RESEARCH INTO POST-CRASH FIRES

By Lauren Graham

In the wake of the Tenerife accident in the Canary Islands last March, interest has increased in passenger safety in post-crash fires. The first in a series on aircraft safety, this article summarizes the conditions existing in aircraft fires, thresholds of human tolerance to them, physiological effects and current FAA plans. This initial article's information is largely based on the FAA report, "Physio-Chemical Study of Smoke Emission by Aircraft Material Interiors: Physiological and Toxicological Aspects of Smoke During Fire Exposure" (FAA-RD-73-50,1), researched by I.N. Einhorn, Director of Flammability Research Center, Univ. of Utah.

The arrival of wide-body commercial jet transports carrying many hundreds of passengers has immensely increased the magnitude of potential aviation disasters. The aviation industry faces new challenges to maintain public confidence in passenger safety. Airlines, regulatory agencies, manufacturers and passengers want to know if passenger safety technology is keeping pace with advances in size, comfort, pollution control, range and speed.

In the aftermath of the March 27, 1977 Canary Islands disaster in which two 747 jumbo jets collided on the runway and burned, attention has been on the necessity of making commercial aircraft less vulnerable to the catastrophic effects of post-crash fires. The Federal Aviation Administration has conducted studies and research for several years in aircraft safety and recently has intensified efforts related to post-crash fires. AVIATION ENGINEERING & MAINTENANCE magazine contacted the FAA's National

Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, to get answers to this and other related questions.

NAFEC has several ongoing research programs in fire safety focusing on flammability, smoke and toxic gases in post-crash fires. Each program addresses one or more of these potentially lethal factors. It is important to both aircraft manufacturers and carriers that these three components of fire are dealt with together rather than separately. Studies of flammability, smoke and toxicity are each likely to result in new regulations and standards which could dramatically affect the industry. If these studies were done independently, it is conceivable manufacturers and carriers would be required to make expensive modifications three different times. FAA officials at NAFEC are well aware of this and coordinate their research so new FAA directives can be issued simultaneously.

Current Practice

Current testing procedures for materials flammability, done with strips of sample material held vertically over a standard Bunsen burner, require only that flame propagation fall within specified limits and self-extinguish in a given distance. Neither smoke nor toxic gas emissions are considered. NAFEC does perform standard flammability testing on samples of materials used in aircraft interiors. In addition, research programs are developing more effective techniques to measure smoke and toxic gas emissions.

Smoke and Toxic Gases

The importance of toxic factors caused by fire was brought to national attention by the 1929 Cleveland Clinic fire. In this tragic fire, x-ray film manufactured from highly combustible nitrocellulose ignited causing 125 deaths. In 1942, a fire at the Coconut Grove, a popular Boston nightclub, killed 491 persons. It became apparent in recent nursing home fires that most fire fatalities are not caused by body burns, but by smoke inhalation, especially smoke from man-made materials. The propensity of certain plastic and elastomeric materials to ignite and burn at a rapid propagation rate with dense clouds of black smoke has encouraged the materials industry, as well as government agencies, to find ways of preventing or reducing the flammability of these materials.

Flame Retardants

One technique to reduce flammability is treating materials with chemical retardants. The use of these agents has increased at a prodigious rate. Unfortunately, this "cure" for flammability has created its own "disease"—increased concentrations of smoke and gases with biological implications that are only now beginning to be understood.

Research on the toxicological aspects of combustion and pyrolysis (high temperature decomposition) has lagged far behind other flammability characteristics of polymeric (e.g., plastic) materials. Even today, the toxic hazards cannot be adequately assessed. But, toxic consequences during combustion can no longer be ignored or minimized, so NAFEC and the Civil Aero Medical Institute (CAMI), Oklahoma City, are currently analyzing them.

Human Tolerance to Fire

Consideration must be given to factors causing death or serious impairment to persons in or near a fire's vicinity. Research indicates the major factors affecting life support are:

- Direct consumption by the fire
- Inhalation of high temperature air
- Absence of oxygen
- Presence of carbon monoxide or other gases
- Presence of dense smoke
- Development of fear

Dangers of the "Survivable Crash"

The crash of a 727 commercial airliner at Salt Lake City Airport in November 1965, killing 43 of the 91 passengers, illustrated the diverse dangers of a post-crash fire. It was one of the rare incidents of what the Civil Aeronautics Board terms a "survivable crash"—no fatalities on impact—and raised a big question regarding the contribution of the plane's interior plastic materials to the fumes and smoke. The accident focused much attention, including the FAA's, on the growing problems caused by burning polymeric materials, such as fibers, coatings, foams and reinforced plastics. Previous industry attempts to fire retard plastics produced improved resistance to flame contact; however, hazards due to smoke and toxic gases were, in general, not fully understood nor recognized. Disasters of the Salt Lake City type clearly show the need for cabin materials with both adequate flame resistance as well as low smoke and toxic gas generation. The necessity has been recognized for developing materials with these properties and more accurate evaluation to predict their behavior in emergency situations. The implications for aviation safety personnel are obvious and far-reaching.

A critical analysis of the hazards to life support found in post-crash aircraft fires starts with a look at the burning process. First, a destructive distillation of the material takes place, producing gases whose nature depends on the composition of the materials. Then, oxygen unites with free carbon forming carbon monoxide. At this time, dense smoke is usually formed, presenting additional hazards. When sufficient oxygen is present, it combines with flammable gases, as well as with carbon monoxide. If sufficient excess oxygen is available to combine with all combustible materials, carbon monoxide burns to form the relatively harmless carbon dioxide. Ordinarily, the products of complete combustion are less harmful than those of incomplete burning.

Ranking of Fire Hazards

FAA researchers list the following life support hazards in post-crash cabin fires:

- Asphyxiation from rapid depletion of available oxygen
- Attack by superheated air or gases (beyond the maximum survivable temperature)
- Smoke
- Toxicity hazards of combustion products
- Flame propagation

Fires involving very rapid flame propagation (apparently the case in the Canary Islands accident), as contrasted to slow burning deep-seated fires, alter the relative importance of these hazards. But, outweighing any of the five individual factors is their combined effect.

Asphyxiation

Complete lack of oxygen causes death within a few minutes and less than normal concentrations of oxygen produce symptoms of hypoxia (Table 1). Even if death does not occur from the lowered levels of oxygen, denial of sufficient oxygen to brain tissue for short periods of time produces irreparable brain damage. Higher concentrations of oxygen, but still below normal, affect the brain cells in a reversible manner, and during this period, the person experiences behavioral changes which may produce faulty judgment and impaired ability to escape.

Table 1. *Toxicity symptoms due to reduced oxygen levels in fire conditions*

% Oxygen in Air	Symptom
20% or above	Normal
12%-15%	Muscular coordination for skilled movements lost
10%-14%	Consciousness continues, but judgment is faulty and muscular effort leads to rapid fatigue
6%-8%	Collapse occurs quickly, but rapid treatment would prevent fatal outcome
6% or below	Death in 6 - 8 minutes

Attack by Superheated Air

Temperatures exceeding 300°F (149°C) can cause loss of consciousness or death within several minutes. The temperatures recorded in several enclosed fires exceeded the maximum survival level within 5 to 10 minutes. This time is greatly reduced in aircraft fires due to a large concentration of available fuel.

The effects of superheated gases on the respiratory system have been cited as a principal cause of fire fatalities. The respiratory system (tracheobronchial tree and pulmonary tissues) can suffer heat damage, chemical damage, anoxic damage or any combination of these injuries during or shortly after fire exposure. Pressure damage may also occur if the fire is accompanied by an explosion.

Until the late 1960s, many investigators doubted heat inhalation damage could occur in the respiratory system because of low specific heat of gases. Caloric burns of the respiratory system may occur from inhalation of incompletely combusted products which continue to burn on the way down the tracheobronchial tree.

Smoke

The dense smoke from post-crash aircraft fires presents a double hazard. By obstructing vision, it can prevent exit from the area and may prevent location of the fire's source thus hindering fire control. The particles in smoke affect the vision of firefighters using gas masks and breathing apparatus. The smoke also produces irritants so persons caught in a fire may not be able to see due to eye tearing or "clouding" of the cornea caused by components in the smoke. The hydrogen fluoride often contained in smoke (which forms hydrofluoric acid when dissolved in water) is capable of etching glass. Thus, even though relatively little smoke (in terms of density) may be generated, the damaged sight of exposed persons could delay escape in time to prevent exposure to lethal concentrations of toxic fumes or fatally high temperatures.

Toxicity Hazards

The most controversial and complicated aspect of fire research regards the toxicological interactions of materials during fire exposure. Many studies have attempted to measure the nature and quantity of toxic gas emissions of combustion. In cases of actual fire exposure, it is nearly impossible to ascertain which of the several gases released is actually the cause of death (an exception is carbon monoxide). Due to this lack of empirical data, it has been even more difficult to determine the toxic potential of any specific material when it burns or is heated. The usual approach has been to generalize based on knowledge of gases formed by classes of material, and to seek toxic information on the individual gaseous compounds where such knowledge is available. The most frequently encountered toxic gases of combustion are discussed below. Their actual concentrations in a "typical" post-crash fire are yet undetermined, as are their effects in combinations on humans.

Carbon Monoxide

Of all gases from burning materials (both natural and synthetic), carbon monoxide (CO) is the most lethal in fire situations. Even though ambient air has low levels of carbon monoxide expressed in parts per million (ppm), animals and humans apparently can tolerate concentrations up to 100ppm for up to 8 hours without undue harm. Fire conditions, however, can release sufficiently large concentrations (5000ppm) to cause death in very short periods. After it is inhaled, carbon monoxide combines with blood hemoglobin (Hb) to form carboxyhemoglobin (CO-Hb). This reaction displaces oxygen in the blood and leads to apoxia and death if the reaction is not reversed. Carbon monoxide also interferes with oxygen release in the tissues, but this appears to be of secondary importance compared to its combination with hemoglobin. Correlations can be made between symptoms of toxicity and the percentage of CO-Hb formed. Table 2 summarizes this information and shows concentrations below 10% produce no symptoms. Most medical experts agree that many persons will not show obvious toxic symptoms below a level of 20% carboxyhemoglobin. From this level on, however, extremely toxic manifestations will occur and death will be imminent in concentrations of 60% or more. As little as .005% CO in the air (5000ppm) will raise a person's CO-Hb to a fatal level within minutes.

Table 2. *Symptoms at various concentrations of carboxyhemoglobin.*

% CO-Hb	Symptom
0%-10%	No symptoms
10%-20%	Tightness across forehead, possible slight headache, dilation of cutaneous blood vessels
20%-30%	Headache and throbbing in the temples
30%-40%	Severe headache, weakness, dizziness, dimness of vision, nausea, vomiting and collapse
40%-50%	Same as above, greater possibility of collapse; syncope and increased pulse and respiratory rates
50%-60%	Syncope, increased respiratory and pulse rates, coma, intermittent convulsions and Cheyne-Stokes respiration
60%-70%	Coma, intermittent convulsions, depressed heart action and respiratory rate, and possible death
70%-80%	Weak pulse, slow respiration causing death within hours
80%-90%	Death in less than an hour
90% or above	Death within a few minutes

Recently, attention has been given to the possible toxic effects of carbon monoxide at levels where symptoms are not obvious; for example, below 10% CO-Hb. It has been shown concentrations as low as 5% CO-Hb can adversely affect judgement and psychomotor abilities, e.g., command and control of an aircraft. This reaction to even small concentrations of CO may be a partial reason victims fail to escape from a fire although the means of safe evacuation appear obvious.

Carbon Dioxide

All fires will produce some levels of carbon dioxide (CO_2) which, in turn, may be inhaled by those in the vicinity. Since CO_2 is an important constituent of the body process, it is not considered toxic at normal concentrations. However, inhalation of carbon dioxide stimulates the respiration rate which increases inhalation of possible toxic components from the fire. Higher than normal concentrations of CO_2 alone will result in toxic symptoms. Concentrations of 10% cause headaches and dizziness, while higher levels (above 20%) can lead to narcosis, e.g., a state of arrested activity.

Sulfur Dioxide

Certain natural and man-made materials, such as natural and synthetic rubbers, have sufficient sulfur content to generate sulfur dioxide (SO_2) when exposed to heat and fire. This gas is pungent, heavy and extremely toxic to humans. The threshold limit value (TLV—concentration of a compound in the air which, if exceeded, may cause toxic signs) is 5ppm. Sulfur dioxide, in contact with moisture, forms sulfuric acid causing extreme irritation if it contacts the skin. Mucous membranes, particularly in the eyes and respiratory tract, are highly susceptible. Death following exposure to high SO_2 concentrations is usually from asphyxiation (blockage of air transport in the upper respiratory tract). Chronic exposure to SO_2 has greater toxic effects on those having cardiorespiratory diseases (apparently causing the high incidence of death during episodes of smog).

Hydrogen Sulfide

Hydrogen sulfide (H_2S), the "rotten egg" gas, is an extremely rapid and powerful systematic toxic agent. Concentrations as low as 50ppm can cause toxic symptoms and 1000 ppm will cause death. Lower levels (below 200 ppm) in the air can be extremely dangerous to mucous membranes due to irritant properties of the gas. In humans, hydrogen sulfide causes headaches, nausea, confusion, weakness and may lead to unconsciousness. Death generally is due to central respiratory paralysis. Because the compound is rapidly metabolized, however, death can be prevented if the victims are removed from the source of the exposure.

Hydrogen Cyanide

Hydrogen cyanide (HCN) can be lethal when ingested as a salt in doses as small as ¼ gram, and concentrations above 20ppm in the air are considered dangerous. Initial inhalation of HCN vapors causes a reflex stimulation of breathing which increases the amounts of gas entering the body. The victim quickly becomes unconscious and, if not removed from the source, dies. Cyanide inactivates certain enzymes in the body and prevents utilization of oxygen by body tissues.

Hydrogen Chloride

Degradation of polyvinyl chloride and other materials containing chloride, a principal constituent of many plastics, produce as one of their major by-products the highly toxic hydrogen chloride (HCl). Combined with water, hydrogen chloride forms hydrochloric acid which is less corrosive than sulfuric acid, but causes destructive damage to mucous membranes. If inhaled, damage to the upper respiratory tract is severe and may lead to asphyxiation and death.

Hydrogen Fluoride

Fluorinated polymers, if heated to a sufficiently high temperature, release a group of compounds called fluorinated hydrocarbons. These compounds, particularly hydrogen fluoride (HF), are extremely toxic when inhaled. Hydrofluoric acid, HF combined with water, is extremely corrosive to all tissues. Inhalation of this compound produces serious damage to mucous membranes in the respiratory tract which may cause death. Death may also be caused by the systematic toxicity of the compound itself.

Acrolein

Acrolein, a three carbon compound (CH_2CHCHO), is given off by burning wood. This compound has extreme lachrymatory (tear producing) effects which normally serve as a built-in warning agent. It affects particularly membranes of the eyes and respiratory tract. The current industrial maximum allowable concentration (MAC) for acrolein is 0.1ppm. Death occurs within a few minutes from concentrations of 10ppm.

Flame Propagation

Flame propagation, fire itself, has historically received the most emphasis, and is the one area where federal standards do exist (FAR 25.853 - May 1972). Ironically, efforts to control flame propagation through flame retardant materials seem to have increased the hazards of smoke and toxic gases. The reason flame propagation has received so much attention is the obvious and dramatic effect of fire on human beings. Flame-induced mutilation and suffering demand action. Medically, the "rules of nine" express the extent of burn. One arm is 9%; a leg is 9%; front and back 9%, etc. The percentage of body involvement is important for both treatment and plotting survival figures. If a third degree burn involves 50% of the body's surface, the mortality rate is about 50%. If 70% or more of the body receives third degree burns, survival is nil. A healthy adult may survive a 10-15% third degree burn without too much difficulty; a healthy child may be expected to survive a 5-10% third degree burn.

Escape Time

There has been recent research to gain a better understanding of actual conditions encountered during aircraft fires. One factor studied is escape time in a simulated aircraft fire. Escape time is defined as elapsed time from the instant of fuel ignition to that time when human tolerance limits prevent an aircraft occupant from escaping through his own efforts. The human tolerance limits determining escape time are:

- Unbearable pain due to heat
- Collapse due to carbon monoxide
- A momentary exposure to an air temperature of 390°F as a respiratory limit.

Results to date indicate fatal burns or incapacitation of passengers subjected to a severe post-crash cabin fire occur in a few seconds. Evacuation from a wide-bodied aircraft, even under ideal conditions, can take minutes. When conditions of smoke, toxic gases, and confusion are present, the survival odds are further reduced.

The Future

Some persons accept the present situation because relatively few people are affected in terms of total aircraft passenger miles. With jumbo jets, however, several hundred persons can be lost to fire in a single crash. In purely financial terms, the probable indemnity loses created by one accident make a reappraisal of the fire safety issue mandatory. Public confidence, both in the safety of commercial airline operations and the government's ability to regulate them, calls for visible action.

The FAA, primarily its NAFEC facility, is actively pursuing research programs to improve the odds for crash survival. Under study, in addition to studies of smoke and toxic gas measurement and control, are cabin fire suppression systems, fuel tank inerting, full-scale cabin fire testing, rapid response airport firefighting vehicles and compartmentation concepts.

In this series, AVIATION ENGINEERING & MAINTENANCE magazine will report the technical issues, the research methodologies and the results. We will also analyze the impact these programs will have on the aviation community in terms of the specifics of proposed regulations as they develop, including required implementation dates, levels of responsibility and the impact of alternate concepts in terms of life cycle cost and technical feasibility.■

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This article is the second in a series on aviation fire safety. The first (See AEM, Sept. 1977, page 52) discussed aspects of fire affecting human survival: heat, smoke and toxic gases. Part two focuses on toxicity, describing the results of two recent FAA research projects measuring the combustion gases of 75 typical aircraft cabin materials and specifying their effects on test animals.

Between 1964 and 1974, approximately 900 people died in aviation transport accidents involving fire. Last March, 577 persons died in the Canary Islands' crash and resultant fire of two 747 jumbo jets. This tragedy dramatically illustrated the increased potential for disaster accompanying the greater economy and comfort of wide-bodied jet transports. It is now recognized that the primary cause of death in most fires is inhalation of toxic gases or smoke.

FAA Concern

The effects of toxic gases on accident victims has been of increasing concern to the FAA since 1965 when a 727 crashed on landing at Salt Lake City. Termed "survivable" by the Civil Aeronautics Board since no one died as a result of the crash impact, this accident's fire effects, including toxic gases, killed 43 of the 91 passengers. In 1967, the FAA's medical research arm, the Civil Aeromedical Institute (CAMI), began routine measurement of carbon monoxide (a leading cause of fire related deaths) in the blood of aircraft accident victims. The FAA's National Aviation Facilities Experimental Center (NAFEC) became directly involved in toxic gas analysis in 1972 following two aircraft accidents in Chicago in which hydrogen cyanide was widely publicized as a major cause of fatalities.

The fire safety challenge facing the FAA, as well as aircraft manufacturers and operators, is to identify design criteria for maximum passenger protection from flammability, smoke and toxic gases which are cost effective in terms of development, installation, weight and maintenance. Solutions are complex and come from varied sources.

Much recent public attention has been focused on the issue of toxic gas emissions because of increasing use of synthetic rather than natural materials in aircraft cabin interiors. A typical wide-body jet contains approximately 600 pounds of plastics, in addition to carpeting and upholstery. FAA recently conducted two concurrent data acquisition projects for 75 typical aircraft interior materials—a gas analysis effort conducted by NAFEC, and an animal exposure and response study by CAMI.

Cabin Material Assessment

The objective of the CAMI and NAFEC projects was to rank aircraft interior materials according to their potential toxicity hazard in a fire. Applying such test methods to the rule-making process will allow the most hazardous materials to be eliminated from service. This is similar to the current FAA flammability regulation, in that the objective is to achieve incremental increases in safety as the state-of-the-arts permits. The 75 materials tested by NAFEC and CAMI were chosen from over 140 in-service materials supplied by the Aerospace Industries Association and leading seat manufacturers. Besides being safe, any materials proposed for use in commercial jet aircraft must be cost effective, functional (durable, easily cleaned, etc.) and aesthetically acceptable.

Experimental Approach

In the NAFEC project, each material was thermally decomposed by exposing a 250mg sample to a 600°C temperature for five minutes in a combustion tube furnace.* An airflow rate of 2 liters per minute (lpm) was maintained while the combustion products were collected. These gases were quantitatively analyzed by appropriate instrumentation, e.g., polarographic

*Laboratory test conditions cannot adequately duplicate an uncontrolled aircraft fire. Consequently, the data does not conclusively prove a material's performance in an actual cabin fire, nor the overall safety of a cabin constructed of such materials. However, the studies do show that relative toxicities can be quantified using a consistent combustion process: For carbon monoxide and hydrogen cyanide, it was demonstrated that effective doses, on a per-gram-of-body-weight basis, are identical for rats, mice and humans. The Federal Air Surgeon at CAMI is establishing relationships between animal toxic response data and human toxicity levels. At this writing, the information was not available on all toxic gases.

analyzer, Spectrophotometer, etc. Three identical tests were made on each sample with the averaged results (Table 1) expressed in milligrams of gas per gram of material.

In the CAMI animal response tests, the thermal decomposition procedure was the same except the airflow over the sample was increased from 2 to 4 lpm to reduce heat stress on the animals. The resulting gases were pumped into small chambers containing three albino rats whose responses were closely monitored. To obtain an identifiable spread of responses, the animals were exposed for 30 minutes and any survivors observed for 14 days afterwards. The principal observation was the time to incapacitation (t_i) and the time to death (t_d) for each animal. Three tests using a total of nine animals were run for each material. The response times represent an average for the nine animals, mathematically "standardized" to compensate for differences in animal sizes.

Toxic Gas Yields and Animal Response Times

Panels. Most of the 13 panel assemblies consisted of an aromatic polyamide honeycomb core covered with fiberglass and differed mainly in the outermost finish layer. Consequently, they did not exhibit large differences in gas yields or toxicity. They all produced carbon monoxide, hydrogen chloride and hydrogen bromide. Material 28, covered with wool carpet, produced the highest yield of hydrogen cyanide and the second highest yield of nitrogen dioxide. It was the only panel material found to contain hydrogen sulfide. Formaldehyde was found in only two of the panels (materials 28 and 34).

Values for time to incapacitation (t_i) ranged from 2.36 minutes (material 11) to 5.85 minutes (material 7). Material 7 exhibited a property perhaps worthy of consideration; that is, no deaths occurred during the 30-minute test period. The interval between incapacitation and death for this material was greater than 25 minutes compared to less than two for material 35 which has about the same t_i. The longer t_i-t_d interval represents an increased survival potential in fire situations which increases the chance for rescue.

Panel Components. Results from panel components indicate relative gas yields and toxicities of each component. The highest yields of hydrogen fluoride were from materials 9, 25 and 10 used for the panels' front faces. Material 23, which is the core for panel 20, produced five times more hydrogen cyanide than any other panel component and more than twice the nitrogen dioxide. It also proved the most lethal with a t_i and t_d of 3.22 and 6.08 minutes, respectively. Small amounts of formaldehyde were found in two materials (22 and 24). It appears the greatest toxicity is from the aramid component, which is an aromatic polyamide in either fiber or honeycomb form.

Foams. As a class, the foams decomposed rapidly under test conditions, leaving little or no residue. All the urethane foams produced carbon monoxide, hydrogen cyanide and formaldehyde. Material 74 produced the highest sulfer dioxide yield of any material tested and twice as much hydrogen chloride as the PVC foam (46). However, the carbon monoxide yield for both 74 and 46 was extremely low, which probably explains why neither foam produced any animal deaths during the 30-minute exposure. Material 37 produced more than twice the formaldehyde than any other foam. All produced very little nitrogen dioxide or hydrogen sulfide, and no hydrogen bromide. Of the nine foams tested, seven yielded similar t_i values (4.29 - 5.55 minutes). An urethane and a polyester urethane (41, 74) produced longer t_i values of 7.55 and 9.58 minutes, respectively.

Fabrics. The highest carbon monoxide yield was from material 70, a cotton/rayon blend, while the second and third highest CO yields were produced by cotton and rayon (50, 51). Material 70 also produced the highest yield of nitrogen dioxide. The modacrylic drape (69) produced the highest yield (62.4 mg/g) of hydrogen cyanide of the 75 materials tested, in addition to a high yield of hydrogen chloride. This material also gave the shortest t_i and t_d (1.15 and 2.34 minutes) of all the materials.

The wool (47) and wool/nylon blends (72, 36) also had high hydrogen cyanide yields. They did not produce nitrogen dioxide or hydrogen chloride although material 72 had a high yield of hydrogen bromide. The wools

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(including 43 and 52) were the only materials producing hydrogen sulfide in significant amounts, although their sulfur dioxide yields were low except for the wool PVC blends (43, 52). These blends produced more than 10 times the sulfur dioxide of plain wool (47) and substantially more SO_2 than pure PVC.

In terms of toxicity, almost all the twelve wool fabrics had quite short t_i values. Eleven gave t_i values of under five minutes and the untreated PVC upholstery fabric (42) gave a t_i of 7.57 minutes. Several of these materials killed the test animals soon after incapacitation. The time between incapacitation and death was less than two minutes for materials 50, 51, 69 and 70. A short survival time following incapacitation is usually associated with supralethal levels of carbon monoxide.

PVC Coated Fabrics. The coated fabrics produced only carbon monoxide, hydrogen chloride and formaldehyde in significant amounts, although the formaldehyde yields were not noteworthy in comparison to that from other materials. Carbon monoxide yields, in general, were inversely related to hydrogen chloride yields.

The shortest t_i was 6.97 minutes for a lightweight, flame retardant-treated polyester (53) used as a seat bottom diaphragm. The heavy upholstery fabrics yielded t_is from 7.47 to 13.71. Two of them appear particularly promising from a toxicological standpoint. PVC/nylon and PVC/cotton (48, 71) had 10.70 and 13.71 minute t_is, respectively, and neither killed the test animals in the 30-minute exposure period.

Both coated cotton materials (44, 71) appear to be less toxic than their uncoated counterpart, material 50. However, since the fabric-to-coating weight ratio is not known, it is difficult to know whether the lowered toxicity is due to less cotton weight or changed combustion characteristics from the PVC coating.

Flooring. Materials 5 and 30 produced more carbon monoxide than the other flooring materials and were the only ones producing nitrogen dioxide. Hydrogen cyanide yields were greatest for the wool carpets (18, 19). Wools were the only hydrogen sulfide and sulfur dioxide producing materials.

The t_i range for this group of composite materials was from 4.94 (5) to 10.90 minutes (12). In general, these materials fall into two toxicity levels, with 5, 18 and 19 having t_i values of about five minutes and t_d values of 1½ to 3 times the t_i. Materials 12 and 29 have t_is of approximately 10 minutes and no observed deaths. Material 30 is between the two groups with a 7.46 minute t_i and a t_d almost twice that. The last two (12, 29) appear to be superior materials from a toxicological viewpoint.

Thermoplastics. Thermoplastics constitute most of the molded plastic panels, seat shrouds, etc. found in aircraft cabin interiors. They can be divided by chemical composition and toxicity into two distinct classes and an intermediate group. The polycarbonate materials (17, 63, 65) are the first group and produce the highest carbon monoxide yields of the 75 test materials and significant levels of hydrogen bromide. They all had t_is of about four minutes and very short t_i-t_d intervals—less than two minutes between incapacitation and death. The second group, the ABS/PVC materials (45, 55, 58) produced much lower carbon monoxide yields. However, they produced high yields of hydrogen chloride in addition to hydrogen cyanide, sulfur dioxide and formaldehyde. These materials produced t_is of approximately ten minutes and no deaths, while the remaining materials, a polyphenylene oxide (66) and a PVC/acrylic (54), gave intermediate animal response times.

Cargo Liners. This category consisted of fiberglass-reinforced plastic sheets containing variable quantities of nonflammable materials. Carbon monoxide yield varied from moderate to low, with only polyester (6) producing hydrogen cyanide or nitrogen dioxide. All the cargo liners produced either hydrogen chloride or hydrogen bromide in moderate amounts. Toxicologically, the t_is were related to the quantity of noncombustible material in each sample; i.e., the more thermally stable components, the longer the t_i.

Materials producing animal incapacitation within 30 minutes were fiberglass/polyester (6) and two fiberglass/epoxy sheets (14, 31). Their respective t_is were 3.99, 7.68 and 10.33 minutes. Two materials neither incapacitated nor killed the animals: a PVF-coated fiberglass/epoxy (13) and an asbestos-impregnated fiberglass/epoxy (67). Animals surviving tests on material 67 were observed for eight days and then sacrificed for post-mortum examination. No ill effects from the asbestos exposure were noted during observation or examination.

Transparencies. The only gases produced by the transparencies were carbon monoxide, hydrogen bromide and formaldehyde. The polycarbonate again produced the highest CO yield and the shortest time to incapacitation, 3.80 minutes, as well as the usual short t_i-t_d interval. Although the polymethylmethacrylates (59, 60) produced much lower CO yields, the fire-retardant material (59) produced over four times as much CO as the untreated material (60). However, the untreated material produced an exceptionally high yield of formaldehyde (63 mg/g). Material 60 caused neither incapacitation nor death to the test animals during the 30-minute exposure.

Insulation. Test materials in this category were limited to three fiberglass insulation batts containing various binders (15, 33, 64) and a single insulation batt cover (16) composed of aluminized PVF and nylon. Melamine (15) was the only material of the total 75 which did not produce a detectable amount of carbon monoxide. It did, however, produce a moderate yield of hydrogen cyanide. Although other gas yields were not significant, the hydrogen fluoride yield from material 16 was second highest of all materials tested. The batts' range of t_i was 3.70 minutes for the melamine to over 30 minutes for a silicone-treated phenolic-fiberglass (33). A nonsiliconed phenolic batt (64), on the other hand, gave a t_i of 12.26 minutes. No deaths occurred from these four materials.

These materials are about 80% fiberglass (by weight), therefore, the amount of material actually decomposing is only about 20% of the loaded weight. This small amount of binding material is responsible for the animal responses. For instance, if the melamine alone accounts for the 3.7-minute t_i and is only 20% of the total weight, then on an equal weight basis, pure melamine would be among the most toxic polymeric materials. This should be carefully considered when using such materials.

Elastomers. The elastomers class consisted of two silicone door-sealing materials. These produced low yields of carbon monoxide and all other gases, but an exceptionally high yield of formaldehyde. From the toxicological standpoint, material 68 was best, producing a t_i of 14.96 minutes and no deaths. Material 62 incapacitated the animals in 9.16 minutes and killed them four minutes later.

Conclusions. Both the NAFEC and CAMI project results support the theory that the greatest toxic hazards to life in a post-crash fire are carbon monoxide and hydrogen cyanide, individually and in combination. The presence of the irritant gases (which form acids when mixed with water) may, in fact, have a positive effect on life support by decreasing respiration and thereby reducing intake of systemic toxins.

Although the thermal decomposition process used for these studies did not represent processes in an actual aircraft post-crash fire, these small-scale tests demonstrated a reliable procedure for judging the relative toxicity hazards of candidate cabin interior materials. Large-scale tests are underway at NAFEC. Clearly, the choice of materials can increase passenger survivability in post-crash fires. How much increased survivability is possible and at what cost, as compared to other options (such as cabin fire suppression systems and fuel inerting) has yet to be determined. AEM will report on research in these and other areas of fire safety and material management including hazard ranking systems in future issues. The potential of fire prevention systems such as Halon 1301 will also be examined. ■

Table 1: Results of NAFEC and CAMI tests on 75 cabin materials, grouped by material types and in increasing order of laboratory animal's time to incapacitation.

ABBREVIATIONS

ABS — Acrylonitrile/Butadiene/Styrene
FR — Flame-retardant treated
PVC — Polyvinyl Chloride
PVF — Polyvinyl Fluoride

CO — Carbon Monoxide
HBr — Hydrogen Bromide
HCHO — Formaldehyde
HCl — Hydrogen Chloride

HCN — Hydrogen Cyanide
HF — Hydrogen Fluoride
H_2S — Hydrogen Sulfide
NO_2 — Nitrogen Dioxide

SO_2 — Sulfer Dioxide
T — Trace Amount
Ti — Time to incapacitation
Td — Time to death

NO.	MATERIAL DESCRIPTION	CABIN USE	MEAN ANIMAL RESPONSE TIME		TOXIC GAS YIELDS (mg/g)								
			t_i	t_d	CO	HCN	H_2S	HCl	HBr	NO_2	SO_2	HCHO	HF
	PANELS												
11	PVF/Epoxy-Fiberglass/Aramid Honeycomb/Epoxy-Fiberglass/PVF	Partition	2.36	4.48	164	6.4	0	T	T	0.26	0	—	7.0
8	PVF/Aramid-Epoxy/Aramid Honeycomb/Epoxy Fiberglass	Acoustic Wall Well	2.38	5.31	174	7.5	0	0	5.0	1.07	0	—	0.3
1	PVF/Epoxy-Fiberglass/Aramid Honeycomb/Epoxy-Fiberglass	Ceiling Panel	2.61	5.47	96	4.7	0	33.0	5.0	0.08	0	—	8.3
2	Epoxy-Fiberglass/Aramid Honeycomb/Epoxy-Fiberglass (Panel No. 1 without PVF finish)	Ceiling Panel	3.07	7.38	101	7.5	0	T	7.1	0.43	0	—	0.2
32	PVF/PVC/Phenolic-Fiberglass Epoxy Adhesive/Aramid Honeycomb/Epoxy Adhesive/ Phenolic-Fiberglass	Overhead Storage Panel	3.07	5.57	142	6.8	0	27.6	0	0.25	0	—	5.5
75	PVF/Epoxy-Fiberglass/Aramid Honeycomb/Epoxy-Fiberglass	Wall Panel	3.19	5.26	143	8.2	T	0	5.5	0.33	0	—	4.1
26	PVF/Phenolic-Fiberglass Screen/ Aramid Honeycomb filled with Phenolic-Fiberglass Batt/ Phenolic-Fiberglass	Drop Ceiling Panel	3.70	6.02	147	5.2	0	11.3	T	0.37	0	—	8.5

NO.	MATERIAL DESCRIPTION	CABIN USE	MEAN ANIMAL RESPONSE TIME		TOXIC GAS YIELDS (mg/g)								
			t_i	t_d	CO	HCN	H_2S	HCl	HBr	NO_2	SO_2	HCHO	HF
	PANELS CON'T												
20	PVF/Phenolic-Fiberglass Screen/ Aramid Honeycomb filled with Phenolic-Fiberglass Batt/ Phenolic-Fiberglass	Center Ceiling Panel	3.90	5.43	156	4.7	0	12.0	2.6	0.39	0	—	4.5
27	PVF/PVC/Phenolic-Fiberglass/ Aramid Honeycomb/Epoxy-Fiberglass	Upper Sidewall Panel	4.18	7.17	124	3.2	0	23.3	0	0.20	0	T	4.4
28	Wool Carpet/Phenolic-Fiberglass/ Aramid Honeycomb/Epoxy-Fiberglass	Lower Sidewall Panel	4.70	7.10	101	8.9	0.9	5.4	8.0	0.63	T	0.4	—
35	PVF/PVC/Phenolic-Fiberglass/ Aramid Honeycomb/Epoxy-Fiberglass	Door Assembly	4.86	6.68	142	4.6	0	19.4	4.1	0.19	0	—	4.5
34	PVC/Phenolic-Fiberglass/Aramid Honeycomb/Epoxy-Fiberglass	Door Liner	5.58	9.15	104	3.4	0	80.0	0	0.15	0.4	2.2	—
7	PVF/Polyester-Chopped Glass/ Aramid Honeycomb Polyester-Chopped Glass	Overhead Stowage Door Assembly	5.85	>30	90	2.3	0	34.4	T	0.09	1.2	—	7.1
	PANEL COMPONENTS												
23	Aramid Honeycomb filled with Phenolic-Fiberglass Batt (Core for No. 20)	Ceiling Panel Core	3.22	6.08	159	16.4	0	0	5.3	2.0	0	T	—
9	PVF/Aramid-Epoxy (Acoustic Skin for No. 8)	Face of Acoustic Wall Panel	3.89	6.94	153	2.9	0	0	6.6	0.15	0	—	36.0
21	Epoxy Coated Phenolic-Fiberglass (Backing for No. 20)	Backface of Ceiling Panel	4.79	9.15	161	0.6	0	0	0	0.62	0	—	T
3	PVF/Aramid Fiber-Phenolic	Face for Side-wall (upper side)	5.07	7.23	159	0	0	4.6	1.7	0.04	0	—	14.0
4	PVF/Aramid Fiber-Phenolic	Face for Side-wall (lower side)	5.22	7.31	162	0	0	22.0	0	0.04	0	—	11.6
25	PVF (Acoustic Skin for No. 20)	Ceiling Panel Finish	5.82	10.16	106	3.2	0	45.2	15.6	0.08	0	—	48.8
22	Epoxy Coated Phenolic-Fiberglass (Adhesive used in No. 20)	Adhesive used in Ceiling Panel	6.09	12.56	124	1.5	0	0	T	0.85	0	0.7	T
24	Epoxy Coated Phenolic-Fiberglass (Screen used in No. 20)	Screen used in Ceiling Panel	8.36	18.22	89	0.7	0	T	5.3	0.29	0	2.1	—
10	PVF (Clear Film)	Panel Finish	13.02	15.42	88	0	0	0	0	0.02	0	—	152
	FOAMS												
37	FR Urethane	Seat Pad	4.29	6.59	129	6.0	0	4.2	0	0.02	0.7	10.6	—
40	FR Polyether Urethane	Seat Cushion	4.80	7.34	105	5.8	0	0	0	0.03	0	3.5	—
38	FR Urethane	Seat Pad	5.04	8.08	108	7.8	0	7.3	0	0.04	0	3.8	—
73	FR Polyester Urethane	Seat Cushion	5.06	7.80	120	11.6	0	23.0	0	0.02	0	2.2	—

NO.	MATERIAL DESCRIPTION	CABIN USE	MEAN ANIMAL RESPONSE TIME		TOXIC GAS YIELDS (mg/g)								
			t_i	t_d	CO	HCN	H_2S	HCl	HBr	NO_2	SO_2	HCHO	HF
	FOAMS CON'T												
56	FR Polyethylene (rigid)	Flotation Cushion	5.25	8.08	149	0	0	8.6	0	T	0	4.3	-
46	PVC (untreated)	Seat Padding	5.50	>30	28	9.1	0.4	56.2	0	T	2.2	3.3	—
57	FR Polyester Urethane	Seat Cushion	5.55	8.65	83	5.0	0	0	0	0.02	0	3.4	—
41	FR Urethane	Seat Cushion	7.55	12.40	68	5.5	0	27.3	0	0.01	0.9	2.7	—
74	FR Polyester Urethane	Seat Cushion	9.58	>30	28	2.4	2.0	137	0	T	16.6	3.2	—
	FABRICS												
69	Modacrylic	Drapery	1.15	2.34	88	62.4	0	182	0	0.52	2.1	0.	—
47	FR Wool	Upholstery	2.00	4.17	89	41.7	13.4	0	0	0	0.3	T	—
49	Aramid	Upholstery	2.15	4.22	63	14.9	0	0	9.6	1.6	8.5	T	—
72	FR Wool (90%)/Nylon (10%)	Upholstery	2.22	4.70	112	37.2	14.2	0	20.5	0	1.5	0	—
39	Aramid	Upholstery	2.23	6.13	96	7.0	0	43.1	0	0.53	11.2	1.2	—
36	FR Wool (90%)/Nylon (10%)	Upholstery	2.72	6.16	78	33.8	13.9	0	0	0	0	0.8	—
70	Cotton/Rayon	Upholstery	2.93	4.24	348	1.9	0	28.0	7.1	1.0	1.8	0.4	—
50	FR Cotton	Upholstery	3.07	4.58	255	1.9	0	0	0	0.57	0	1.3	—
43	FR Wool (76%)/PVC (24%)	Upholstery	3.47	6.12	112	19.5	10.7	88.0	0	0.03	4.8	0.8	—
51	FR Rayon	Upholstery	4.18	5.72	144	3.8	0	14.5	5.1	0.39	0.9	1.3	—
52	Wool (49%)/PVC (51%)	Upholstery	4.64	10.18	70	11.2	6.2	205	0	0.04	4.9	3.8	—
42	PVC (untreated)	Upholstery	7.57	14.45	92	0	0.3	536	0	0.01	3.0	3.7	—
	COATED FABRICS												
53	FR PVC—Polyester	Seat Bottom	6.97	10.28	114	0	0	114	0	T	0	1.2	—
44	PVC/Cotton (untreated)	Arm Rest Cover	7.47	13.43	103	0	0	221	0	T	0	1.9	—
48	FR PVC/Nylon	Seat Arm Cap	10.70	>30	70	0	0	259	0	0.02	1.4	2.3	—
71	PVC Cotton	Upholstery	13.71	>30	56	0	0	220	0	0.01	0.9	2.2	—
	FLOORING												
5	Aluminum/Aramid Honeycomb/ Aluminum	Floor	4.94	6.88	94	6.7	0	0	0	0.32	0	T	—
18	Wool Pile/Polyester Backing/ Latex Coating	Carpet	5.26	11.73	55	14.9	5.3	21.9	0	0	2.2	T	—
19	Wool Pile/Polyester Backing/ Latex Coating/Urethane Pad	Carpet	5.53	15.35	46	13.5	6.1	24.9	0	0	2.5	1.0	—
30	PVC/Stainless Steel/Epoxy Adhesive/Aramid-Phenolic Honeycomb/Epoxy Adhesive/ Stainless Steel	Floor Panel	7.46	12.97	77	3.1	0	158	0	0.04	T	1.5	—

29	Wool Carpet/Epoxy Adhesive/ Aluminum/Balsa Wood/Epoxy Adhesive/Aluminum	Floor Panel	9.84	>30	52	4.1	0.7	19.0	0	0.01	1.4	3.7	—
12	Epoxy-Fiberglass/PVC/ Epoxy-Fiberglass	Floor	10.90	>30	41	2.4	0	82	0	T	0	0.5	—
	THERMOPLASTICS												
17	Polycarbonate	Molded Part	3.70	5.02	398	0	0	0	21.0	T	0	0.6	—
65	Polycarbonate	Passenger Service Units	3.83	5.50	406	0	0	0	47.0	T	0	T	—
63	PVF/Polycarbonate/PVF	Molded Parts	4.0	5.56	342	0	0	23.0	10.3	0.04	0	—	4.8
66	Polyphenylene Oxide	Flight Station & Lavatory Parts	5.19	6.89	196	0	0	0	0	T	0	2.7	—
54	FR PVC-Polymethyl Methacrylate	Seat Shroud	6.01	8.44	148	0	0.2	387	0	0.01	1.9	8.9	—
55	FR PVC/ABS	Seat Shroud	9.41	>30	54	2.2	0	197	0	T	2.6	5.9	—
58	ABS-PVC	Molded Part	9.59	>30	55	1.7	T	321	0	T	1.1	8.7	—
45	ABS-PVC (untreated)	Side Seat Panels & Tray	10.79	>30	55	4.1	0	162	0	0.02	2.9	6.6	—
	CARGO LINERS												
6	Fiberglass-Polyester	Side Cargo Liner	3.99	6.20	90	8.6	0	88.0	0	0.59	0	0.8	—
14	Fiberglass-Epoxy	Cargo Liner	7.68	14.61	66	0	0	105	0	T	0	0.9	—
31	Epoxy-Fiberglass	Cargo Liner	10.33	>30	62	0	0	61.0	0	0.01	0	2.6	—
13	PVF/Fiberglass-Epoxy/PVF	Cargo Liner	>30	>30	31	0	0	4.3	8.5	0.01	0	—	8.8
67	Fiberglass-Epoxy/Asbestos	Cargo Liner	>30	>30	23	0	0	0	17.0	0.02	0	3.3	—
	TRANSPARENCIES												
61	Polycarbonate	Windscreen	3.80	5.28	345	0	0	0	15.5	0.01	0	0.4	—
59	FR Polymethyl Methacrylate	Scratch Shield	7.56	14.73	86	0	0	0	47.1	T	0	4.6	—
60	Polymethyl Methacrylate	Window Pane	>30	>30	21	0	0	0	0	T	0	63.4	—
	INSULATION												
15	Melamine-Fiberglass	Fuselage Insulation	3.70	>30	0	15.0	0	0	0	0.34	0	0.8	—
16	Aluminized PVF/Nylon Scrim	Cover for Insulation Batt	6.56	>30	37	3.1	0	27.7	0	0.01	0	—	63.1
33	Silicone-Treated Phenolic-Fiberglass	Fuselage Insulation	>30	>30	21	7.3	0	0	0	0.38	0	1.5	—
64	Phenolic-Fiberglass	Fuselage Insulation	12.26	>30	31	2.7	0	0	0	0.22	0	2.2	—
	ELASTOMERS												
62	Silicone	Door Seals	9.16	13.66	45	0	0	0	0	0.01	0	25.6	—
8	Silicone	Door Seals	14.96	>30	9	0	0	0	0	0.01	0	26.7	—

FIRE DETECTION DEVICES

By Lauren Graham

Focusing on fire warning systems for aircraft application, this third-in-a-series article reviews a wide range of state-of-the-art devices with the greatest early warning capability. It discusses the operating principle, accuracy, reliability, false alarm propensity, weight and approximate cost of each type detector.

Efficient fire management as an approach to aircraft cabin fire safety involves effective and reliable early warning fire detection. Technical and economic aspects considered in the design of a successful aircraft early warning system are:

- Reliability of detection;
- Absolute minimum of false alarms;
- Function throughout the aircraft operating envelope;
- Interface compatibility with other aircraft systems;
- Maintenance;
- Weight;
- Cost;
- Endurance.

Costs discussed usually reflect available data on commercial/industrial units. The high reliability and ruggedness required for aircraft application would substantially increase the price. Advances in this technology are rapid.

Sensing environmental changes is the basis of all fire detectors. Fire casts these tell-tale indicators into the atmosphere:

Aerosols
- Solid particles
- Liquid droplets

Gases
- Thermal degradation (pre-ignition)
- Pyrolysis (post-ignition)

Energy
- Ultraviolet (UV) radiation
- Visible light
- Infrared (IR) radiation
- Heat from exothermic chemical reactions

A fire develops from overheat, to smoldering, and finally to flaming combustion. With an aircraft's limited fire fighting resources, very early detection and extinguishment becomes especially important. Rapid egress of passengers is not always possible, so smoke and noxious gases must be minimized. Thus, detectors of primary interest are those sensitive to indicators in the pre-ignition or early smoldering phase. Aerosols and gases are given off in these early stages; energy emission in significant amounts is usually delayed until flaming combustion.

AEROSOLS

Ionization Detectors

A number of detectors are based on sensing the presence of aerosols, i.e., invisible particles in the 0.1 to 0.3 micrometer range (Figure 1). Slightly later, coagulation produces particles in the visible range and smoke can then be sensed. Ionization detectors can sense aerosol particles in the "invisible" range.

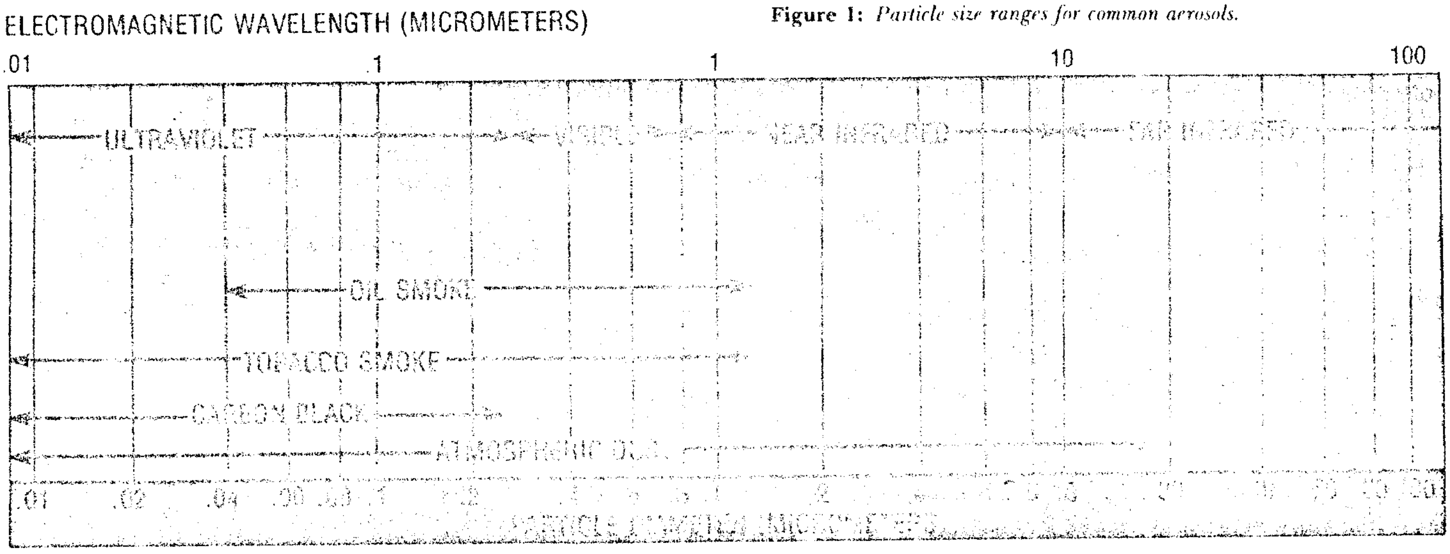


Figure 1: *Particle size ranges for common aerosols.*

The operating principle is ionization of air molecules by a radioactive source which establishes a steady state current between an anode electrode and a cathode electrode (Figure 2). Many negative ions attach to aerosols entering the area. The relatively large aerosol particles move slowly compared to the ions, reducing the current flow and unbalancing the sensing circuit. Various techniques have been used for increasing sensitivity and/or compensating for changes in ambient conditions. These techniques involve geometrical changes such as placing the radiation source close to the negative electrode (uni-polar), and using a reference chamber (dual chamber type). Recent advances in solid state circuitry have reduced the electronics and size so that these detectors are increasingly used for industrial and residential early warning fire detection. The overall detector, including integrated solid state electronics, weighs approximately 1.5 pounds.

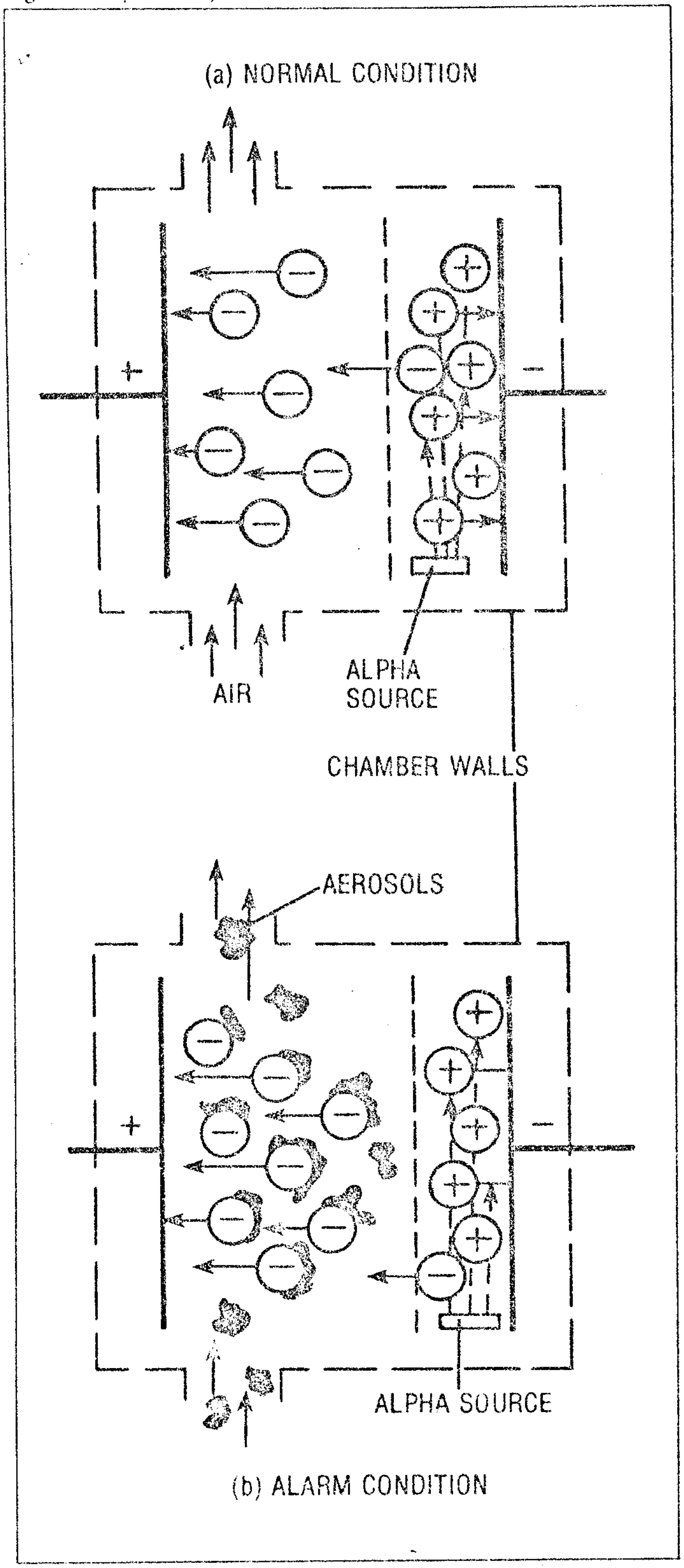


Figure 2: *Operation of an ionization chamber.*

Photoelectric Devices

Aerosols in the visible range can be detected by photoelectric devices which are the predominant type of compartment smoke detectors used in current commercial aircraft. Recent chamber design improvements and application of solid state electronics technology indicates these devices have the potential to also detect "invisible" range aerosols.

The principle of operation is the particle attenuation of a light beam intensity integrated over a beam path length, or the scattering of a light beam either in the

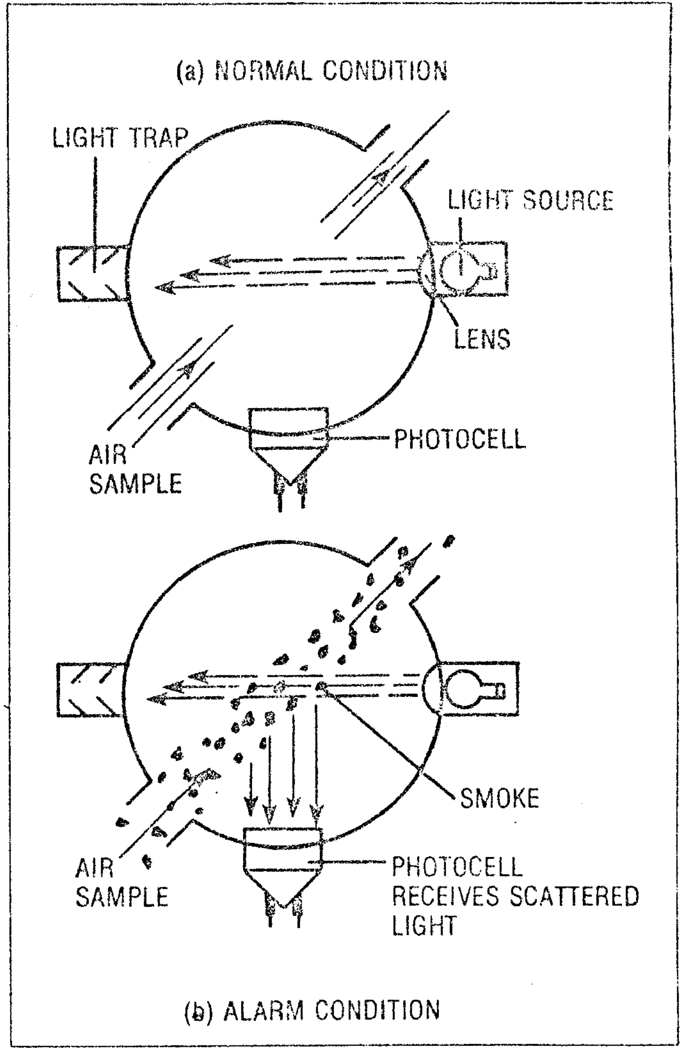


Figure 3: *Photoelectric detector using side scattering*

forward direction or at various angles to the beam paths. Both the "beam" type and the "Tyndall Effect" type use a light source and a photocell receiver. The beam type, not extensively used, is sensitive to alignment, dust or dirt on the source and/or receiver, and voltage variations. The Tyndall Effect type is more popular and uses a target to shield the photocell from the beam, or the beam source and photocell are arranged at some angle, generally 90°. As particles enter the chamber, they scatter the light reflected onto the photocell (Figure 3), providing a current flow for smoke indication. Early models are effective only at 8—10% light obscuration; new detectors in the 0.4 to 1.5% range. The life of the incandescent lamp light source is limited on earlier detectors, especially under vibrating or moving systems. This shortcoming has been improved with light-emitting diodes (LEDs) or gas-filled flash tubes as light sources with lifetimes of 10—20 years. Another attractive advantage is the low current drain (50 microamps to 50 milliamps) of these light sources.

Sensitivity improvements of photoelectric detectors will come with incorporation of light sources having a major spectral component in the near ultraviolet and blue-green wavelengths and a matching photocell to respond to the larger invisible aerosols, since the best scattering of energy occurs when the particle diameter approaches the wavelength of incident radiation. Recent tests indicate good photoelectric detectors are comparable in overall performance to ionization detectors. If a fire is slow and smoldering without flame, a good photoelectric detector has superior detection time to a good ionization detector. Conversely, if flames are present, the ionization detector will respond faster. A good photoelectric detector is less prone to false alarms from cigarette smoke (.01 to 1.0 μm). Photoelectric Tyndall Effect detectors cost between $50 and $160. Weight range is between 14 ounces and 1.5 pounds.

GASES

As a material approaches ignition temperature, thermal degradation emits trace gases. Because these gases depend on the material's specific chemical nature and their concentration in the atmosphere is so low, they have not been significant in fire detection. However, once ignition occurs, substantial quantities of gases common to many materials are emitted. Gases in most fires include water vapor, carbon monoxide and carbon dioxide, of which carbon monoxide is the most promising indicator because of its normally low background level. In some cases, emission of gases specific to known fuels might be sensed. But detectable quantities of gases lag behind the emission of aerosols, making this approach less suitable as an early warning signal.

Semiconductor Gaseous Detectors

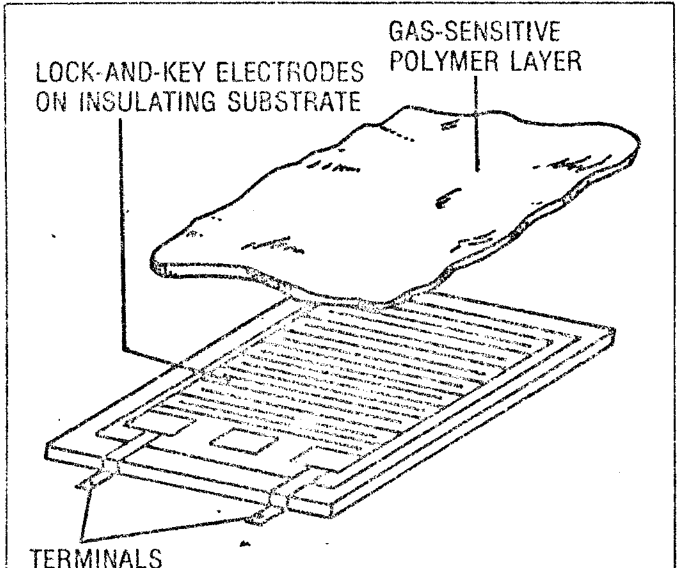
One type gas detector uses a semiconductor to sense reducing or combustible gases, such as unburned hydrocarbons, carbon monoxide and hydrogen sulfide. Some employ a heated n-type semiconductor composed of a metallic oxide coating (generally tin dioxide), and were originally developed for combustible gas detection. In contact with normal air, oxygen molecules are absorbed by the highly porous coating. When a reducing gas contacts the coating, the molecules react with the trapped oxygen causing an electron release and increasing the coating's conductivity. An operational requirement is the presence of hydrocarbons or combustibles. However, not all combustion processes release these by-products, e.g., burning gasoline. Unfortunately, many devices using these n-type semiconductors are being marketed as "Smoke-Fire Detectors." Their response is comparable to ionization and photoelectric devices in small-scale smoldering cellulosic fires, however when tested in twenty-six large-scale fires, they responded only once. Other problem areas are a propensity for false alarms caused by commonly present aerosols (such as cigarette smoke) or humidity changes, and lack of long-term sensitivity. The basic sensor integrated with control and alarm functions is in the $25 to $50 range and weighs about 1.5 pounds.

Polymeric Early Warning Detector

A relatively new type of sampling early warning or incipient fire detector is the polymeric type of gas detector, referred to as "lock and key device" (Figure 4). This detection technique is based on the electrical property change of selected polymeric compounds in the presence of certain gases (believed to be the result of complex formation and transfer of charges between the gaseous molecules and the polymer). Devices have been fabricated from eight polymers and their performance evaluated for response to temperature, humidity, and combustion by-products. Polymers responded to sulfur dioxide in the 10 ppm range.

Efforts continue to improve specificity of response to gases such as carbon monoxide; decrease sensitivity to humidity variations; investigate new and combined polymers, and techniques for miniaturizing and lowering device cost. Active consideration of these detectors for aircraft compartments awaits further evaluation of long-range stability, reliability and performance under reduced pressure (altitude).

Figure 4: *Polymeric detector.*



ENERGY

Many forms of heat detectors are commonly used on aircraft and buildings, for example, the water sprinkler system with fusible actuation. The aircraft industry has used heat-sensitive detectors, such as bimetallic devices and continuous line eutectic metal elements, for many years. It is current practice to protect engine nacelles, auxiliary power unit compartments and equipment bays with such detectors. However, since substantial heat must develop for their actuation, they do not provide early warning. Somewhat earlier detection can be accomplished by sensing energy radiating from an open flame. Radiation surveillance devices generally detect ultraviolet or infrared with various techniques to compensate for sunlight and other ambient sources of radiation. An integrated IR-UV system with a continuous element heat sensor has been applied to engine fire detection to achieve high reliability and low false alarm rate. The primary disadvantages of radiation sensing are the requirement for open flaming, and the difficulty of locating a detector that "sees" a flame in any part of a complex compartment.

IR and UV Fire Detectors

An important flame detection application of the UV sensor was on NASA's Skylab Space Vehicle. Considering the spacecraft's operating environment, the UV flame detector was judged the best system for volume flame surveillance of all areas within the spacecraft. The requirements were for proven volume surveillance reliability, low maintenance, minimum propensity for false alarms and maximum sensitivity. The photoconductive tube used to sense UV radiation is a Geiger-Mueller type consisting of two parallel plate electrodes in a gas-filled, UV transmitting glass envelope. UV radiation incident on the tube releases photoelectrons from the metal electrode, triggering an avalanche conduction ionization process. If the UV radiation continues, the conductivity of the tube rises sharply, generating voltage pulses at the output. The pulse frequency indicates a fire. These detectors have a cone of vision up to 180°, the sensitivity decreasing from 100% straight ahead to 40% sideways. They can detect a 1-inch high hydrocarbon flame at a 10-foot distance or a 3/4-inch diameter candle flame at 6 feet, with response times ranging between 5 milliseconds and 3 seconds. Since the detector tube is totally sealed, ambient pressure fluctuations have negligible effects. These detectors can operate at 300°F, and on special applications up to 650°F. Typical weight of the UV detector without microprocessor is approximately 10-12 ounces.

Combined IR and UV sensors as an integrated fire detection system have been developed for engine nacelle applications. These systems give an alarm when a pre-determined deviation from the ambient IR-UV balance occurs.

Laser Beam Fire Detection

This system combines aerosol and energy detection. A coherent, monochromatic laser beam, where the energy is being propagated in phase, detects changes in the air refraction index when the air molecules are heated. The laser beam reacts similarly to a photoelectric detector if smoke particles attenuate the beam energy. Based on these principles, a system has been developed (Figure 5) using a laser beam source with a telescope for long projection, a corner cube mirror to compensate for misalignment and vibration, and heat and smoke photocells with appropriate filters. Practical range of the alarm is about 300 feet. Reasonable response times of 10 to 20 seconds with small test fires in tunnels make this system promising for long, uninterrupted compartments. System tests for varying environmental conditions, power consumption, false alarms and endurance need to be performed for full evaluation.

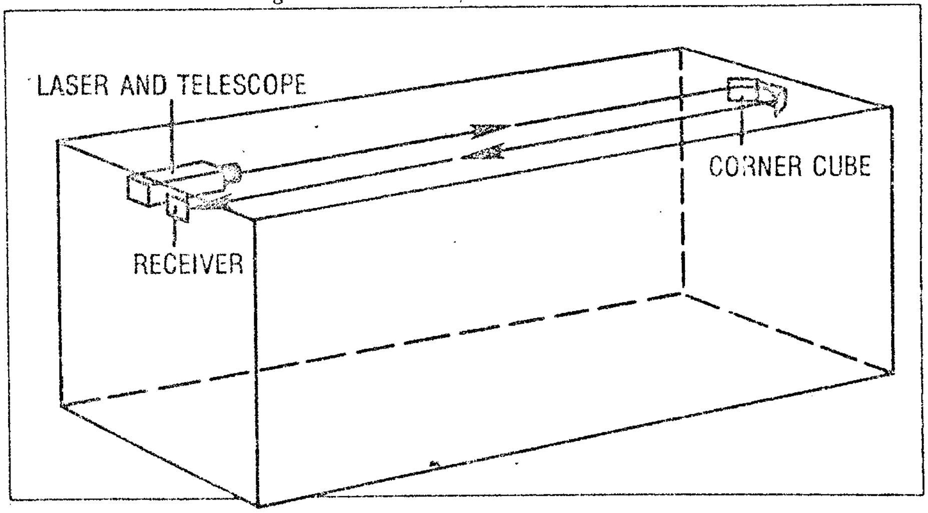
Condensation Nuclei

Materials well below their ignition temperature generate large quantities of aerosols. The temperature generating submicrometer particles is the material's thermal particulate point. The condensation nuclei is a very early warning detector capable of sampling particles in the .001 to .1 micrometer range. This device aspirates an air sample into a chamber of 100% humidity, and the air then passes through an expansion section. This action condenses water onto the aerosol particles and a sensitive photoelectric system measures the resulting fog. These detectors, although quite sensitive to combustion aerosols, require very careful calibration, repeated sensitivity settings due to changes in ambient conditions and frequent maintenance.

Resonant Quartz Crystal Detectors

This is a sampling type device like the condensation nuclei, but with a different method of detection. They utilize a specially designed jet-forming nozzle to separate particles of 0.7 micrometers or less from an aspirated air sample and impact them on a quartz piezoelectric crystal. Larger particles bypass the sampling tube and pass through the pump unit. As the submi-

Figure 5: *Schematic of a laser detector.*



crometer particles collect on the quartz sensing crystal, the crystal resonant frequency is changed proportionally to the mass change. Mass on the sensing crystal lowers its frequency, thus increasing the difference between it and the reference crystal. A regenerator is designed into the detector to periodically clean the crystal. The separator concept developed through this work has application to any detector sensing aerosols.

Conclusion

Figure 6 classifies the above detectors by at least eight important parameters necessary for aircraft application. The most promising early warning detection concepts are based on ionization and light-scattering principles. Concept modifications are flow-through, dual chamber ionization and LED photoelectrics. Concepts that may prove promising, pending further development, are polymeric and semiconductor gas sensing detectors, plus the laser detector for long passageways. The UV and/or IR systems offer special advantages for early flame detection.■

This article was based on the FAA report, "Feasibility and Tradeoffs of a Transport Fuselage Fire Management System" (FAA-RD-76-54).

Figure 6: *Summary of fire detector data.*

[1] Mean Time Between Failure
[2] Built-In Test Equipment
[3] Line Replaceable Unit
[4] Information Not Available
[5] Photoelectric Detectors Response Range

TYPE	SENSITIVITY	TIME RESPONSE (Sec)	POWER REQUIREMENT		MTBF[1] (Hrs)	BITE[2]	LRU[3]	WEIGHT (Oz)	CURRENT STATUS
			AC	DC					
Condensation Nuclei	.001-.1 Micrometer	NA[4]	NA	NA	NA	NA	No	NA	Limited Laboratory Use
Ionization	.01-1.0 Micrometer	26-51	.04 Amp 120 V	10^{-9} to .25 Amp 220 to 11 V	10^5	Yes	Yes	24-48	In Residential & Industrial Use
Flow-Through Ionization	<.7 Micrometer	10-15	None	.18 Amp 28 V	2x10^4 approx.	Yes	Yes	24	Undergoing Qualification Tests
Polymeric	5-10 ppm Gases	NA	None	5x10^{-10} Amp 50V	NA	NA	NA	<16	In Advanced Development
Semiconductor	>50 ppm Gases	36	.03 Amp 115 V	0.5 Amp 12 V	NA	Yes	Yes	24-30	In Residential & Industrial Use
Photoelectric	0.4 to 1.5% Light Obscuration	26-150[5]	50^{-6} to .04 Amp 220 to 120 V	.08 to .05 Amp 6-24 V	8x10^4 to 1.7x10^5	Yes	Yes	12-24	In Residential & Industrial Use
Laser Beam	NA	10-20 to heat, 25 To Smoke	NA	NA	NA	NA	NA	240 Approx.	In Limited Use (Great Britain)
Infrared	.65-.85 Micrometer Wavelength Range	.005-6 (to flame)	NA	.01 Amp 12-24 V	NA	Yes	Yes	16-24	In Aircraft Eng. & Marine Use
Ultraviolet	.17-.30 Micrometer	.005-6 (to flame)	.04 Amp 120 V	.006 to .012 Amp 12-24 V	NA	Yes	Yes	11-16	In Aerospace Use