - $57.95 million (1). Prior to the commencement of the April 5 trial, Monsanto, General American Transportation, and Dresser Industries settled out of court for an estimated $8 million. This court decision represents the first time a jury has concluded that dioxin caused permanent harm to humans and thus has highlighted the more than 30 waste disposal sites within the State of Missouri that contain polychlorinated dibenzo-p-dioxins (PCDDs)(3).

Recently, in November and December of 1983, three separate suits (4)(5) were filed in St. Louis Circuit Court: in one case, by 57 persons who contend they suffered general systemic effects from dioxin-tainted soils at six sites in eastern and central Missouri - for $684 million; in a second case, by 25 dockworkers and a widow of a former dockworker of a trucking firm in St. Louis - for $620 million; and finally, by 183 people at Times Beach and Castlewood who assert that they suffered serious health deficiencies as a result of dioxin exposure - for $1.8 billion.

Therefore, this situation has catalyzed an acute public and governmental awareness of the potential severity and explosiveness of the PCDD problem. PCB transformer fires, accidental spills, and inappropriate disposal have compounded the problem particularly in regards to PCDFs (furans) and to some extent PCBPs (biphenylenes).

INTRODUCTION

The most toxic and extensively studied polychlorinated dibenzo-p-dioxin (PCDD) and -furan (PCDF) isomers are 2,3,7,8-tetrachloro-p-dioxin (2,3,7,8-TCDD) and 2,3,7,8-tetrachlorodibenzofuran (2,3,7,8-TCDF), respectively. There are pronounced differences in biological and toxicological effects between different PCDD and PCDF isomers. Those isomers with the highest acute toxicity are 2,3,7,8-TCDD, 1,2,3,7,8-PCDD, 1,2,3,4,7,8-HCDD, 1,2,3,6,7,8-HCDD, 1,2,3,7,8,9-HCDD, 2,3,7,8-TCDF, 1,2,3,7,8-PCDF, 2,3,4,7,8-PCDF, and 2,3,4,6,7,8-HCDF (See Figure 1).

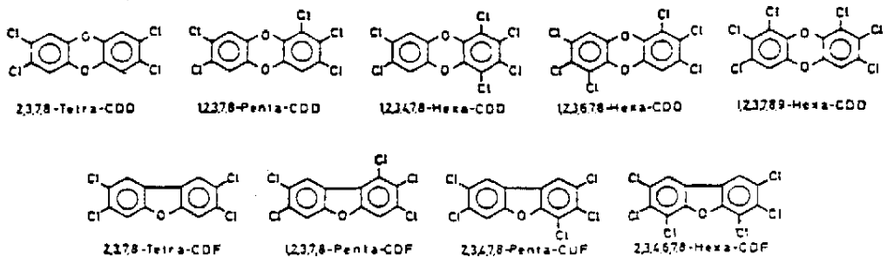

Figure 1. The most toxic PCDD and PCDF isomers (6).

Each of these isomers has its respective four lateral positions substituted for chlorine and each has LD_{50} values in the range of 1-100 ug/kg for the most sensitive animal species (generally the male guinea pig). There exist 75 PCDD isomers and 135 PCDF isomers. Acute toxicity among the isomers can vary up to 100,000 times (See Table 1). In comparison, the most acutely toxic PCB isomer is only about one-fourth as toxic as 2,3,7,8-TCDD (8).

Table 1. Acute oral toxicity of polychlorinated dibenzo-p-dioxins as dose expected to cause death of 50% of the animals within 30 days (7).

	Acute Oral LD_{50}, ug/kg Body Weight		
PCDD	Guinea Pig	Rat	Mouse
Di 2,7		>1,000,000	>2,000,000
2,8	>300,000		
Tri 2,3,7	30,000		>3,000
Tetra 1,3,6,8 mixed		>100,000	
1,3,7,9			
2,3,7,8	0.6	22 (M)	
	2.1	45 (F)	
	2		280
Penta 1,2,3,7,8	3		340
1,2,4,7,8	1,100		>5,000
Hexa 1,2,3,4,7,8	73		825
1,2,3,6,7,8	70-100		1,250
1,2,3,7,8,9	60-100		>1,440
Mixed Isomers		100,000	
Hepta 1,2,3,4,6,7,8	>600		
Octa 1,2,3,4,6,7,8,9		>1,000,000	>4,000,000

Recent information arising from a 1983 National Cancer Institute carcinogenicity study of a mixture of 1,2,3,6,7,8- and 1,2,3,7,8,9-HCDD in female rats led to the preliminary conclusion that this mixture of hexachlorodioxins was carcinogenic. Because public comment criticized the manner in which the experiments were conducted, the National Institute of Environmental Health Sciences/National Toxicological Program (NIEHS/NTP) was asked to reexamine the results of the study. It is therefore the opinion of NIEHS/NTP that the hexachlorodioxin mixture was indeed carcinogenic under the conditions of the test (9).

Analyses of Commercial PCB Mixtures

PCBs contain a complex mixture of PCDFs with up to 40 isomers being present. Rappe and Buser (6) have analyzed a number of commercial PCBs and their findings are shown in Table 2. The highest concentration of PCDFs, found in a Mitsubishi PCB fluid used for over two years, amounted to 10 ug/g (ppm), with 1.25 ug/g being the 2,3,7,8-TCDF isomer. When commercial mixtures or well defined isomers are heated in air in a sealed glass container or ampoule, yields of PCDFs have been observed in the 1-5% range and this technique has been successfully employed to prepare PCDF standards (10). Using the synthetic standards currently available, the major PCDF isomers present in commercial PCBs have been identified (See Figure 2).

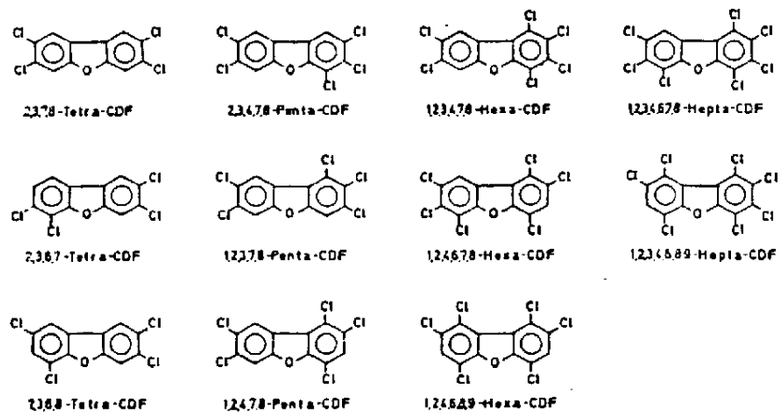

Figure 2. PCDF isomers identified in commercial PCBs (6).

Table 2. Concentrations of PCDFs in commercial PCBs, ug/g (6).

Sample	3-Cl	4-Cl	5-Cl	6-Cl	7-Cl	Total PCDF
Aroclor 1248 (1969)	-	0.5	1.2	0.3	-	2.0
Aroclor 1254 (1969)	-	0.1	0.2	1.4	-	1.7
Aroclor 1254 (1970)	-	0.2	0.4	0.9	-	1.5
Aroclor 1254	0.10	0.25	0.70	0.81	-	1.9
Aroclor 1254 (lot KK 602)	-	0.05	0.10	0.02	-	0.2
Aroclor 1260 (1969)	-	0.1	0.4	0.5	-	1.0
Aroclor (Lot AK 3)	-	0.2	0.3	0.3	-	0.8
Aroclor 1260	0.06	0.30	1.0	1.10	1.35	3.8
Aroclor 1016 (1972)	-	<0.001	<0.001	<0.001	-	-
Clophen A 60	-	1.4	5.0	2.2	-	8.4
Clophen T 64	0.10	0.30	1.73	2.45	0.82	5.4
Phenoclor DP-6	-	0.7	10.0	2.9	-	13.6
Prodelec 3010	0.41	1.00[a]	0.35	0.07	-	2.0
Mitsubishi (used)	2.13	4.00[b]	3.30	0.53	-	10.0

[a] Major isomer 2,3,7,8-TCDF
[b] Contains 1.25 ug/g 2,3,7,8-TCDF

Discussion of Various PCB Fires

° Binghamton, New York

On February 5, 1981 at approximately 5:30 a.m., an electrical panel in the basement of a 22 story office building located in a governmental complex was involved in an incident described as an explosion. A nearby electrical transformer containing about 1100 gallons of Aroclor 1254 (65%) and tri- and tetrachlorinated benzenes (35%) was involved. Leakage occurred and about 180 to 200 gallons of fluid leaked from the transformer. Due to the ventilation system of the building, smoke contaminated with soot-containing chemicals, was spread in a non-uniform fashion to most work areas of the building as well as to interstices within air conditioning ducts, false ceiling areas, elevator shafts, and within desks and file cabinets. This appears to have been facilitated by air ducts or simply open shafts running from the basement area, up to the top of the building, with openings into the men's and women's bathrooms on each floor. These bathrooms had only metal gratings separating them from the open shaft area. In addition to this architectural arrangement, fire or smoke safety doors, which were designed to open in the presence of smoke as a health measure, did just that during the series of explosions that occurred at the time of the incident. Because the outside air temperature was below freezing at the time, the opening of safety doors on the roof, which were located above the building's two stairways, caused a small vacuum that sucked air containing smoke, soot, and as was later found, toxic chemicals from the bathroom areas on each floor and deposited the residue in a non-uniform fashion into most areas of the office building later tested.

Chemical analyses were performed at: Galson Laboratory in Syracuse, New York and at General Electric Laboratory in Schenectady, New York and revealed PCBs in soot and air, which was strongly suggestive of PCDFs present in substantial amounts; The National Fish and Wildlife Laboratory in Columbia, Missouri, which established the presence of many of the dioxin isomers; and by the New York State Health Department's Division of Laboratories and Research, which established the presence of 2,3,7,8-TCDD. A later examination of material from the underground garage that was contaminated and washed (twice with steam and detergent) was found still to have trace amounts (nanograms per square meter) of PCDFs and PCDDs in some areas by Wright State University. Total PCDF isomers in the soot were initially found to be as high as 2160 ug/g, PCDDs 10-20 ug/g, and PCBs 100,000-200,000 ug/g (See Table 3). It is noteworthy that the most toxic isomers are the major components within each group, viz., 2,3,7,8-TCDD, 2,3,7,8-TCDF, 1,2,3,7,8-PCDD, 1,2,3,7,8-PCDF, and 2,3,4,7,8-PCDF (See Figure 1). Since the tri- and tetrachlorinated benzenes comprise 35% of the dielectric fluid, it is not unreasonable to assume that this diluent mixture represents the precursor to the PCDDs produced as a result of the fire.

Nearby Binghamton City Hall, which was used as a staging area during the initial cleanup efforts in February 1981, was also contaminated. The County Building also next door to the Binghamton State Office Building was contaminated to a lesser extent.

There have been $12 million allocated so far by the State of New York for the cleanup. The building is self-insured so no insurance funds are available. It has been closed since February 5, 1981. Over ~~$9 million~~ in lawsuits have been threatened by some of the more than 500 persons who were, or believe they were, exposed to toxic chemicals, and who are themselves concerned with physical or psychological/medical damages.

° Stockholm, Sweden

In August 1981, a fire broke out in a 10 KV capacitor battery in an electrical power station in Stockholm, which was probably caused by a malfunctioning electrical system. Wipe tests were taken about one meter from the capacitor (13). Inspection of the chromatograms revealed several peaks, in addition to PCBs, with molecular weights corresponding to di-, tri-, tetra-, and pentachlorobiphenylenes (PCBPs). It is probable that these PCBPs were formed by a direct cyclization of PCBs present. The level of PCDFs was found to be 1375 ng/m^2 (See Table 4), whereas a rough estimate for PCBPs gave levels of 25,000-30,000 ng/m^2. Polychlorinated pyrenes (PCPYs) were also detected, but not quantified.

Table 3. Levels of PCDFs (ug/g) from accidental burning of PCB-containing electrical equipment.

Isomers	Capacitor Skovde, Sweden(10) 0.5m*	3m**	Transformer Binghamton(10)	Transformer Miami (11)#	Transformer Boston (12)¢
Total PCDFs	0.8	0.2	2160	n.d.-1.79	165
Total Tri-CDFs				n.d.-0.18	50
Total Tetra-CDFs	0.6	0.1	28	n.d.-0.53	60
2,3,7,8-Tetra-CDF	0.1	0.02	12	n.d.	3
Other isomers	0.5	0.06	16		
Total Penta-CDFs	0.1	0.04	670	n.d.-1.0	35
1,3,4,7,8-Penta-CDF			65		
1,2,4,7,8- "			25		
1,2,4,7,9- "			22		
1,2,3,7,8- "			310		
1,2,3,6,7- "			60		
1,2,6,7,8- "			25		
2,3,4,7,8- "			48		
2,3,4,6,7- "			12		
Other isomers			110		
Total Hexa-CDFs	0.04	0.04	965	n.d.-0.18	15
1,2,3,4,6,8-Hexa-CDF			50		
1,3,4,6,7,8- "			125		
1,2,4,6,7,8- "			50		
1,2,3,4,7,8- "			510		
1,2,3,6,7,8- "			150		
1,2,3,6,8,9- "			58		
2,3,4,6,7,8- "			10		
Other isomers			250		
Total Hepta-CDFs	0.01	0.01	460	n.d.	2
1,2,3,4,6,7,8-Hepta-CDF			230		
1,2,3,4,6,7,9- "			120		
1,2,3,4,6,8,9- "			55		
1,2,3,4,7,8,9- "			55		
Octa-CDF	0.005	0.005	40	n.d.	n.d

* soot sample taken 0.5m from capacitor on the floor
** soot sample taken 3m above capacitor on the wall
\# Detection limit: 10 ng/g
¢ Detection limit: 100 ng/g

Table 3. Levels of PCDDs (ug/g) from accidental burning of PCB-containing electrical equipment. (cont'd)

Isomers	Capacitor Skovde, Sweden(10) 0.5m*	3m**	Transformer Binghamton(10)	Transformer Miami (11)#	Transformer Boston (12)¢
Total PCDDs	-	-	20	n.d.	n.d.
Total Tri-CDDs				n.d.	n.d.
Total Tetra-CDDs	-	-	1.2	n.d.	n.d.
2,3,7,8-Tetra-CDFs	-	-	0.6	n.d.	n.d.
Other isomers	-	-	0.6		
Total Penta-CDDs	-	-	5.0	n.d.	n.d.
1,2,3,7,8-Penta-CDDs	-	-	2.5		
Other isomers	-	-	2.5		
Total Hexa-CDDs	-	-	4.7	n.d.	n.d.
1,2,3,4,6,8-Hexa-CDD	-	-	1.2		
1,2,4,6,8,9 "	-	-	1.2		
1,2,3,4,7,8 "	-	-	0.7		
1,2,3,6,8,9 "	-	-	0.6		
1,2,3,7,8,9 "	-	-	0.4		
1,2,3,4,6,7 "	-	-	0.5		
1,2,3,4,6,7,9-Hepta-CDD	-	-	4	n.d.	n.d.
1,2,3,4,6,7,8- "	-	-	3	n.d.	n.d.
Octa-CDD	-	-	2	n.d.	n.d.

* soot sample taken 0.5m from capacitor on the floor
** soot sample taken 3m above capacitor on the wall
\# Detection limit: 10 ng/g
¢ Detection limit: 100 ng/g

Table 4. Analyses of wipe samples from various PCB fires.

Isomers	Skovde(14) ng/m^2	Stockholm(14) ng/m^2	Cincinnati(13) ng/m^2
Total PCDFs	n.d.-873	1375	n.d.
2,3,7,8-Tetra-CDF	n.d.-100	150	n.d.
1,2,7,8-Tetra-CDF		150	
2,3,6,8-Tetra-CDF		125	
1,4,6,9-Tetra-CDF		75	
2,4,6,7-Tetra-CDF		37	
3,4,6,7-Tetra-CDF		7.5	
1,3,6,7-/1,3,6,9-Tetra-CDF		300	
Other Tetra-CDFs		750	
Total Tetra-CDFs	<1-600	1200	n.d.
2,3,4,7,8-Penta-CDF		45	
1,2,4,7,8-Penta-CDF		38	
1,2,3,6,7-Penta-CDF		15	
1,3,4,7,8-Penta-CDF		11	
2,3,4,6,7-Penta-CDF		7.5	
1,2,4,6,8-Penta-CDF		3.8	
1,2,4,7,8-Penta-CDF		3.8	
1,2,3,6,7-Penta-CDF		3.8	
1,2,4,8,9-Penta-CDF		3.8	
2,3,4,6,8-Penta-CDF		2	
1,2,3,7,8-/1,2,3,4,8-Penta-CDF		15	
Other Penta-CDFs		19	
Total Penta-CDFs	n.d.-100	175	
Total Hexa-CDFs	n.d.-60	<0.5	
Total Hepta-CDFs	n.d.-8		
Octa-CDF	n.d.-5		
Total PCDDs	n.d.		n.d.
Total Tetra-CDDs	n.d.		n.d.
2,3,7,8-Tetra-CDDs	n.d.		n.d.

° Skovde, Sweden

In March 1982, a 400 volt capacity battery, serving a high frequency oven in a casting line of a foundry in Skovde, experienced an electrical malfunction leading to a fire (13)(14). The dielectric fluid employed comprised either mineral oil or PCBs. The fire started in a mineral oil capacitor and burned for about two hours before being extinguished. Temperatures exceeding 1100°C were realized because copper electrical wiring melted. The smoke spread from the basement into the building above, an area of 60 x 30 meters. The capacitor battery contained 21 capacitors filled with 5 kgs of PCBs each. Post-fire inspection showed leakage from 12 of these capacitors. Both wipe tests and samples were taken. Results are tabulated in Tables 3 and 4. These show that high levels of PCDFs (>100 ng/m^2 and <800 ng/g) could only be found in an area near the fire. Concentrations of PCDFs dropped off dramatically with distance from the fire. The highly toxic 2,3,7,8-TCDF was one of the major tetra-CDF isomers present. Other chlorinated compounds that may be present are the PCPYs, but verification could not be obtained due to lack of standards. No PCDDs were identified in samples taken from this fire (there were no chlorinated benzenes used as diluents). No PCBPs were observed.

° Miami, Florida

On April 13, 1982, an underground electrical fire occurred in a transformer vault in Miami. City of Miami firemen were called in to extinguish the blaze. They also voiced their concerns about the possible contamination of fire equipment and protective clothing used during the performance of their duties. As a result, the International Association of Fire Fighters in Washington, DC, contacted the NIOSH Region IV representative and the latter agency conducted a thorough investigation. Table 5 contains the results of the analyses of surface samples taken during the investigation. As expected, samples removed from inside the vault indicate the heaviest contamination levels (up to 27,400 ug/100 cm^2 PCBs). Results of prior NIOSH investigations indicate that normal background levels of PCBs on uncontaminated surfaces should be less than 0.5 ug/100 cm^2. As indicated by the sampling results, turnout coats, boots, helmets, and other personal protective equipment were not found to be contaminated from the fire. This is probably due to the decision to allow the fire to self-extinguish, thus minimizing exposures to the smoke and soot. The only contaminated piece of equipment found at the station was the smoke ejector fan, which contained greater than 31 ug/100 cm^2 PCBs because the area wiped for this particular sample was estimated to be less than the standard 100 cm^2. The fan blade guard was found to be heavily coated with soot and dirt from the smoke exhausted from the vault fire.

Results of PCDD and PCDF analyses are shown in Table 3. No PCDDs were detected, but tri-, tetra-, penta-, and hexa-CDFs were found, ranging from non-detectable (n.d.) to 1790 ng/g. No 2,3,7,8-TCDF was detected in any of the samples. However, the samples did exhibit high levels of PCBs through Cl_{10} and polychlorinated diphenylethers (PCDPEs) through Cl_8.

Table 5. PCB residue from Miami transformer vault fire (11).

Sample Location	Type Sample#	PCBs* (ug/100 cm^2)
Inside transformer vault		
Wall behind transformer	(soot) wipe	434**
Top of primary cable above fire	(soot) wipe	389
Primary cable support bracket	(soot) wipe	704
Floor near isolating switch	(dirt) wipe	27,400
Ceiling near fire location	(soot) wipe	860
Secondary bus near vault ceiling	(dirt) wipe	195
Wall next to exit ladder	(dust) smear tab--dry	2
Rung of exit ladder	(dust) smear tab--dry	79
Above transformer vault:		
Sidewalk grating	smear tab--dry	2
Water at curb near vault	wipe	3
Firemen's clothing/equipment:		
Miscellaneous clothing	smear tab--dry	<0.1
Smoke ejector fan	smear tab--dry	>31
Normal PCB Background***	wipe	<0.5

* As Aroclor 1260 (used as standard for quantifying samples).

** As mixture of Aroclor 1254 (231 ug) + Aroclor 1260 (203 ug).

*** As determined by previous NIOSH Health Hazard Evaluation.

Wipe samples were collected on sterile cotton pads soaked in n-hexane.

° Cincinnati, Ohio

On December 3, 1980, a capacitor containing PCBs for a 1/2 HP electric motor overheated in a basement storage room of a private elementary school. This capacitor contained 22 ml of dielectric fluid comprised of 21.9 ml of a biodegradable fluid and 0.1 ml of PCBs. Approximately one-half of the fifth-grade students using three classrooms in the basement area complained of itchiness of the skin. Power to the electric motor was shut off and the exterior door was opened to allow ventilation of the smoke from the room. Since air is locally recirculated, central distribution via a mechanical system throughout the school did not occur.

PCBs were not detected in any air sample at a limit of detection of 0.05 ug/sample, which is equivalent to an airborne concentration of approximately 1 ug/m^3.

Table 6 summarizes the results of 63 wipe samples collected by NIOSH. Fifty-one of the 63 samples were taken from surfaces within the school including books, desks, walls, floors, ceilings, and other surfaces. Two were taken from surfaces within a mobile classroom and ten were obtained from surfaces at three locations in eastern, central, and western Cincinnati to establish background levels of PCBs for this area. The 20 samples obtained from Room 27, which contained the overheated capacitor, ranged from non-detectable to 7200 $ug/100\ cm^2$ PCBs. The remaining rooms ranged from non-detectable to 0.45 $ug/100\ cm^2$.

The two wipe samples with the highest PCB concentrations were also analyzed for PCDDs and PCDFs, with particular emphasis on the 2,3,7,8-tetra-isomers. Neither PCDDs nor PCDFs (See Table 4) were detected in either of the samples. The detection limits employed were 0.10 and 0.09 ug/sample, respectively.

° Boston, Massachusetts

In January 1982, there was an electrical fire involving PCBs in a Boston office building. One bulk soot sample was analyzed for PCDDs and PCDFs. Table 3 shows that high concentrations of the tri- through the hepta-CDFs were found in the soot sample, ranging from 2 - 60 ug/g (detection limit = 0.1 ug/g). No PCDDs were found. A considerable amount of the highly toxic 2,3,7,8-TCDF was detected--3 ug/g. Levels of PCBs were also found at 10 - 100 times that of the PCDFs.

Table 6. Summary of PCBs wipe sample results, Our Lady of Visitation School, Cincinnati, OH (capacitor fire) (15).

Sample Location	Mean PCB level, ug/100 cm^2 *
Room 27 (capacitor location)	n.d. - 7200**
Room 25	n.d. - 0.14
Room 24	n.d. - 0.06
Room 26	n.d.
Hallway	n.d. - 0.07
Room 8	n.d. - 0.08
Room 22	n.d. - 0.29
Room 10	n.d. - 0.20
Room 11	0.07 - 0.11
Room 12	0.06 - 0.09
A.V. Room	n.d.
Principal's Office	0.05 - 0.45
Mobile Classroom	0.06
Background Levels (3 Cincinnati locations)	n.d. - 0.13

* Detection limit: 0.05 ug/sample (sample = quantity wiped per 100 cm^2).

** Two wipe samples with highest concentrations of PCBs were found to contain no detectable PCDFs or PCDDs.

° St. Paul, Minnesota

On June 22, 1982, a transformer fire occurred in a public high school in St. Paul. NIOSH took both surface wipe and air samples on June 23 (the day after the fire) and on July 7 (after the area was decontaminated). Table 7 contains measurements of air contamination, pre- and post-cleanup, by PCBs, trichlorobenzenes, and tetrachlorobenzenes. The NIOSH recommended permissable limit of 0.001 mg/m^3 (8-hr TWA) for PCBs was exceeded in all areas sampled except for two locations. The tri- and tetrachlorobenzenes found did not exceed any existing limits.

Table 8 shows the effect of the decontamination methods employed. The transformer vault room PCBs (wipes) were reduced from a high of 4,000 ug/100 cm^2 to 120 ug/100 cm^2 or less. No PCDDs or PCDFs were found in the liquid sample of Askarel provided (detection limit = 40 ng/g (40 ppb)). However, it is interesting to note that NIOSH did not analyze for PCDDs or PCDFs in the soot. The results may have shown significant concentrations of these isomers, given the areal concentrations of tri- and tetrachlorobenzenes detected.

Table 7. Areal concentration of PCBs and chlorinated benzenes, Hill-Murray High School, St. Paul, MN (transformer)(16).

Sample Site	Airborne Concentration, mg/m^3					
	PCBs*#		T_3CBs		T_4CBs	
	A	B	A	B	A	B
Transformer vault, 5 ft above floor	0.05	0.007[c]	22.6	0.331	18.2	0.651
Transformer vault, 1 ft above floor	0.09	-	17.6	-	25.7	-
Outside of transformer vault doors	0.02	n.d.	10.2	0.048	11.7	0.229
Woodshop	0.004	n.d.	0.73	0.020	1.21	0.089
Head of stairs	n.d.	n.d.	0.12	0.011	0.26	0.037
Cafeteria	n.d.	n.d.	0.35	0.010	0.27	0.032
8-hr time-weighted average exposure criteria	0.001[a]		40[b]		none	

A = June 23, 1982; B = July 7, 1982

* = Detection limit : 0.001 mg/m^3

= as Aroclor 1260

a NIOSH recommended permissable exposure limit. OSHA permissable exposure limit is 0.001 mg/m^3 8-hour time weighted average.

b ACGIH threshold limit value. Neither NIOSH nor OSHA has exposure criteria.

c sample taken 3 ft above floor

Table 8. Analyzed PCBs# in wipe samples,
Hill-Murray High School, St. Paul, MN (transformer) ¢(16).

Sample Site	PCBs#, ug/100 cm^2	
	A	B
Vault room	n.d. - 4000	2 - 120
Ventilation dust	n.d.	-
Corridor outside vault room	n.d.	-
Cafeteria	0.22 - 0.24	n.d.
Gymnasium	0.29	-
Rooms 106, 109, 138	0.26 - 2.1	n.d. - 0.8
Outside Room 106	5.8	0.8
Woodshop	n.d.	-

Detection Limit : 5 ug/sample

A = June 23, 1982; B = July 7, 1982

¢ = no analyses conducted for PCDFs or PCDDs.

DISCUSSION

The previous PCB transformer/capacitor incidents are but a representative sampling of cases where data are readily available. Other electrical equipment episodes include: Toronto, Ontario, Canada in 1977; and Norrtalje and Surahammar, Sweden and Imatra, Finland in 1982 (17). More recently, in the U.S., three such episodes have occurred:

Date	Location	PCB Fluid
5/15/83	San Francisco, CA	1242 only
9/28/83	Chicago, IL	65% Aroclor/35% Chlorobenzenes
12/21/83	Syracuse, NY	87% 1254

Because of the continuance of such incidents, the Environmental Defense Fund and the Natural Resources Defense Council challenged the August 25, 1982 PCB Electrical Use Rule issued by EPA. As a result, a Start Action Request has been initiated by the EPA Office of Pesticides and Toxic Chemicals, which includes the following court-ordered schedule for the issuance of an Advanced Notice of Proposed Rulemaking (ANPR) regarding PCB transformer fires (18):

ANPR: March 1984
Proposed Rule: October 1984
Final Rule: July 1985

The objective of an ANPR is to present data that indicate a reason for concern and, more importantly, to solicit data for the Proposed Rule. The major elements of the ANPR include:

- Description of risks associated with PCB transformer fires through analyses of Binghamton, San Francisco, Chicago, Syracuse, etc. events.
- Description of number and distribution of PCB transformers.
- Solicitation of data on number and location of such electrical equipment.
- Presentation of information on other lesser-known fires.
- Presentation of estimates of frequency of fires.
- Solicitation of data on other fires and frequency of other fires.
- Discussion of PCDF/PCDD formation (and PCBP, PCCY (crysenes), PCDPE, PCPY, etc. where data are available on these compounds).
- Solicitation of data on mechanisms of formation.
- Presentation of possible regulatory options.
  - Substitutes
  - Retrofilling
  - Fire hazard inspections
  - Costs/benefits of various mechanisms to reduce spread of PCBs, PCDFs, PCDDs, etc. from fires - use of early warning protection devices

Currently, the EPA Office of Research and Development (ORD), in support of the Agency's Dioxin Strategy (18), released publicly on December 15, 1983, is planning to conduct research on PCB fires, which will cover three areas: (a) the chemistry of PCB fires and a theoretical discussion of products of thermal stress based on composition of askarel used; (b) emergency response protocols for firemen, including protective clothing (this research will be conducted in cooperation with NIOSH); and (c) practical remedial measures for building cleanup.

As a result of my participation in the preparation of the Dioxin Strategy document and in several Agency dioxin workgroups, including the Dioxin Disposal Advisory Group and the PCB Transformer Fires Workgroup and based upon my expertise concerning the subject matter (20), I believe that I enjoy a perspective that few EPA technical staff have. Because of this, I can relate to you the following facts: Given that chemical production facilities in the U.S. no longer produce 2,4,5-trichlorophenol (the most significant historical source of 2,3,7,8-TCDD), I can state that soot produced as a result of PCB transformer/capacitor fires contains the highest concentrations of PCDFs and PCDDs (the latter only if chlorobenzene diluents are present in the askarel mixture) found in the U.S. today; on a weight basis, however, municipal combustion devices account for the largest quantity of PCDFs and PCDDs produced currently. The soot from the Binghamton fire was evaluated by the New York State Department of Health in tests using chick embryos in 1981 (21). Results were positive. In other words, the PCDDs and PCDFs in the soot were not inactivated (as in the case of fly ash from an incinerator or by activated carbon) as demonstrated by the chick embryo fetotoxicity and teratogenicity tests performed. The soot can therefore be considered toxic and may contribute to "environmentally induced or promoted cancers, reproductive abnormalities, immunologic deficiency, and possibly premature death from infection, neurologic and gastrointestinal system pathology and possibly, by elevating serum triglyceride and cholesterol levels, excess or avoidable cardiovascular and cerebrovascular pathology" (22, p. 678).

I thus stand firmly behind the convictions that firemen responding to such incidents must have the most up-to-date information at their disposal and that remedial methods employed must be practical, sound, and effective. As a result, EPA-ORD is in the process of securing PCB samples from Binghamton, NY, Chicago, IL, San Francisco, CA, and Syracuse, NY. The EPA analytical laboratory in Cincinnati, OH will conduct a chlorobenzene isomer screen on the samples together with homologue analyses for PCBs, the purpose being an attempt to correlate PCDDs and PCDFs content of soot and wipe samples (in the vaults) with chlorobenzene and PCB content in the transformer fluid. The information gathered will be shared among the electrical utilities, insurers, firemen associations, EPRI and NIOSH.

In closing, I wish to share some recent and quite pertinent information. The NIEHS/NTP has concluded two animal studies involving bioaccumulation of 2,3,7,8-TCDD from contaminated soils and has submitted these papers (23) to Science for publication. These papers conclude that 2,3,7,8-TCDD in soil from two sites in Missouri, namely, Times Beach and Minker-Stout, is absorbed in a highly efficient manner (>50%) and that 2,3,7,8-TCDD

-contaminated soil presents a hazard to humans if ingested. Thus, further laboratory evidence has been amassed regarding potential risk to humans for 2,3,7,8-TCDD. I believe that this audience is sufficiently astute to comprehend the long-term implications of these investigations.

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SMOKE TOXICOLOGY
A SPECIAL REPORT

Fdc
Haz. Fire

Where There's Smoke, There's Ire

As synthetics increasingly replace natural materials in buildings, angry debate swirls around whether this heightens the danger of fires and whether anything can—or should—be done.

BY LINDA GARMON

In the early morning of March 6, 1982, fire broke out in room 404 of the Westchase Hilton Hotel in Houston. The presumed culprit: a carelessly placed cigarette. Local fire officials described it as a "simple room fire," and the deputy fire chief reported that extinguishing the blaze was a "fairly straightforward" operation. The room's occupants escaped unharmed. But ten other guests on the same floor died in their rooms from smoke inhalation.

Smoke—not flames—has for many years been recognized as the primary killer in fires. Of the roughly 7,500 fire fatalities in the United States each year, smoke fells more than 80 percent. Traditionally, nearly all smoke-inhalation deaths have been summarily attributed to carbon monoxide, a toxic gas produced during the combustion of essentially everything that burns. However, researchers from the Foundation for Fire Safety pieced together a different picture of the Westchase fire.

According to Merritt Birky, director of research at the foundation during the investigation, blood samples taken from the victims did show elevated levels of carbon monoxide, but they were not high enough to be the direct or sole cause of death. On the other hand, all the victims had elevated levels of hydrogen cyanide in their blood, and two had levels high enough to be lethal. The victims also had sustained severe respiratory damage, suggesting exposure to hydrogen-chloride gas.

These poisonous gases were generated by the combustion of synthetic materials in the room, says Birky. The foundation's tests indicated that the hydrogen cyanide came from polyurethane carper padding, nylon carpet and blankers, and a polyurethane cushion on an upholstered chair.

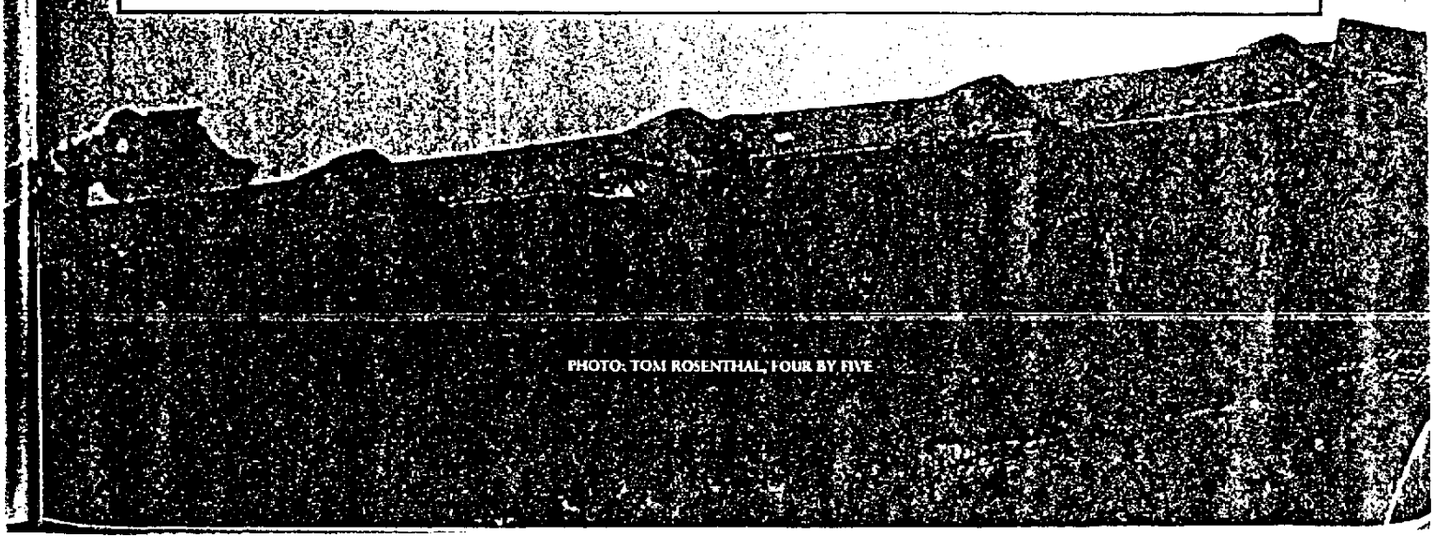
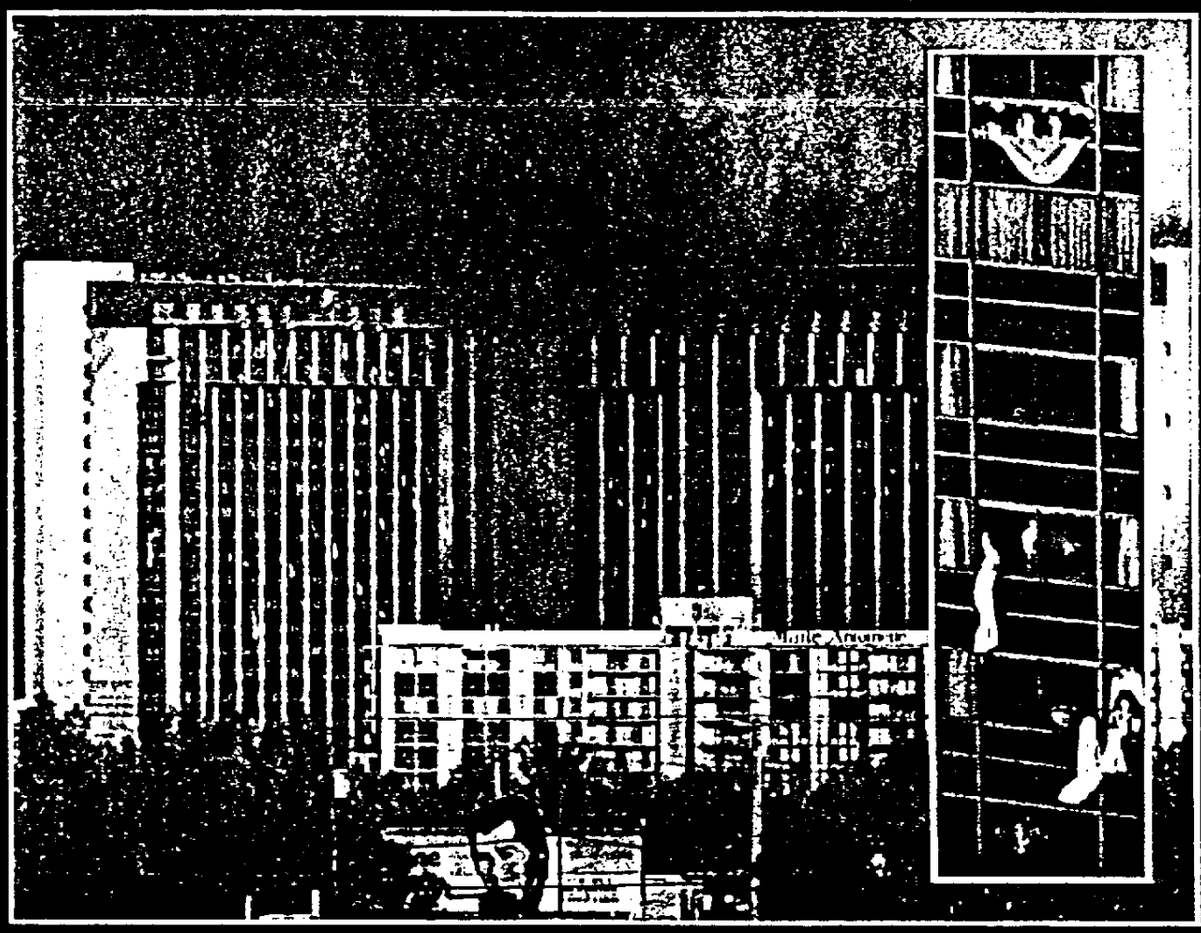
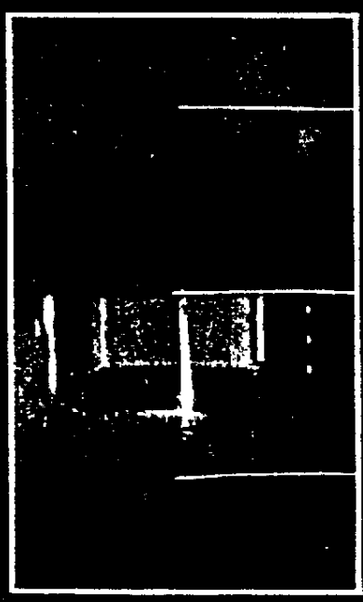
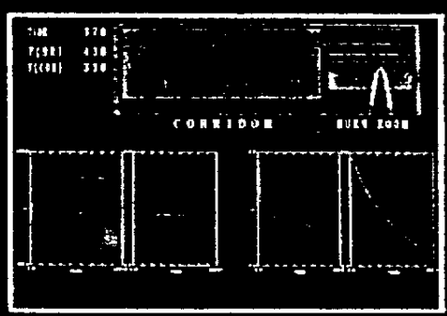
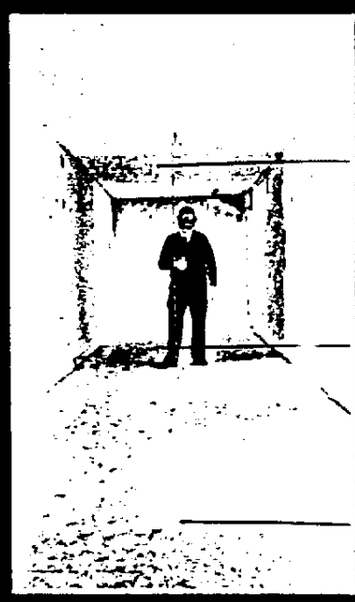


PHOTO: TOM ROSENTHAL, FOUR BY FIVE









Eighty-three people died, most from inhaling smoke, in the 1980 Las Vegas MGM fire (top). Some observers say we can reduce such deaths now—for example, by establishing a combustion-toxicity data bank. Others claim we first need better hazard-assessment tests, such as a computerized method being developed at the National Bureau of Standards. The photographs left and right show how smoke from a "test burn" that quickly fills a corridor can be modeled on a computer screen above.

Smoke—not flames—is the primary killer in fires, and toxic gases generated when synthetic materials burn may be making smoke even more deadly.

The hydrogen chloride came from a polyvinyl-chloride wall covering. Birky says the study concluded that deadly gases from the burning synthetics "contributed to most, if not all," of the deaths.

Representatives of synthetics manufacturers have assailed Birky's conclusions. For example, John Lawrence of the Society of the Plastics Industry says, "There were a lot of synthetic materials in the room where the fire occurred, but there were a lot of burnable nonplastics, too." He notes that the Houston medical examiner listed inhalation of carbon monoxide and soot as the cause of death of every victim except for the people in one room, who had lethal levels of hydrogen cyanide in their blood. Even then, Lawrence says that blood-cyanide measurements are often suspect because the body itself produces some hydrogen cyanide. "We feel that plastics, where properly used, do not present any increased hazard," he concludes.

Clash of Interests

The dispute over the Westchase Hilton tragedy is part of a larger, long-standing, and heated controversy in fire safety. There is no question that use of synthetics in buildings is rapidly increasing. "We live in a synthetic world," says Birky, where plastics and other synthetic materials have become commonplace in furnishings. Perhaps less visible is the growing role of synthetics in construction. In the mid-1960s, plastics represented only 2 percent of total building materials. By 1981, they had captured 10 percent of that market, according to Predicasts, a Cleveland market-research firm. And trends suggest that use of plastics may grow even more during the rest of the decade.

Has this shift heightened the danger of fires? Should the use of plastics and other synthetics somehow be regulated based on the toxicity of the smoke generated when they burn? Are laboratory tests well-enough developed to compare the smoke toxicities of various products, and to become the basis for selecting—and perhaps restricting—the use of furnishing and construction materials?

Answers to these questions have proved elusive, partly because combustion toxicology is a complex science, but also because huge economic stakes are involved and the issues have been clouded by corporate maneuverings and rhetoric. The most vociferous charges have been exchanged between the Society of the Plastics Industry (SPI), a trade association, and Allied Tube & Conduit Corp., which produces steel conduits used to contain and protect electrical wiring. Such conduits, along with pipes used in plumbing and to carry gas, have been one of the fastest growth areas for plastics in the U.S. construction industry.

Against this backdrop, an increasing number of toxicologists, legislators, and fire-safety officials has begun to sort through the tough regulatory and scientific issues. Indeed, the smoke-toxicity debate—which really gained steam during the widely publicized string of hotel fires starting with the Las Vegas MGM Grand Hotel disaster in 1980—has reached white-hot intensity.

Spurring the latest round is a report urging New York State to require manufacturers of building and furnishing materials to use a standard laboratory test to identify the poisonous gases generated when their products burn. The report, prepared by Arthur D. Little, a consulting firm based in Cambridge, Mass., recommends that such information on toxicity be filed in a central data bank. The New York Legislature, following the 1980 fire at Stouffer's Inn in Harrison, N.Y., which claimed 26 lives, had asked ADL to examine the feasibility of regulating smoke toxicity.

The fate of this proposal is still uncertain. New York Secretary of State Gail S. Shaffer is expected to recommend that the state establish a pilot program requiring manufacturers of mattresses, furniture, and interior finishings such as wall covering to test their products and submit the results to a data bank. However, she is expected to exclude construction materials.

Should New York adopt even this limited program—which is considered likely—it would be a landmark in fire-safety regulation. Of course, construction methods and materials are already subject to numerous other fire-safety-related regulations. A multitude of building-code provisions calls for fire alarm systems, fire doors, fire escapes, fire extinguishers, and exit corridors. And the Consumer Product Safety Commission has set mandatory flammability standards for mattresses and carpets and voluntary standards for upholstered furniture. But precious few codes, standards, or laws specifically address smoke toxicity.

One emerging code involves plastic conduit—a tube, composed mostly of polyvinyl chloride, or PVC, that is used to enclose electrical wiring. Because it is more flexible and easier to install, plastic conduit offers an attractive alternative to its metal counterpart in certain construction situations. But concern over the risk of smoke toxicity prompted the National Fire Protection Association to take action. The 1984 National Electric Code—a model code published every three years by the association, which local jurisdictions can choose to adopt—recommends that PVC conduits be permitted only in structures no taller than three stories. Some cities have already taken other steps. For example, New York City spent $2 million in 1982 to replace with metal some of the PVC conduits in the subway system.

Other regulations related to smoke toxicity include general proscriptions in several states and local jurisdictions to the effect that building materials cannot release combustion products more toxic than those of wood. But these laws, written years before scientists began developing standard laboratory tests of smoke toxicity, go largely unenforced. However, about a half-dozen states are now taking a hard look at just how toxicity testing might be used to regulate a broad spectrum of products. What New York decides to do with the ADL report could set the stage for these other states to act.

Report Gets Mixed Reviews

The ADL study evaluated the dozen or so published methods for testing the toxicity of combustion products, including one that Birky helped develop when he was at the National Bureau of Standards (NBS). The study, led by Rosalind C. Anderson, concluded that the most useful test is one developed by Yves Alarie and Anderson when she was at the University of Pittsburgh. Anderson said she sees no conflict of interest in recommending a test that she helped design; she also helped design the NBS toxicity test that was rejected.

In the Pittsburgh test, mice in a special chamber are exposed to smoke from burning materials. This method determines what's called an LC_{50}—the amount of material that produces a "lethal concentration" of smoke noxious enough to kill 50 percent of the animals exposed for 30 minutes. (Anderson says a shorter period wouldn't address most fire situations where people are waiting to be rescued,

PHOTOS: NATIONAL BUREAU OF STANDARDS

and a longer period would probably kill all the mice.) The lower the LC_{50} value, the more toxic the material. According to the Pittsburgh test, the LC_{50} of Douglas fir, for example, is 31 grams, while that of wire coated with polytetrafluoroethylene (Teflon) is 3 grams.

The ADL report recommends that manufacturers submit LC_{50} data on their products to a state agency, where the information would be accessible to architects, engineers, and the public. Anderson says the ADL study ruled out, for the time being, other regulatory uses of the data, such as bans on specific materials and requirements for product labeling.

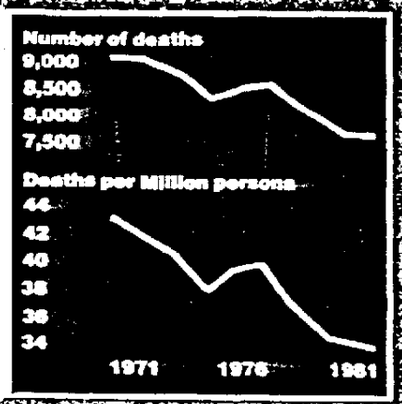
Reviews of the report have been mixed. Firefighters and fire-safety officials have generally approved, though some say they would have preferred ADL to voice stronger recommendations, such as the use of LC_{50} data to ban specific products. Critics, on the other hand, have charged that a smoke-toxicity data bank would be worthless. "The problem here is that the kind of data collected will be of no value in saving lives," said G.R. Munger, president of the Society of the Plastics Industry, in his comments to the New York Legislature. Simple, small-scale toxicity tests are not representative of the complex hazards of real fires, he said.

In fact, Munger and others claim that such tests could sometimes lead builders to select products that ignite more easily or whose flames spread faster as a tradeoff against their lower combustion toxicity. For example, PVC has largely replaced cotton as an insulating material for electrical wires, in part because its higher ignition temperature makes it less likely to burn. "We think that's an example of increased fire safety from using plastics," says SPI's Lawrence. He also points out that many fires are caused by electrical short circuits, which often result from improperly grounded metal conduits. And while burning PVC plumbing has been implicated—controversially—in some of the 83 deaths in the MGM Grand fire, he points out that a short in a metal conduit started the fire. Thus, even if tests show gross differences in smoke toxicity, the results should be interpreted with caution since other flammability properties are involved in assessing hazard.

Barbara C. Levin of the NBS Center for Fire Research agrees that an LC_{50} data bank is unnecessary. In her comments to the New York State Legislature, she stated that "a toxicity test alone does not constitute toxic hazard assessment." She noted that NBS is now developing a computerized method for assesing the hazards of combustion that takes into account a product's rate of heat release, ignitability, and other fire-related characteristics as well as smoke toxicity. The method is expected to be ready in about five years.

ADL's Anderson counters that, while more research will undoubtedly improve assessment techniques, the fact that most fire victims are being killed by smoke means we shouldn't sit idly by until a hazard index is developed. And there is another pressing issue. "As melodramatic as it sounds, firefighters are out there watching their colleagues being hurt and even die," she says. She cites a study by the National Fire Protection Association that found that firefighters say that fires are getting harder to fight. Fires burn faster and hotter, and smoke develops more rapidly and is thicker and more irritating to the respiratory tract. "There appears to be an increase in firefighter casualties from smoke inhalation," the association concluded. "The smoke in today's fires . . . may be producing increased risk of inhalation injury to firefighters as well as to building occupants."

SPI officials maintain that there is only anecdotal evidence to support the contention that fires are now more threatening because of smoke from burning plastics. They point to two SPI-supported studies—one reported in March 1979 by the Harvard School of Public Health and the other in May 1981 by the Southwest Research Institute—that show high levels of carbon monoxide to be the most hazardous air contaminant detected by gas-sampling



equipment worn by firefighters.

However, Birky says the SPI-supported studies are not only limited; they also do not explain why postfire investigations have turned up sublethal doses of carbon monoxide in victims' blood. Such doses were found not only in the Westchase fire, he says, but also in the MGM Grand disaster, where half of the 83 people who died at the scene were found to have sublethal carbon-monoxide levels. He acknowledges that such an effect has been uncovered in only a few instances, "not because it doesn't occur, but because the follow-up toxicological studies on the victims have not been thorough enough to demonstrate this factor." (Birky has left the Foundation for Fire Safety, located in Rosslyn, Va., to start a fire-toxicology consulting service in Boonsboro, Md.)

Charges and Countercharges

Calling this the most important question in fire safety, the foundation last year embarked on a national study to pinpoint which toxic gases are causing deaths by smoke inhalation. "We have developed a post-mortem protocol," says Thomas Casey, former executive director and now a consultant to the foundation, "and we are working with paramedics, medical examiners, and fire services to ensure that more complete autopsies are performed on fire victims. For example, we specify that blood samples be drawn within three hours of the fire and that they be properly stored and handled." Thirteen cities, including Seattle, Miami, Denver, and Dallas, are already participating in the study. Thus far, the foundation has collected data on 60 fire victims, but plans to gather data on 250 before drawing conclusions.

SPI officials are already skeptical of the study. They point out that the foundation is largely funded by the Allied Tube & Conduit Corp. and other members of the metal industry. These firms, according to an SPI statement, have "embarked on a 'fear and smear' campaign against plastic products in order to win back [their] position in the marketplace." John Lison, vice-president and general counsel for Allied, counters such charges: "Instead of developing safe products, the giant plastics industry has used its extensive public-relations apparatus to attempt to turn what is a very vital question of public safety . . . into a seemingly commercial battle between two industries."

"There's no doubt that this is a commercial fight," says Gordon Vickery, president of the foundation and former head of the U.S. Fire Administration. "I do not offer one ounce of apology for the funding of the foundation by the Allied Tube & Conduit Corp. We invite, as we have in the past, the plastics industry to support us in like manner."

The impact of commercial interests can also be seen in recent actions of the National Institute of Building Sciences (NIBS), created by Congress in 1974 to unify and improve the heterogeneous network of U.S. building codes. When the rash of hotel fires brought burning plastics under close scrutiny, NIBS officials felt pressured to address this issue. In June 1982, they formed a 12-member task force to consider whether the results of laboratory tests of combustion toxicity, such as the NBS and Pittsburgh methods, should be incorporated into building codes. For example, a code could forbid the use of products judged by one of those tests to be more toxic than wood, unless those products are accompanied by early-detection fire-protection systems such as smoke detectors and sprinklers. Wayne Ellis, manager of industry standards for the H.B. Fuller Co., which makes synthetic adhesives, sealants, and coatings used in building construction, was named chairman. The task force also included SPI's Munger, two DuPont officials, and representatives from Dow Chemical, Rohm & Haas, and Armstrong World Industries. Only one member—James R. Bell of the National Fire Protection Association—was not affiliated with a corporation, trade association, or the government.

Later that summer, the task force hosted

PHOTOS: UPI; HOUSTON CHRONICLE; FOUNDATION FOR FIRE SAFETY

a meeting and invited people holding points of view at odds with those of the synthetics industry, but the group did not include these people on the agenda of speakers. "The only speaker designated to explain the 'state-of-the-art' in toxicity testing methodology," says an Allied spokesperson, "was Gordon Hartzell of the Southwest Research Institute. Significantly, the SRI study that formed the basis of Hartzell's remarks and conclusions was commissioned and paid for by none other than the Society of the Plastics Industry." Thus, it came as no surprise, says the Allied representative, that Hartzell described available tests as "primitive" and insufficiently developed for regular use.

Ultimately, in an official report released last May, NIBS recommended against setting building codes based on smoke toxicity. Part of its reasoning was that such codes would not include interior furnishings. But Anderson counters that while it is tempting to think of furnishings as the more significant hazard, "fires do start in the basement, attic, or storage area and travel between the walls, burning only structural elements." She also says the distinction between structural and furnishing fires "has never been addressed on a percentage basis; nobody has measured it."

More importantly, however, the NIBS report concluded that laboratory tests of combustion products are inadequate and should not yet be used to compare the smoke toxicities of any materials. But this is "ridiculous," says Eugene Rider of the United States Testing Co., in Hoboken, N.J., "Take the NBS protocol: years of research and millions of dollars went into it," he says, adding that the quality of research behind that test exceeds that upon which most flammability tests are based.

Money—and Lawsuits—May Talk

Still, a group of state legislators is concerned with the cost of *not* taking action. This group, called the National Task Force on Firegas Toxicity, is composed of lawmakers from California, Illinois, Indiana, Ohio, Maryland, and Michigan. While the group believes the benefit of regulating smoke toxicity could ultimately be measured in lives saved, it recently focused on a "cost of not regulating" that is infinitely easier to gauge: lawsuits. Injuries and deaths from smoke inhalation are posing "a whole new series of product-liability questions," says Ohio Sen. Charles Butts. "This seems to be happening with the law-

suits stemming from the MGM fire; plastics companies have been brought into the lawsuits and may bear a liability even though they weren't responsible for how the fire started."

The task force, which has conducted several hearings on the smoke-toxicity issue, will issue a final report this year that "may very well have recommendations for legislation," Butts says. Like the ADL report to New York State, this one will probably call for establishing a data-gathering agency for combusion toxicity. "We need to have some kind of data bank; we need to use some kind of testing mechanism," Butts says. "Now, 'specifiers' [architects, engineers, buildings owners, and so on] have no information on which to base their decisions. They are making decisions that may be allowing buildings to become more dangerous, and that may be leaving themselves vulnerable to lawsuits." Butts also says that insurance companies, fearing "their clients will find themselves in a toxicity lawsuit," may soon become involved in the smoke-toxicity debate. This, he envisions, would provide a powerful impetus to the movement to establish procedures for testing the combustion toxicity of building and furnishing materials.

That's the best-case scenario, ADL's Anderson says. For a worst-case scenario, she draws parallels to the asbestos story. Information on the health effects of asbestos "had been there for years," she says. "Unfortunately, some of the people who were in positions to make decisions and change policy had only fragments of that information. That's the type of situation some people are saying is developing as we bring new products into buildings. There is the fear that we are stacking the indoor environment with materials that, if we could only see all the combustion-toxicity data available, would be deemed unacceptable in terms of fire safety."

Says Anderson: "I'm not suggesting we ban products—we don't have enough data yet to take this regulatory route. And product labeling is good for only about 30 seconds; once you have the wallpaper up, you've forgotten what's on the label. But if we had a centrally located combustion-toxicity data bank, we could start drawing useful conclusions."

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TOXICITY OF COMBUSTION PRODUCTS: CURRENT KNOWLEDGE

FREDERIC B. CLARKE, III

IN THE MARCH 1983 ISSUE OF FIRE JOURNAL,[1] the NFPA published a report on the toxicity of the products of combustion. The report is the result of a year that the NFPA Standards Council's Committee on the Toxicity of the Products of Combustion spent compiling and analyzing a vast amount of technical information. The Council's report sets forth a number of significant principles and policies for both NFPA committees and for the fire community in general.

Those who are unfamiliar with combustion-product toxicology may have been surprised to discover that a subject that excites so many questions provides so few clear answers. There are a number of reasons why this is so. The field is a new one, scarcely ten years old. Furthermore, the most desired answers cannot be supplied by combustion toxicology alone, but must come from contributions from several different fields.

It is likely, therefore, that combustion-product toxicity will occupy a prominent place in firesafety discussions, within the NFPA or elsewhere, for some time to come. Members of the NFPA will increasingly feel compelled to become acquainted with the subject, perhaps as participants in the discussion and certainly as informed professionals. This article is a brief introduction to combustion-product toxicity — the capabilities, limitations, and central issues. It supplements a comprehensive review of the subject prepared by Benjamin/Clarke Associates for the NFPA Committee on the Toxicity of the Products of Combustion. (Copies of the review document are available from the NFPA.)

Early Concerns Over Toxic Combustion Products

The first major recognition that the environment might pose threats from fire that were not anticipated by past experience came with the Cleveland Clinic fire in 1929. In that fire, nitrocellulose film (then a newly-developed material) played a major role. For the first time, a major fire had produced considerable quantities of toxic combustion products, in addition to the ubiquitous oxides of carbon. Although the oxides of nitrogen produced by this material are not prominent in today's spectrum of common combustion products, the incident foreshadowed a concern that would become acute with the avalanche of synthetic materials in the 1950s and 1960s: how to assess the risks associated with combustion products from a multitude of new materials.

The NFPA first began to inquire into the detailed effects of smoke in fires in the 1950s.[2] Since that time, a significant amount of literature has been published, primarily in the medical field, on the treatment of smoke inhalation victims. Cornish,[3] Boettner,[4] and Autian[5] called specific attention to the threat that might arise from new, synthetic materials that became an increasing part of building fire loads in the 1960s. However, their concerns were prospective, arising from the recognition that synthetic materials differ chemically from traditional materials, rather than retrospective, i.e., arising from fire experience.

We depend today on a variety of polymeric materials — both man-made and naturally-occurring — and the smoke produced when these materials burn can differ in its toxicity. While experience had taught us that there is no such thing as "healthy" smoke, it was suspected that different materials might produce combustion products for whose toxic properties we were unprepared. Some common families of polymers, both natural and syn-

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[1] "Report of the Committee on the Toxicity of Products of Combustion to the Standards Council of the National Fire Protection Association," FIRE JOURNAL, Vol. 77, No. 2 (March 1983), pp. 21–27.

[2] NFPA Committee on Fire Gas Research, "Fire Gas Research Report: Report of Research by Arthur D. Little, Inc.," *NFPA Quarterly*, Vol. Q45, 1952, pp. 250–306.

[3] H. Cornish, and E. Abar, "Toxicity of Pyrolysis Products of Vinyl Plastics," *Archives of Environmental Health*, Vol. 19, No. 1, 1969, pp. 15–21.

[4] Edward A. Boettner, and Benjamin Weiss, "Analytical System for Identifying the Volatile Pyrolysis Products of Plastics," *American Industrial Association Journal*, Vol. 28, No. 6, 1967, pp. 535–40.

[5] J. Autian, "Toxicologic Aspect of Flammability and Combustion of Polymeric Materials," *Journal of Fire and Flammability*, Vol. 1, 1970, pp. 239–68.

thetic, are listed in Table 1, along with the combustion products that they may, on the basis of their chemical composition, possibly produce. The degree to which these products actually present new risks was unknown.

The first statistical examination of fire fatalities came from the United Kingdom. Bowes[6] pointed out in 1971 that, while there had been only a modest increase in overall fire casualties in Britain in the previous ten years, a relatively large increase had occurred in the number of smoke inhalation injuries. Bowes suggested that increased amounts of synthetic polymers in buildings might account for this change. The British report discounted the possibility that smoke from modern fires was any more toxic than smoke in earlier fires, since survival rates of smoke inhalation victims were unchanged.

However, even this report contained some uncertainties. In order for one category of injury to increase without significantly changing the total number of injuries, it is necessary for burns, the other major category of fire injury, to have decreased in Britain during the same time period and there are no obvious reasons for this to occur. Other, more recent studies[7] in the United Kingdom have shown that a large percentage of supposedly burned fire victims were actually victims of smoke inhalation, as well. Since postmortem examination of fire fatalities is a fairly recent procedure, Bowes' conclusion would be strengthened if it were known to what extent burn fatalities in early years were later counted as smoke inhalation fatalities.

Systematic laboratory investigations of the toxicity of combustion products began in the early 1970s. Although there was already a large amount of chemical data, as well as preliminary biological experiments, it was recognized that a much more systematic approach was required.

Toxicity's Part in Today's Fire Problem

The sheer variety of combustible materials now in our everyday environment means that there is also a very broad spectrum of combustion products in typical smoke

[6] P. Bowes, "Smoke and Toxicity Hazards of Plastics in Fire," *Annals of Occupational Hygiene*, Vol. 17, 1974, pp. 143–157.

[7] W. Harland, and W. Woolley, "Fire Fatality Study, University of Glasgow," Building Research Establishment, BRE Information Paper IP 15/79, London, August 1979.

Table 1.
Some Common Polymers and Their Major Combustion Products

Polymer Name	*Chemical Elements Present*	*Commonly Found in*	*Possible Combustion Products In Addition to CO,CO₂*
Acrylonitrile-Butadiene-Styrene (ABS)	C, H, N	Appliances, phone components, pipe, engineering, plastic applications	H_2O, HCN
Cellulose	C, H, O	Wood, paper, cotton, jute	H_2O, acrolein
Keratin (protein)	C, H, O, N, S	Leather, wool	H_2O, HCN
Polyacrylonitrile (PAN)	C, H, N	Modacrylic fiber	H_2O, HCN
Polyamide (nylon)	C, H, O, N	Engrg. plastics applications, carpeting	H_2O, NH_3, HCN
Polymethyl-methacrylate (PMMA)	C, H, O	Window panes, lighting fixtures	H_2O, aldehydes
Polyphenylsulfone	C, H, O, S	Engrg. plastics applications	H_2O, SO_2
Polyethylene (PE, HDPE)	C, H	Kitchen ware, upholstery, carpeting	H_2O, aldehydes
Polystyrene (PS, HIPS)	C, H	Appliances, cabinets, foam insulation, engrg. plastics (high impact)	H_2O, aromatic hydrocarbons
Polytetrafluoro-ethylene (PTFE)	C, F	Coatings, wire insulation	HF, COF_2, fluorinated organics
Polyurethane (PU)	C, H, O, N	Rigid insulation, flexible seat cushions	H_2O, HCN, isocyanates
Polyvinylchloride (PVC)	C, H, Cl	Upholstery, wire coating, pipe, wall and floor covering	H_2O, HCl, aromatic hydrocarbons

today. It does not follow, however, that the fire problem worsens as the use of synthetic materials increases. Since the number of fire deaths in the United States has declined significantly in recent years,[8] one could argue, on the basis of those statistics, that modern materials result in increased safety. However, it is also conceivable that the decline in deaths would be even larger for a different mix of combustible materials, so such an argument is, at best, speculative.

One clue to the real situation may come from the fire experience of other countries. It is often noted that the US death rate is considerably higher than those of western European countries and Japan. Recently, building materials and furnishings that have been commonplace in this country for a number of years have appeared increasingly in Europe and Japan. If the US fire loss record is inescapably a result of the kind of materials that burn, one would expect to see dramatic increases in the fire death rates in these countries as their built environment and furnishings become increasingly similar to those in the United States. To our knowledge, this has not yet been observed. From a purely statistical point of view, there is little evidence to support the hypothesis that present-day materials, and the combustion products associated with them, have exacerbated the fire problem.

However, gross statistics do not provide the details needed on the causes of fire deaths. An investigation of the causality of fire deaths must include both the immediate causes of fire fatality and the contributory causes, i.e., the reasons why the persons received a lethal exposure. Table 2 summarizes this information for fire deaths not involving burns. Note that the immediate causes of fire fatality shown in the table are poisonings by airborne chemical agents, or asphyxiation by oxygen depletion.

Table 2.
Causes of Fire Deaths

Possible Reasons for Lethal Exposure	*Possible Immediate Causes of Fire Fatality*
Vision obscuration	Carbon monoxide poisoning
Irritants impeding vision and/or escape capability	Carbon dioxide intoxication and oxygen depletion
Motor and/or judgment impairment	Poisoning by other airborne fire product(s)

The search for contributory causes is more difficult. For example, it is known that smoke can impair visibility, and thereby, it is suggested, impede a person's ability to escape. In such cases it is tempting to postulate other impairments to escape, such as irritants or incapacitants. Irritants might so preoccupy the victims that they no longer concentrate on escape; other incapacitants may disorient and confuse them. Although there are clinical methods for determining carbon monoxide poisoning, poisoning by other airborne fire products is more difficult to detect: a potential agent must be identified before it can be analyzed, and a method of analysis must exist.

The lethality of carbon monoxide, which seems to be present in virtually all accidental fires, has long been known. The presence of carboxyhemoglobin (COHb) in levels equal to or greater than 50 percent of total hemoglobin is generally assumed to be lethal.[9,10] Many studies have also appeared[11] on reduced biological, and presumably motor, functionality of people exposed to sublethal amounts of carbon monoxide. Therefore, this gas may function as both the cause and the reason for fire fatalities. A check of carboxyhemoglobin level in the blood is generally the first step in determining the cause of death in fire.

Postmortem detection of chemical irritants is uncommon. If the irritant is pulmonary, the lungs can be examined, and pulmonary edema (the accumulation of fluids in the lungs) can be taken as evidence of pulmonary injury. However, detecting the actual agent of irritation is generally not possible. Pulmonary edema, for example, can be caused by aldehydes, such as acetaldehyde and acrolein from wood, hydrogen chloride, hydrogen fluoride, and their precursors. Furthermore, death from pulmonary edema can occur up to several days after exposure to the fire.[12]

In 1972, a major study of fire deaths in the state of Maryland was undertaken by The Johns Hopkins University Applied Physics Laboratory.[13] Detailed postmortem examinations were made of 511 fire fatalities occurring over a five-year period. These comprised 64 percent of the statewide fire fatalities in Maryland during that time. The study has some bias toward urban populations, but can generally be taken as the most comprehensive, and only systematic, study of fire fatalities conducted in the United States.

The overall breakdown of Maryland fire fatalities by medical cause of death is shown in Table 3. The study assumed that those victims whose bodies contained more than 50 percent carboxyhemoglobin died of carbon

[8] M. Karter, "Fire Loss in the United States During 1980," FIRE JOURNAL, Vol. 75, No. 5 (September 1981), p. 60.

[9] A. Cooper, ed., "Carbon Monoxide: A Bibliography with Abstracts," US Dept. of Health, Education and Welfare, Public Health Service Bib. No. 68, 1968, p. 40.

[10] This is the value generally accepted by forensic pathologists. However, the victim's physical condition, age, and level of activity during fire exposure can have significant effects on the level found in postmortem examination.

[11] Cf. R. Stewart, et al., "Experimental Human Exposure to Carbon Monoxide," *Archives of Environmental Health*, Vol. 21, 1970, pp. 154–164; and R. Stewart, et al., "Experimental Human Exposure to High Concentrations of Carbon Monoxide," *Archives of Environmental Health*, Vol. 26, 1973, pp. 1–7.

[12] B. Zikria, et al., "Smoke and Carbon Monoxide Poisoning in Fire Victims," *Journal of Trauma*, Vol. 12, No. 6, 1972, pp. 641–645.

[13] W. Berl and B. Halpin, "Human Fatalities from Unwanted Fires," NBS grant/contract report NBS-GCR-168, 1979, p. 57.

Table 3.
Clinical Causes of Death,
State of Maryland, 1971–1977

Category	*Cause*	*Percent of Deaths*
1	Burns	15
2	Carbon monoxide alone (COHb greater than 50 percent)	45
3	Carbon monoxide and other factors*	16
4	Heat and carbon monoxide not significantly involved	15

* Included in this category are victims with COHb between 30 and 50 percent, plus cyanide and/or pre-existing heart disease.

monoxide poisoning. Searches for additional evidence of combustion-product toxicity focused on the fire fatalities that did not involve lethal levels of carbon monoxide or lethal heat exposure: categories 3 and 4 in the table. Category 3 reflects the effect of contributory causes (preexisting heart disease or simultaneous exposure to hydrogen cyanide) on susceptibility to carbon monoxide. Unfortunately, the study did not record the relative importance of these two very different contributors. Category 4 includes those dying of all miscellaneous causes, including heart attacks, falls, and the like. About half of the category, some 10 percent of the total fire deaths, is made up of those deaths that are essentially unexplained by carbon monoxide, burns, or other clear cause, and includes those with symptoms expected from pulmonary irritants. This portion of the fire deaths contains the major unknown effects of toxic combustion products. Unfortunately, we have no way to determine whether this 10 percent is a recent phenomenon or whether there has always been a similar portion of fire deaths that has been essentially unexplained.

Measurement Systems For Toxic Combustion Products

The early discussions of combustion toxicology were characterized by debates on whether chemical analysis or animal testing was the better approach. As capabilities for chemical analysis improved, it became clear that a very large number of pyrolysis products could be generated even from materials whose original composition was well-characterized and relatively simple. Early workers[14] identified over 50 different compounds produced by the pyrolysis of a single sample of polyvinylchloride. Wood produced similar results.[15] This complexity convinced early investigators that they could not confidently predict the toxicity of smoke by chemical analysis.

Another drawback of chemical analysis is that, without biological tests, there would be no way of detecting a single toxic product unless its existence had been previously predicted. In 1977, an unpredicted toxic product was reported by Petajan and coworkers at the University of Utah.[16] This toxin, identified as a bicyclic organic phosphate, was produced by the reaction of a phosphorus-containing fire retardant with one of the components of the urethane formulation tested. The product was first detected by its acute effects on laboratory animals, including epilepsy-like seizures, as well as observable psychomotor effects on several of the human investigators.

Fortunately, the urethane formulations that produce the toxic agent are not reported to be commercial products. Actually, it was later discovered that the supposedly highly toxic agent was, in fact, no more potent than many other combustion products and was distinguished principally by the unusual nature of its effects. Nonetheless, reports of this toxic agent created a great stir at the time, and served to resolve, at least for the moment, any lingering controversy between the chemists and the animal testers. It was convincing evidence of the need for a screening device to identify materials that produced unexpectedly toxic smoke.

The development of a screening-type of test to identify materials that produce highly toxic combustion products is commonly viewed as easier to accomplish than a test that determines how smoke from each burning material in a fire contributes to the overall toxicity hazard. However, whatever their specific goals, all such tests methods have several elements in common: a combustion and pyrolysis method, an exposure chamber, and toxicological measurements.

Combustion and Pyrolysis Method

The method chosen to convert the solid sample into airborne material for exposure to test animals is crucial in determining the relation of any laboratory test method to full-scale situations. In general, one cannot simply build the expected room fire and expose laboratory animals, because the heat of the smoke will mask the toxic effects. If the smoke is cooled prior to the exposure, one risks condensing out components of the smoke before they reach the exposure chamber. Although there are almost as many methods of generating the smoke as there are test methods, the methods fall into three main categories: tube furnaces, open cups, and radiant heat.

Methods employing tube furnaces generally contain the sample in a glass tube that is inserted in a furnace or

[14] Edward A. Boettner, and Benjamin Weiss, "Analytical System for Identifying the Volatile Pyrolysis Products of Plastics," *American Industrial Hygiene Association Journal*, Vol. 28, No. 6, 1967, pp. 535–40.

[15] National Academy of Sciences, *Proceedings of the International Symposium on Physiology and Toxicological Aspects of Combustion Products*, Salt Lake City, Utah, March 1974.

[16] J. Petajan, et al., "Extreme Toxicity from Combustion Products of a Fire Retarded Polyurethane Foam," *Science*, Vol. 187, 1975, pp. 742–744.

some other heating device whose temperature can be controlled. A stream of air or nitrogen is passed through the tube to carry the products to the exposure chamber and to support combustion if it occurs. The smoke generated in this way is frequently mixed with additional air after it leaves the heated zone to provide cooling and dilution. The advantage of using this approach is good temperature control.

In the open cup furnace, the sample is placed in a glass or steel cup and heated by heating the cup. This method allows smoke to be transported to the animal exposure chamber by convection. It permits the addition of a sample after preheating, so that the temperature that the sample encounters can be closely controlled. There are two principal disadvantages to this method. First, heat transfer to the sample is inefficient, especially for low-density materials. Second, and more important, access of air to the sample is hampered, especially when the sample fills the cup, and in such cases burning often occurs only with difficulty.

In both furnaces and cups, heat is supplied to the sample largely by conduction from the hot walls of the apparatus. It has been suggested that the burning conditions that result are not typical of most real fires, where radiation is the principal mode of heat transfer.

Methods that use radiant heat avoid this difficulty. In addition, radiant heat appears to be the best method of exposing nonhomogeneous materials such as composites, since their combustion in either cups or tubes often requires them to be cut into small pieces or pulverized.

The utility of a given method of pyrolyzing or burning the sample depends largely on what the test method is intended to accomplish. One cannot, for example, take it for granted that combustion products in real fires will be similar in detail to those produced in tests, because real fires usually involve open flame, while none of the commonly used test methods employ flames as a major heat source. In at least one case, polytetrafluoroethylene, the use of a flame instead of an electrical heating method can reduce the toxicity of the smoke about one thousandfold.[17] Although this is probably an extreme example, it suggests that one must decide whether it is important to maintain laboratory conditions similar to real fire conditions. If actual fire conditions are intended, particular care must be used in interpreting test results.

Exposure Chamber

Exposure chambers, and the method used to move the combustion products to the chamber, vary considerably. In some cases, test animals are placed entirely in the chamber, a situation that approximates reality; in other tests, they are exposed "nose-only." The latter method reduces heat stress on the animals, keeps them from ingesting combustion products orally or breathing through another animal's fur, and allows easier instrumentation of the animals.

Beyond their size and materials of construction, exposure chambers differ principally by being either "static," where the entire charge of smoke is caught and held during the exposure, or "dynamic," where a continuous flow of smoke from the combustion chamber is provided. Both types of chambers have their supporters and their advantages.

One attractive feature of the static chamber is that it permits ready calculation of the smoke concentration, since the volume is fixed. A schematic representation of a generic, static-type test apparatus is shown in Figure 1. The static arrangement simulates, to some degree, exposure to a fire in or near the room of origin, in situations where the smoke accumulates, i.e., there is limited flow-through ventilation. One disadvantage is that the static chamber is impractical to use for studying pyrolysis products at a varying temperature over the course of the experiment, since the chamber contains the smoke generated over the entire temperature range. Another drawback of the static system is that considerable attention must be paid to ensuring uniform distribution of the smoke throughout the chamber. Finally, the chamber must be large enough so that oxygen will not be depleted during the course of combustion and carbon dioxide from the animal's respiration will not build up to interfering levels.

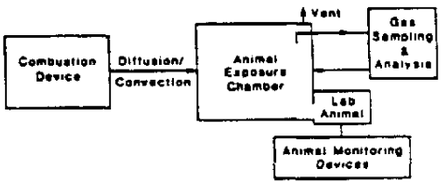


Figure 1. Schematic representation of static-mode combustion product toxicity test apparatus.

The dynamic chamber design, schematically depicted in Figure 2, is more amenable to temperature variation and also permits dilution of the smoke. Thus, it is generally a good deal faster, and thereby less expensive, to screen an unknown material using a dynamic system.

Toxicological Measurements

The variety of toxicological measurements made on the test animals is almost as large as the number of tests methods in existence. Most of the tests share the concept

[17] S. Williams, and F. Clarke, "Combustion Product Toxicity: Dependence on the Mode of Product Generation," *Fire and Materials*, Vol. 6, Nos. 3 and 4, 1982, pp. 161–162.

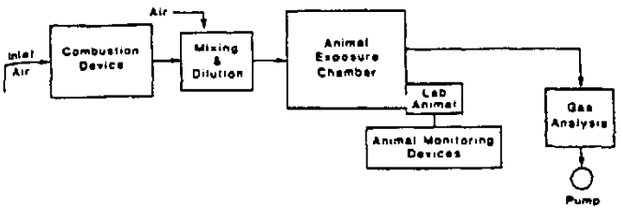


Figure 2. Schematic representation of dynamic mode combustion product toxicity test apparatus.

of lethality, although there is disagreement on whether time-to-death, lethal dosage, or both are the most appropriate measures of potency. In addition, there are a number of techniques for determining incapacitation of the test animals, although the utility of existing incapacitation techniques is still under discussion.

Classical toxicity studies of lethality center around the concept of dose-response, in which a chosen biological function is monitored as a function of the dose of the toxic agent. Lethality is the "customary starting point" of most toxicological investigations. Relating the fraction of an animal population succumbing within a fixed time to a given amount of agent yields a dose-response curve for lethality. The number generally reported is the dose that kills 50 percent of the animals.

In inhalation toxicology, dosage is normally expressed as the airborne concentration to which the animal subjects were exposed, and thus "LC50" refers to the concentration at which 50 percent of the test animals succumbed. For dynamic systems, the actual smoke concentration at any time is not generally known directly, so that data reported by the two systems generally cannot be directly compared.

Lethality data are generally presented on a logarithmic scale, partly because different materials can have measured lethalities that span several powers of ten. In addition, the reproducibility of such measurements is low, and potencies must differ by a factor of 3 to 5 before it is possible to attach any significance to the findings.

Time-to-lethality is also an important concept, since the outcome of any life-threatening fire is determined by its relationship to the time needed to escape. For many materials, the product of dosage and time-to-death is a constant, e.g., animals live twice as long when exposed to half the dose. At present, combustion-product lethality is determined by both time and dosage.

The desirability of an incapacitation monitor has long been recognized, since escape capability is so important in firesafety. In recent years, a number of approaches have been developed. We shall examine just a few.

The use of a tumble cage or variants, in which the animal is placed within a rotatable, wheel-like cage, is the basis of measurement in two test procedures. In one test, incapacitation is the point at which the animal can no longer maintain its equilibrium; in the other test, it is the point at which the animal no longer shows an inclination to turn the wheel.

Another approach involves monitoring the animal's avoidance of a mild electric shock. Avoidance can be the conditioned ability to move to an unelectrified location in the apparatus[18,19] or, if the animal is restrained, it can be the ability to keep a foot raised and out of contact with a charged electrical plate.[20] The latter is the so-called "hind-leg flexion" response used in the development of two test methods.

Although all of these methods have been or are now incorporated in some test procedure, they have been found to vary in sensitivity depending on the type of smoke being evaluated. Incapacitation measurements have been criticized because the dosage for incapacitation generally approaches the lethal level.[21] The National Bureau of Standards (NBS) has observed that the comparative toxicity of most materials is the same regardless of whether incapacitation, immediate lethality, or immediate-plus-post-exposure lethality are used as indices. These facts have prompted NBS to discontinue the separate measure of incapacitation in its test.

Another approach to incapacitation is to use biological measurements such as respiratory rate, blood pressure, and heart rate. These can be quite sensitive, and form the basis for the procedures of Alarie[22] and Gaume.[23] However, their relationship to actual incapacitation is not well established.

Common Test Methods

In Table 4, we have tabulated the seven common test methods that are the best documented. The fact that there are so many is ample evidence that little consensus exists among combustion-product toxicologists as to the best method of measurement. Two of the seven methods, DIN and JMC, are used in material control, both abroad. Three others have been proposed as standard methods in ASTM E-5 — R/F, NBS, and USF. The methods developed by Alarie and by FAA are also in-

[18] G. Pryor, J. Dilley, R. McKee, and S. Martin, "Behavioral Techniques in Fire Toxicology," Paper presented at the first California Conference on *Fire Toxicity*, San Francisco, California, 1979.

[19] R. Hartung, et al., "The Performance of Rats on a Rotorod During Exposure to Combustion Products of Rigid Polyurethane Foams and Wood," *Journal of Combustion Toxicology*, Vol. 4, 1977, pp. 506–522.

[20] J. Petajan, "Survival Response During Fire Exposure" in *Physiological and Toxicological Aspects of Combustion Products*, International Symposium of National Academy of Sciences, National Research Council, Salt Lake City, Utah, 1976.

[21] Y. Alarie and R. Anderson, "Toxicologic Classification of Thermal Decomposition Products of Synthetic and Natural Polymers," *Toxicology and Applied Pharmacology*, Vol. 57, 1981, pp. 181–8.

[22] Y. Alarie, "Irritating Properties of Airborne Materials to the Upper Respiratory Tract," *Archives of Environmental Health*, Vol. 13, 1966, pp. 433–449.

[23] J. Gaume, P. Bartek, and H. Rostami, "Experimental Results on Time of Useful Function (TUF) After Exposure to Mixtures of Serious Contaminants," *Aerospace Medicine*, Vol. 42, No. 9, 1971, pp. 987–90.

Table 4. Common Test Methods for Toxic Combustion Products

Method	*Fixes*	*Varies*	*Using*	*Time to Death*	*Time to Incapacitation*	*Incapacitating Dose*	*Lethal Dose*	*Lethal Sample wt.*	*Lethal Pyrolysis Temperature*	*Lethal Area Burned*	*Gas Analysis*	*Blood Chemistry or Pathology*
Federal Aviation Adm. (FAA)	sample size, temp.	—	rats	X	X						X	X
German National Standard (DIN)	sample size, exposure time	dosage to chamber, oven temp.	rats				X		X		X	X
University of Pitts. (Alarie)	rate of temp. rise, exposure time	sample size	mice	X		X		X				X
National Bureau of Standards (NBS)	temp. conditions exposure time	sample size	rats	X			X				X	X
Japan Ministry of Construction (JMC)	radiant flux	—	mice		X							X
University of San Francisco (USF NASA)	sample size temp. conditions	—	mice	X								X
BETR Laboratories (BLF)	radiant flux exposure time	sample size	rats	X	X					X		X

cluded. The most striking feature of this table is the lack of commonality of experimental variables and constants, to say nothing of the differences in experimental setup.

• *FAA-CAMI Test*

This method, developed at FAA's Civil Aeromedical Institute by Smith, Crane, and co-workers, has been used to determine the acute toxicity of aircraft materials.[24,25] It is a static system using a tube furnace. Rats are exposed to a fixed charge of material; times to incapacitation and death are reported.

The FAA approach was designed to determine the comparative escape times available when different materials undergo a set of thermal conditions in an aircraft cabin. However, it presents the common problem of having a relatively contrived combustion scheme.

• *NASA-USF Test*

This method was developed at the University of San Francisco by C. Hilado under contract to the National Aeronautics and Space Administration (NASA).[26,27] It consists of a tube furnace that exhausts into an exposure chamber containing four unrestrained mice. Air flow can be provided and the system is operated with either a constant or linearly rising temperature.

It can accommodate samples of varying size, but very little of the large amount of data reported by this laboratory involved dosage; the method has been used mainly to determine time-to-death or incapacitation, along with a periodic analysis of oxygen and carbon monoxide. The animals are not instrumented, and loss of function is determined visually.

The USF/NASA method is as simple and fast as the other methods are painstaking and complex. However, it also has drawbacks, the most serious of which is that visual observation alone is not a very effective way to determine or explain biological effects.

• *Japanese Ministry of Construction Test*

The only biological test method upon which an established regulation is based is maintained by the Japanese Ministry of Construction and carried out by four different laboratories in that country.[28] The test applies strictly to wall linings, and is used in conjunction with fire tests for noncombustibility and surface flame.

The toxicity test itself is dynamic, and uses female mice as the test subjects. The combustion apparatus is a small furnace in which a vertical sample is heated, first with a gas pilot flame, then with the pilot flame and a radiant heat source. Total heating time is 6 minutes; total exposure time is 15 minutes.

(Continued on page 94)

[24] C. Crane, et al., *Inhalation Toxicology. I Design of Small-Animal Test System. II Determination of the Relative Toxic Hazards of 75 Aircraft Cabin Materials*, Federal Aeronautical Administration report no. FAA-AM-77-9, NTIS AD-A043 646/9ST, 1977, p. 59.

[25] C. Crane, "The Prediction of Human Incapacitation by the Combustion Products Carbon Monoxide and Hydrogen Cyanide Using a Small Animal Test Protocol," Ann. Meeting, Aerospace Medical Association, 1979, pp. 151–2.

[26] C. Hilado, "Evaluation of the NASA Animal Exposure Chamber as a Potential Chamber for Fire Toxicity Screening Tests," *Journal of Fire and Flammability, Combustion, Toxicology Supplement*, Vol. 2, 1975, pp. 298–314.

[27] C. Hilado, A. Furst, and W. Marcussen, "The Use of the NASA Animal Exposure Chamber in Fire Toxicity Tests," *Proceedings of Western Pharmacological Society*, Vol. 19, 1976, pp. 397–400.

[28] Anonymous, "Sandard Method of Testing for Fire Protection Properties of Wallcovering Materials," Wallcovering Association of Japan.

The endpoint is incapacition, as measured by the failure of the mouse to continue to turn the rotatable cage in which it is contained. The standard requires that acceptable interior finish materials have an incapacitation time equal to or longer than that of the Philippine (Luan) plywood used as the test standard. Lethality is not determined.

It is important to note that use of the test is restricted to products in a single application — room interior finish; that the toxicity effects are measured in the hope of providing an empirical comparison of escape time; that the combustion method chosen is at least a logical mock-up of expected real exposure conditions; and that the test is used in conjunction with two other flammability tests.

- *German (DIN) Test*

This method, adopted by the German Commission on Standards as Deutsche Industries Normal 53 436,[29] is the second of two "national" standard test methods. The DIN method is dynamic. The design of the combustion tube and the dilution mechanisms used allow the determination of LC50 and the pyrolysis temperatures accompanying given levels of lethality. Rats are the test subjects; duration of the exposure period is 30 minutes.

No incapacitation measurements are made. Mortality, plus postmortem pathological examination and blood analyses, and some chemical smoke monitoring are the primary diagnostics.

- *National Bureau of Standards (NBS) Test*

The method that has received by far the most attention in the United States was developed by the Center for Fire Research, National Bureau of Standards.[30,31] This is a static method using a cup furnace. It was developed at NBS in conjunction with an *ad hoc* committee of workers from industry, government, and academia. As such, the method developed has been closely scrutinized and exhaustively debated. It does not represent a consensus — there was none — but it does represent a great deal of thought.

The NBS method is the only US method that has been extensively checked for interlaboratory reproducibility. In this regard, it compares favorably with the DIN method. The principal biological measurement is lethality — LC50. Despite a lengthy investigation, no practical incapacitation measure could be found that gave significant information beyond that provided by lethality data. The method also includes an optional provision for a 10-minute exposure at relatively high loading levels (30 mg/liter) of material. The most controversial aspect of the test method is its choice of combustion chamber — a cup furnace. Recently, the size of the cup was increased to approximately 1 liter, which improves its ability to handle substantial amounts of low-density material.

NBS has reported[32] that materials were most toxic in the nonflaming mode just below the autoignition point and, similarly, toxicities in the flaming mode were highest just above the autoignition point. It is desirable that any test used to screen materials avoid "false negatives," and choosing the most severe conditions would minimize this likelihood. Unfortunately, the premise that these conditions always exist near the autoignition point is empirical, if not speculative (especially in view of doubts about the relevance of the combustion device used), and there is no guarantee that false negatives will always be avoided.

At least seven laboratories in the United States have run the NBS method. Table 5 shows data collected for flaming exposures at a 30-minute exposure period and a 30-minute and 14-day observation period. Given the uncertainties of the measurements, these data do not support the often-heard statement that plastics, unlike natural products, are more toxic in the flaming mode. The data do appear to confirm the assertion that materials are somewhat more toxic near their respective ignition points than at a fixed temperature of 440°. With the exception of polytetrafluoroethylene (PTFE), however, the differences in toxicities between the two temperatures are small.

- *BETR Laboratories (RH) Test*

Recently, Packham[33] at BETR Laboratories has proposed a test method that uses a radiant heat exposure in conjunction with the NBS chamber. The method uses radiant heaters located outside the chamber itself; this reduces the problem of by-product heat, which has generally been troublesome in radiant exposure. Samples are sized by surface area, rather than by weight.

The procedure suggested by Packham is also novel. Both time to incapacitation and lethality are measured. Additional tests are made on appropriately sized samples if the lethality indicated by initial dose is high. To date, no data are available from Packham's procedure. It appears to have a number of desirable characteristics, particularly the merits of radiant heat, which have been discussed previously, and the ability to translate toxicity in units of surface area.

[29] Deutsche Industrial Normal (Jan. 1979) DIN 53 436, "Erzeugung Thermischer Zersetsungsproducte von Wekstoffen unter Luftsufuhr und ihre Toxikologische Prufung. Part 1, Zersetzungsgert under Bestimmung der Versuchstemperatur. Part 2, Verfahren zur thermischen Zersetzung," (draft).

[30] B. Levin, et al., "Further Development of a Test Method for the Assessment of the Acute Inhalation Toxicity of Combustion Products," National Bureau of Standards, NBSIR 82-2532, June 1982.

[31] M. Birky, et al., "Development of Recommended Test Method for Toxicological Assessment of Inhaled Combustion Products," National Bureau of Standards, NTIS/PB81-110884, 1981.

[32] B. Levin, op. cit.

[33] S. Packham, "Proposed Method of Test for Toxic Combustion Products," submitted to ASTM Committee, E-5, 1981.

Table 5.
Normalized Data From NBS Test Method
LC50 (Douglas Fir)/LC50 (Material)
30 Minutes & 14 Days

Material	*Flaming Exposure*	*Nonflaming Exposure*	*440°C*
Red oak	.65 ± .2	.69 ± .2	B
Flexible polyurethane foam	A	.76 ± .2	B
Wool	.86 ± .4	.93 ± .4	.72 ± .2
Polystyrene foam	.91 ± .1	A	B
Douglas fir	(1.0)	(1.0)	(1.0)
Polyphenylsulfone	1.6 ± 1	1.4 ± .9	A
Polyvinylchloride (PVC)	1.9 ± .5	1.4 ± .4	1.1 ± .3
Acrylonitrile-stylene-butadene (ABS)	1.9 ± .4	0.6 ± .2	0.6*
Rigid polyurethane foam	2.6 ± 2	A	A
Polyvinylchloride containing zinc ferrocyanide	3.1 ± .6	2.1 ± .1	1.9 ± .1
Modacrylic	6.3 ± 3	3.6 ± 2	3.1 ± 1
Polytetrafluoroethylene (PTFE)	170 ± 170	170 ± 100	1.1 ± .2

A: not reported because apparatus cannot accommodate a large enough sample to reach LC50, normalized value <1.
B ignition point lies within 50° of 440°C.
* ...gle laboratory — no standard deviation calculated.

• *Pittsburgh (Alarie) Test*

Professor Y. Alarie of the School of Public Health, University of Pittsburgh, and his colleagues have developed testing methods that take into account both sensory irritation and lethality.[34,35]

The apparatus consists of a temperature-programmable furnace, a small (2.3-liter) exposure chamber, and a set of four mice as the test animals. The animals can be monitored for respiration rate. The method is a dynamic one, permitting the dilution of the product stream with air.

A typical experiment using this method involves decomposing the sample at a heating rate of 20°C/minute, and diluting the smoke stream with dry air. A typical time history is shown in Figure 3 for a sample of polyurethane foam at its LC50 loading.[36] Different responses can occur at widely differing concentrations. Figure 4, for example, shows Alarie's plot of respiratory decrease and lethality for a sample of polyvinylchloride (PVC).

From a research point of view, Alarie's approach is the most sophisticated one taken to date. Whether it is appropriate for assessment of actual hazard has not been established. For example, Potts and Lederer[37] have reported that human subjects exposed to smoke from red oak experience no respiratory decrease or other ill effects at concentrations equivalent to those that reduce respiration in mice. Unfortunately, data for other materials are not available.

Comparison of Test Data

There are few published comparisons of any of the seven techniques, and the authors of the study for NFPA

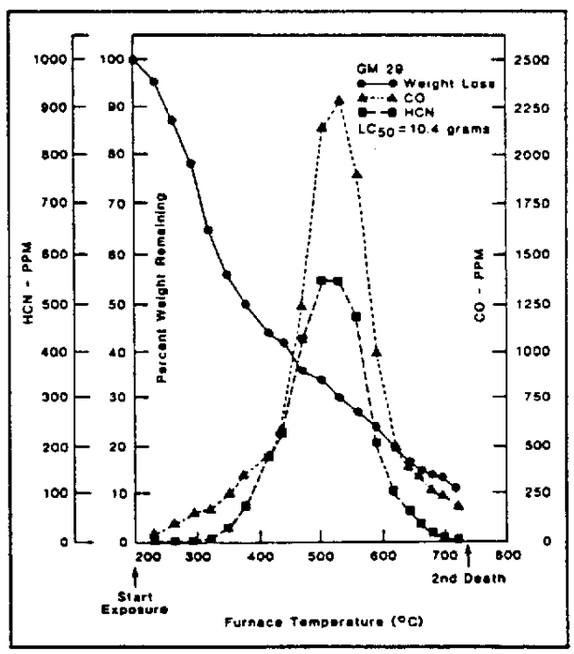


Figure 3. Record of weight loss, carbon monoxide, and HCN release for polyurethane foam during increase in furnace temperature. Reproduced by permission.

[34] Y. Alarie, C. Lin, and D. Geary, "Sensory Irritation Evoked by Plastic Decomposition Products," *American Industrial Hygiene Association Journal*, Vol. 35, No. 10, 1974, pp. 654–61.

[35] Y. Alarie and S. Barrow, "Toxicity of Plastic Combustion Products. Toxicological Methodologies to Assess the Relative Hazards of Thermal Decomposition Products from Polymeric Materials," National Bureau of Standards, NBS Grant/Contract Report NTIS PB-267 233/5ST, 1977, p. 313.

[36] Y. Alarie and R. Anderson, "Toxicologic Classification of Thermal Decomposition Products of Synthetic and Natural Polymers," *Toxicology and Applied Pharmacology*, Vol. 57, 1981, pp. 181–8.

[37] W. Potts and T. Lederer, "Some Limitations in the Use of the Sensory Irritant Method as an End-Point in Measurement of Smoke Toxicity," *Journal of Combustion Toxicology*, Vol. 5, 1978, pp. 182–95.

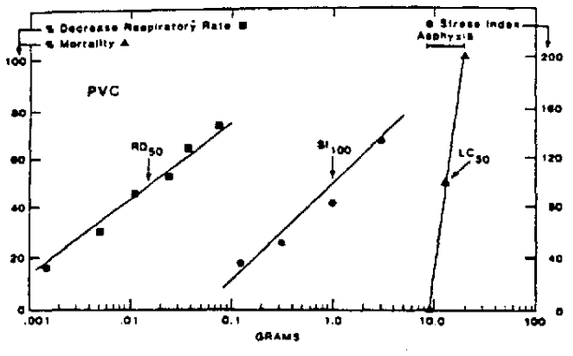


Figure 4. Concentration-response curves obtained for sensory irritation, physiological stress, and acute mortality, for exposures to thermal decomposition products of different sample sizes of polyvinylchloride. The RD50, SI100, and LC50 presented were obtained as given in the text. The sample-size range resulting in asphyxiation is also given. Reproduced by permission.

therefore spent considerable effort surveying the literature to see where such comparisons can be made. The principal difficulty is in finding data on materials that were sufficiently well-characterized so that one could determine whether they appeared in reports on more than one method. For comparison of the Alarie and NBS methods, there are six materials that we know are identical and two more that are probably so. This is no accident, since the Pittsburgh and NBS laboratories worked closely together and NBS supplied the samples to Pittsburgh as well as to these laboratories working on its own approach. The eight materials are two polyurethanes from the Product Research Committee (PRC)[38] sample bank, Douglas fir, urea-formaldehyde foam, wool, polytetrafluoroethylene, and two formulations based on polyvinylchloride (PVC).

The NBS protocol specifies a nonflaming and flaming mode of exposure, and both 30-minute and 14-day animal observation. The Alarie protocol does not control flaming; observations are made for 30 minutes plus a 10-minute recovery period. One would expect closest agreement between the methods when Alarie's data are compared to NBS 30-minute data. Figure 5 shows this comparison. Results from the Alarie test are plotted against those of NBS for the same material. If the two methods give the same toxicity in comparison to Douglas fir, the points would fall on the plotted line of 45 degree slope; they do not, and there is poor correlation, whether flaming or nonflaming data from the NBS method are used.

One possible explanation is that mice, used by Alarie, are more sensitive and show the same effects in 40 min-

[38] The Products Research Committee (PRC), 1976–1980, supported a significant amount of fire research and established a bank of well-characterized material samples so that work at various laboratories could be compared on the basis of its having been carried out on the same materials.

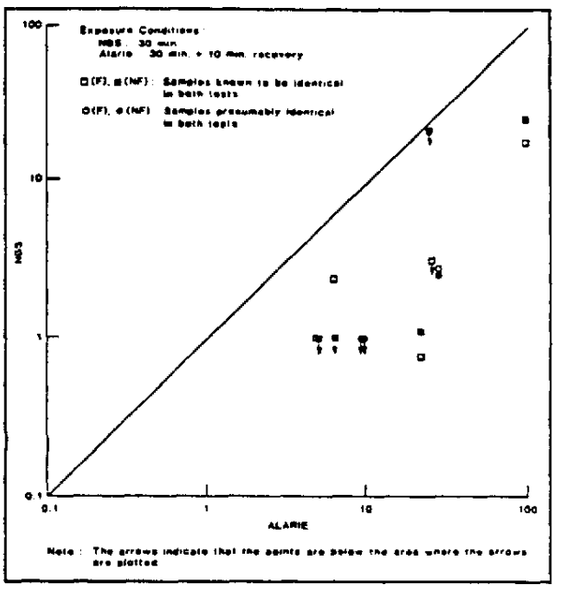
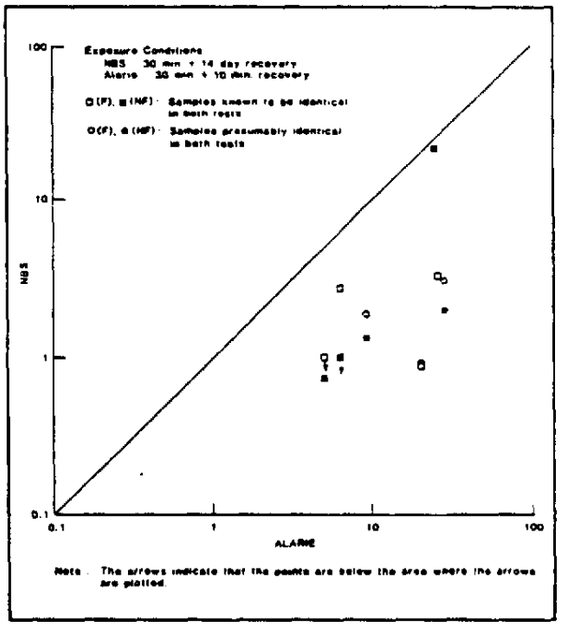


Figure 5. Comparison of lethality relative to Douglas fir for seven materials evaluated by methods of Alarie and NBS.

utes that take two weeks to develop in rats. We have, therefore, also plotted the 14-day data from the NBS test against Alarie's results. As Figure 6 shows, this argument may hold true for one material, but for the others, results are essentially unchanged.

Figure 6.



It is possible that more data would fail to confirm the apparently greater toxicity of materials in the Pittsburgh method, i.e., if enough data were available, perhaps the points would scatter more or less symmetrically about the line shown in the two plots. If this is true, the inherent imprecision of laboratory combustion-product toxicology will be approximately an order of magnitude. In other words, there will be no validity to comparisons of quantities that do not differ by at least a factor of ten. Alternatively, it may be that more data will show that the difference in methods is real and systematic. If this is the case, they cannot both be "right."

At present, it is not possible to determine if the differences between the two approaches are systematic or random. It is clear, however, that the differences are large, and more data are needed.

In one series of experiments, Cornish[39] has demonstrated that the order of toxicity of a set of materials can be greatly influenced by the choice of combustion conditions. In one procedure, rats were kept for four hours in a chamber containing smoke produced by sudden thermal exposure of a material at 700°C. In another procedure, the same materials were gradually heated to the same final temperature over 140 minutes, and the smoke passed through the exposure chamber. The results, shown as sample weight to produce 50 percent mortality — are presented in Table 6. The ranking can be almost completely reversed, depending on the combustion conditions.

The essentials of Cornish's observations are borne out by the comparison of the Alarie and NBS test methods. The Alarie dynamic method shows wool, polyvinylchloride, and the urethanes to be substantially more toxic than wood (Douglas fir). The static NBS method shows the same materials to be comparable to or somewhat less toxic than wood. It seems likely that the explanation for these differences is related to the fact that the static methods expose the animals to all the combustion products at once. By contrast, depending on the heating rate and the air flow, the dynamic methods can expose the animals to few products, or to a single product, at a time. This is particularly significant when the material is heated gradually during the course of the test. In the case of polyvinylchloride, for example, the evolution of hydrogen chloride can begin at temperatures well below the onset of carbon monoxide evolution. The dynamic exposure chamber may therefore be cleared of hydrogen chloride before the animal encounters appreciable carbon monoxide. In the static chambers, the animal will encounter carbon monoxide and hydrogen chloride simultaneously, or at least close together. Since hydrogen chloride depresses respiration rate, its presence or that of a similar irritant will slow the uptake of carbon monoxide. (In Cornish's work, there may be an additional problem: the static chamber, constructed of stainless steel, may have reacted with acid products like hydrogen chloride.) If the combination of slow uptake and carbon monoxide level meets certain conditions of time separation, the animal may survive a static exposure and die in a dynamic one. Conversely, when two toxins are synergistic, i.e., when they magnify the effects of one another, one would expect materials burned in the static chamber to show comparatively greater toxicity.

[39] H. Cornish, K. Hahn, and M. Barth, "Experimental Toxicology of Pyrolysis and Combustion Hazards." *Environmental Health Perspectives*, Vol. 11, 1975, pp. 191–6. See also: H. Kaplan, H. Grand, and C. Hartzun, *A Critical Review of the State-of-the-Art on Combustion Toxicology*. Southwest Research Institute, Final Report No. 01-6562 for the Society of the Plastics Industry, June 1952.

Table 6.
Data of Cornish, Showing Differences in Lethalities of the Same Materials by Different Test Methods.

Static Chamber		*Most Toxic*	*Dynamic Chamber*	
*LC*50, g	*Sample*		*Sample*	*LC*50, g
9	Red Oak	1	Wool	0.4
10	Cotton	2	Polypropylene	0.9
21	ABS (FR)	3	Polypropylene	1.2
23	SAN	4	Urethane Foam (FR)	1.3
25	Polypropylene (FR)	5	Polyvinylchloride	1.4
28	Polypropylene	6	Urethane Foam	1.7
31	Polystyrene	7	SAN	2.0
33	ABS	8	ABS	2.2
37	Nylon 66	9	ABS (FR)	2.3
37	Nylon 66 (FR)	10	Nylon 66	2.7
47	Urethane Foam (FR)	11	Cotton	2.7
50	Urethane Foam	12	Nylon 66 (FR)	3.2
50	Polyvinylchloride	13	Red Oak	3.6
60	Wool	14	Polystyrene	6.0

Interpreting Combustion-Toxicology Data: Time vs Dosage

The controversy over time measurements or dosage measurements as the better indicator of hazard is a long-standing one. Three of the toxicity test methods listed measure only time effects, two measure dosage, and two measure at least one aspect of both time effects and dosage.

Supporters of time measurement argue that, since escape time is the controlling variable in most fires, knowing how a material will affect this parameter is paramount. In the straight time tests, a relatively large sample is exposed to severe thermal conditions so that the time for decomposition is relatively short with respect to the time of exposure. The Japanese test method is something of a variant. Its thermal conditions, while not particularly severe, were specifically chosen to approximate the performance of room wall linings when exposed to the radiant heat typical of a developing fire.

Alarie and Anderson[40] have criticized the "time to effect" approach because it groups all materials in a narrow range of times. In the FAA and USF procedures, for

[40] R. Anderson and Y. Alarie, "Screening Procedure to Recognize 'Supertoxic' Decomposition Products from Polymeric Materials Under Thermal Stress," *Journal of Combustion Toxicology*, Vol. 5, 1978, pp. 54–63.

(Continued on page 101)

example, virtually all observed times-to-death cluster between 5 and 30 minutes. Alarie and Anderson claim that determining lethal dosage, by contrast, offers a range for possible values of about 1,000. Recall, however, that Alarie's and NBS' measurements of lethality disagree by a factor of ten. If the best one can expect from lethality measurements is accuracy to this level, then, on a logarithmic scale, the ratio of uncertainty to available range is log 10/ log 1000, or one-third. From this viewpoint, the superiority of using lethal dose to classify materials is not quite so apparent.

Packham has argued[41] that the two quantities are so closely coupled that it is equally misleading to rely solely on either. He points out that it is possible for an agent to be rapidly incapacitating at levels below its lethal dose, just as it is possible to have delayed lethal effects that would go undetected if time were the only discriminant.

Packham's logic is most persuasive if the suitability of materials must be assessed for a variety of fire scenarios. For example, interior finish materials of high flame spread are likely to become involved fairly rapidly, producing relatively large amounts of smoke in a short period; time measurements may be appropriate for this scenario. It may be no accident that the Japanese Ministry of Construction and the FAA have chosen to monitor time, since both tests are primarily conducted on compartment interior finish. By contrast, structural materials and some furnishings will produce smoke at a relatively constant rate over a longer period, since the surface-to-volume ratio is much lower. For these products, weight-based measurements may be better. In general, it may be most appropriate to concentrate on one or the other lethality parameter if the product or material use is known.

Summary and Discussion

A major concern in the field has been to identify so-called "supertoxicants," whose presence in materials would go unrecognized in the absence of a specific test. The fire community was concerned that some smoke might contain highly-toxic materials that would either kill directly or would incapacitate at such low concentrations, or at such an early stage in the fire, that escape would be impossible from an otherwise relatively tenable situation.

There is no consensus that any such materials have actually been found to date. The previously unknown cyclic phosphate discovered by the University of Utah group turned out to be unique, primarily in the type of effects that it showed and was, moreover, not produced commercially. Commercial materials that have attracted attention are urea-formaldehyde foam and PTFE. In both cases, the materials have relatively high thermal stability and do not support their own combustion. Maintaining the high temperatures necessary in practice for the decomposition of these materials requires that other fuels be burning. Thus, for PTFE, urea-formaldehyde, or any other thermally-stable material, the contribution to hazard in actual practice depends, first, on whether it produces a similar set of products under real fire conditions[42] and second, on the degree to which the products contribute to the toxicity of the total smoke generated, since most of the smoke will come from other fuel(s).

At present, the utility of a screening test would appear to be more to prevent such hazards in new products than to identify major existing threats. While NBS has suggested that its test is useful as a screening tool (primarily for product development),[43] others[44] argue that any screening test for toxicity is vulnerable on several counts. First, they assert, there is no guarantee that the combustion or test conditions used are representative of real fires; second, controlling materials on the basis of toxicity could lead to a suboptimization based on this single property; and third, they believe that even a well-thought-out approach could be misapplied, leading to an overall increase in hazard. NBS[45] has suggested that a screening test should be used only to determine when a material should be subjected to detailed examination of all of its fire properties, but that the test itself was an insufficient basis for material control. The debate continues.

The procedures for toxicological testing have variations in the method of pyrolysis, the method of exposure, and the animal model. It is not surprising, in view of the plethora of test methods, that there is also a range of test results. With respect to "validity," the only option available is to compare different methods that purport to measure the same effect. Because identical materials have not been tested in each method, comparisons are limited, but the comparisons that can be made would indicate poor correlation or even contradictory results.

Comparison of relative toxicity data between Alarie and NBS test methods, for example, shows wide disagreement in the toxicity of several materials relative to Douglas fir. The reason for the discrepancies may be several, among them the use of rats vs. mice and the effect of static vs. dynamic systems. However, at this time, there is no understanding of the differences and therefore no agreed-upon way to evaluate toxicity of

(Continued on page 108)

[41] S. Packham, op. cit.

[42] In the case of PTFE, there is evidence to suggest that real fire conditions produce much less toxic products: c.f. Footnote 17.

[43] B. Levin, op. cit.

[44] Cf. J. Punderson, "A Closer Look at Cause and Effect in Fire Fatalities — The Role of Toxic Fires," *Fire and Materials*, Vol. 5, No. 1, 1981.

[45] F. Clarke, I. Benjamin, and M. Birky, "The Use of Laboratory Toxicity Measurements for Decision-Making," *Fire and Materials*, Vol. 5, No. 2, 1981.

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$1,221,909. He assured the Board that in spite of the results, financial stability has never been stronger. Growth, in fact, over the three-year cycle just completed was in excess of $525,000 (more than double that of the previous cycle). Dr. Bell also pointed out that early indications for 1983 are very favorable and growth over the financial cycle just beginning is anticipated to be better than that just completed.

5. Mr. Grant reported on several administrative changes within the staff of the Association to strengthen NFPA operations.

6. Mr. Roux, Chairman of the Membership Committee, moved that the Board approve the proposal of the Michigan Society of Fire Inspectors to form a chapter of the Fire Marshals Association of North America and authorize that the chapter be known as Chapter No. 1 — Michigan. Mr. Roux also moved that the Executive Committee of the Fire Marshals Association of North America report to the Board in May of 1984 on the first year of operation and the adequacy of the arrangements for the chapter. In particular, the Board should be informed of any problems that arise from the fact that a number of the members of the Michigan Society of Fire Inspectors are not eligible for membership in the Fire Marshals Association of North America. Dr. Bell seconded the motion and it carried unanimously.

7. Mr. Stevens reported that in response to the request of the Board, the Standards Council voted to recommend to the Board that an ad hoc group be formed to include representatives of affected NFPA Technical Committees to conduct the study on the contribution of furnishings and similar contents to the fire problem. The Council offered to establish the ad hoc group, to review the recommendations of the ad hoc group and to report back to the Board on the direction the Association should take on this subject. Dr. Bryan moved that this recommendation be adopted by the Board. Mr. Johnson seconded the motion and it passed unanimously.

8. Mr. Martin, Chairman of the Fire Equipment Manufacturers Association's Appeal Subcommittee, reported that the Subcommittee considered fully each of the four issues raised by the appellant, and upon consideration of the issues and the arguments, it was the determination to affirm the action of the Standards Council on NFPA 14.

9. Mr. Sanders confirmed that the December Board of Directors Meeting will be held on December 2 and 3, 1983 at LaCosta Hotel and Spa, Carlsbad, California. △

Toxicity of Combustion Products *(continued from page 101)*

pyrolysis gases. Until large-scale tests have been run with varying scenarios to validate the laboratory tests, the controversy will probably continue.

Even where agreement is reached, whatever test approach is used will still have built-in limitations. As a consequence of inherent time-dependence, each fire may, at different times in its development, create different conditions of combustion and occupant exposure. Moreover, a given material may be involved in not one, but a number of different fire scenarios. It should therefore be clear that there is no "correct" single set of real fire conditions identifiable with a material. By the same token, there is not a single "correct" set of small-scale test conditions, nor a single "correct" ranking of materials based on toxicity tests. The situation is not the fault of existing test methods and will not be changed by more research; it is inherent in the complexity of fire and fire hazard. This does not mean that toxicity testing is fruitless — far from it — but it does mean that one is seldom free to take at face value the results of any given test.

The other major problem is one where more research can help: how to integrate toxicity considerations with flammability parameters. As an illustration of the problem, consider the following hypothetical dilemma for a code official. The code now requires a flame spread of 75 (Class B) by NFPA 255 for many interior finish applications. Suppose a code official wishes to add a requirement that smoke from wall linings be no more toxic than wood — say, red oak — when burned under similar conditions. (This is a commonly suggested code provision.) Now, untreated red oak has a flame spread of 100 and hence could not be used in this application. What is the toxicity of an acceptable interior finish so that the net effect is the same hazard level posed by red oak, which is not allowed in the first place?

As an even more practical illustration, suppose a manufacturer wishes to gain code approval of a new material with a flame spread of 40 but with a toxicity twice that of red oak. The amount of smoke produced is proportional to the amount of material burning, so there will be less smoke produced in a given time by the lower flame spread material. Since there will be less smoke, is it permitted to be more toxic? One might intuitively answer "yes" to this question, but then, how much more toxicity is acceptable? If, instead, one answers "no," it is possible that a safer material than those in use will have been barred.

Although no one has clear answers to these questions, not long ago no one even knew enough to ask them. The evolution of new knowledge from laboratory findings to everyday practice is always a slow journey. As our understanding increases, our expectations from combustion product toxicology must undergo a corresponding evolution. This report may be helpful on both counts. △