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CABIN CREW SAFETY

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U.S. Reports Examine New Tools Aimed at Improving Survival Rates in Aircraft Fires

Determining the toxicity of smoke released from various cabin materials in aircraft fires is difficult, because toxicity depends on specific conditions that affect smoke composition, says one report summarizing the status of materials toxicology research. Other reports discuss computer evacuation models and cabin water-spray systems.

Robert L. Koenig
Aviation Writer

In-flight fires are rare in modern aircraft, but fire is an ever-present danger following an accident. Cabin occupants often survive the initial forces of a crash, only to succumb to smoke inhalation before they can be evacuated.

Three recent reports from the U.S. Federal Aviation Administration's (FAA's) Civil Aeromedical Institute (CAMI) in Oklahoma City, Oklahoma, U.S., present the state of research into several avenues that have been explored in the interest of making airplane crashes more survivable. These avenues include reducing smoke inhalation–related mortality; using computer models to simulate evacuation scenarios; and deploying cabin water-spray systems.

Aircraft Fires, Smoke Toxicity, and Survival: An Overview, written by Arvind K. Chaturvedi and Donald C. Sanders of CAMI, reviews efforts to determine the relative degrees of toxicity of incendiary fumes from materials in aircraft cabin interiors.

Two reports cited by the researchers indicate the extent of fire-related accidents and deaths:

- The U.S. General Accounting Office (GAO) found that approximately 16 percent (32 accidents) of all U.S. transport aircraft accidents between 1985 and 1991 involved fire. An estimated 22 percent (140 deaths) of the fatalities from those accidents resulted from the effects of fire and smoke, the GAO found.[1]

- Worldwide, the London-based International Cabin Water Spray Research Management Group reported in 1993 that 95 fire-related accidents involving civil-passenger aircraft claimed the lives of about 2,400 persons during a 26-year period.[2]

During the past three decades, advances in fire-retardant materials and improved fire-extinguishing systems have made in-flight fires uncommon. However, the report found that "survivable crashes followed by fire occur, primarily from fuel spills around the downed aircraft.

"Although cabin occupants may survive the initial forces of such crashes, they are frequently unable to escape from the fire environment because of performance impairment from the smoke-caused toxicity," as well as their difficulty in seeing through the dense smoke.

Smoke has many components, of varying toxicity. For example:

- Carbon monoxide and hydrogen cyanide, both of which tend to be present when fires produce substantial amounts of smoke, can cause incapacitation and death if present in high enough concentrations. Exposure to nonlethal concentrations of the two compounds can make smoke victims dizzy or confused;

- Irritants present in smoke can cause pain, induce tears or make smoke victims disoriented; and,

- Other "reactive molecules" in smoke sometimes have delayed toxicological or pathological effects.

Research has shown that carbon monoxide is toxic because it combines with hemoglobin in the blood and interferes with the transport of oxygen. Hydrogen cyanide inhibits cells in using oxygen. "The simultaneous exposure to both gases produces a combined effect of severe hypoxia," the report said, and even "less-than-lethal amounts of these gases can cause dizziness, confusion and physical incapacitation."

Another smoke component, carbon dioxide, has no direct toxic effect, but it increases a victim's respiratory rate, resulting in the victim inhaling more toxic smoke.

Decreasing levels of oxygen caused by fire diminish the amount of oxygen available for people who are struggling to breathe.

CAMI found that, from 1967 to 1993, 360 persons who died as a result of 134 fire-related civil aircraft accidents in the United States showed signs that smoke or other toxic fumes had impaired their ability to escape from the aircraft.[3] That conclusion came from CAMI's analysis of postmortem blood samples.

"Each fire is different," the report noted.

Postcrash fires are the most important factor in pilot fatalities in accidents involving commuter aircraft and air taxis.[4]

Determining exactly how fire and smoke affect accident victims is extremely difficult because fire is a complex and dynamic phenomenon. "Each fire is different," the report noted. But all fires involve rapidly developing chemical reactions that generate smoke, heat and flame.

Smoke is especially difficult to analyze because it is "a complex of particulate matter, vapors and gases suspended in the fire atmosphere," the report said. "It may be light, dark, thick or thin, and may diminish the transmission of light in obscure vision."

Studying the toxicity of fire is complex because "a material burned under one condition could be practically nontoxic, but could be very toxic when burned under a different condition."

One example: cotton, when burned under smoldering, low-oxygen conditions, produces relatively large amounts of poisonous carbon monoxide. But burned under hotter, flaming conditions, cotton's main emission is the less-toxic carbon dioxide.

Another example: nylons, when flaming, produce toxic hydrogen cyanide gas. But when smoldering under lower temperatures, nylons tend to break down into relatively nontoxic substances.

Efforts to retard fires in certain materials can at times be counterproductive. For example, some fire retardants that make materials less flammable may also make the smoke from those materials more toxic.[5]

"Most cabin furnishings contain carbon, and will produce carbon monoxide when burned," the CAMI report said. "Silk, wool and many nitrogen-containing synthetics are common sources of hydrogen cyanide in fires.

"Irritants, such as hydrogen chloride and acrolein, can be produced from burning wiring insulation and some other cabin materials. Generally, carbon monoxide levels increase as oxygen concentrations decrease during fires."

After a Capitol International Airways McDonnell Douglas DC-8 crashed and burned beyond the runway after an unsuccessful takeoff in freezing drizzle at Anchorage, Alaska, U.S., in 1970, researchers found traces of cyanide in blood specimens of the accident's 47 victims.

The U.S. National Transportation Safety Board (NTSB) concluded in its 1972 report that the victims had inhaled the cyanide during the fire that engulfed the aircraft after the crash. The FAA and other government agencies then sought the sources of the deadly cyanide, and to recommend action to prevent such toxic releases in future aircraft fires.

That is how the FAA began its research into fire and smoke toxicity — research that has involved both the CAMI program in Oklahoma City, which has specialized in the medical impact of fire and smoke on passengers and crew members, and the FAA Technical Center in Atlantic City, New Jersey, U.S., which has focused its work on the engineering components of cabin-fire research.

Since then, industries, government agencies, research institutes and universities in many parts of the world have conducted research into fire and smoke safety and toxicity. While the scientific and engineering knowledge have increased greatly, the CAMI report found that more research is needed.

"Continuing fundamental research in smoke toxicity, fire safety and fire hazard assessment in aircraft accidents is clearly warranted," the report concluded. "As fire science changes from a descriptive discipline to a mechanistic one, multidisciplinary skills will be required to develop practical applications from existing and projected research."

The report recommended promoting such cooperative global efforts through national and international colloquia on advances in combustion toxicology with a special emphasis on opening new avenues for research. Cooperative research between engineering and biomedical scientists "will greatly increase the chances for fire survival," the study said.

One goal of such global research, the report suggested, would be to help develop "a scientifically valid smoke toxicity test standard for materials." But that is more difficult than it might appear.

"Why are aircraft cabin interior materials not regulated based on their potential fire toxicity?" the report asked. "Since cabin materials are regulated on the basis of flammability, the question is a logical one."

The answer is that there is no "standard" fire. Because the conditions of burning sometimes alter the smoke composition — and, therefore, the toxicity — of emissions from burning materials such as cotton and nylon, "no single test condition would allow the relative potential toxicity ranking of all materials based on their probable performance in an actual fire," the report said.

Developing "a scientifically valid smoke toxicity test standard for materials" is more difficult than it might appear.

The report emphasized that any test method that is developed "must be based on firm scientific principles and must remain unbiased in its application. Validation of such a small-scale test will require parallel experiments with large-scale fires to compare the results of defined loads of test materials."

For those and other reasons, the report says, it might take several years of additional work to develop "an acceptable, scientifically valid test."

Throughout the past decade, researchers at CAMI and elsewhere have made advances in modeling fires and predicting the conditions and rates at which cabin materials emit combustion gases. In the 1980s, CAMI scientists designed and developed combustion assemblies and animal-exposure chambers for the analysis of smoke and combustion gases under various conditions.

Using rats, the researchers evaluated the net effects of exposure to smoke and/or gases, measuring how much time it took for the rats to become physically incapacitated.

"By relating the cumulative gas-concentration exposure time required to produce incapacitation, equations were developed that permitted the prediction of escape time in known concentrations of combustion gases," the report said.

That scientific approach also helped researchers take smoke toxicity into account when developing fire models. And, in recent years, researchers extended the studies to consider mixtures of carbon monoxide and hydrogen cyanide gases,[6,7] as well as mixtures of carbon monoxide and acrolein,[8] in the same cabin-like environment.

Meanwhile, CAMI researchers working in cooperation with scientists at the FAA's Technical Center had ranked 75 cabin-interior materials on the basis of the toxicity of their combustion products, with the measurement standard being time to incapacitation in rats.[9,10] That study, in the late 1970s, "produced very precise and reproducible incapacitation times for each material, when burned under identical conditions," the report said.

Other studies showed how changes in the pyrolytic (chemical change caused by heat) conditions affected time-to-incapacitation and, consequently, the relative toxic ranking of materials.

Researchers analyzed the toxic-gas output of aircraft panels,[11] seat fire-blocking materials[12] and wiring insulation.[13] In all, more than 100 aircraft-cabin materials have now been given "toxicity rankings," based on the lethalness of their emissions, and the length of exposure to those emissions before someone would likely become physically incapacitated.

While that research has been extensive and productive, the report recommends further work in several related areas, including:

- Obtaining more precise mathematical data for future fire-modeling programs, especially data on "material behavior and toxic-gas production."

  "Relationships between laboratory and large-scale material combustion tests must be established before small-scale tests can be used to estimate new material behavior in a real fire," the report said.

  "The toxic contributions of fire-generated aerosols, the visible components of smoke, are not well understood and their contribution to overall smoke toxicity needs to be evaluated."

- More closely examining fire retardants, "since some enhance smoke toxicity when heated above the fire-retarded material's ignition temperature."

- Exploring the specific toxicity mechanisms for individual combustion gases and multiple gas interactions.

> "Blood levels of these gases should be correlated with exposure concentration and duration, using suitable toxicological endpoints related to escape time," the study said.

- Establishing causal relationships between blood levels of combustion gases and the physiological impairment of humans. That would help medical examiners interpret postmortem forensic findings after aircraft accidents.

- Carefully studying the comparative toxicology of the newer, environmentally safe Halon [a pressurized-liquid fire extinguishant] substitutes proposed for use inside aircraft cabins.

Despite the crucial importance of fire research, the best way to save lives in most accidents is to evacuate the crew and passengers as swiftly as possible from a crippled or burning aircraft. In recent years, researchers have turned to sophisticated computer modeling to find the safest and most efficient ways to evacuate aircraft under various accident and fire conditions.

A Review of Computer Evacuation Models and Their Data Needs, a recent study by CAMI researcher Jeffrey H. Marcus, reviews the history and current status of such computer models, and suggests ways to evaluate such evacuation models and plans.

A fire inside an aircraft cabin "may be a fire safety official's 'worst nightmare,'" the report said. In some cases, hundreds of passengers are crowded into the cabin — in essence, a long, narrow aluminum tube — and surrounded by tens of thousands of gallons of highly flammable jet fuel.

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In most major aircraft accidents, passengers and crew members "are alive at the moment that the aircraft stops, but perish while trying to escape from the fire that follows," the Marcus report says.

Among the FAA safety regulations is the "90-second rule," which requires aircraft manufacturers to demonstrate that an aircraft cabin can be evacuated safely in less than 90 seconds with half the usable exits blocked, in darkness and with a prescribed mixture of passengers of different ages and sexes.[14]

"Given that safe evacuation is so critical to surviving an aircraft accident, and that showing compliance with the 90-second rule can be so burdensome, a computer simulation of the evacuation of an aircraft cabin is needed," the Marcus report said.

Such models also could help explain why some passengers die in an accident, while others survive, and how the cabin's design might be changed to reduce fatalities. Computer models also could give aircraft designers a valuable tool for use early in their design process to consider ease of evacuation.

There are two main types of evacuation models: queuing models, which involve the dynamics of people waiting in lines to escape, and network models, which develop paths between people and aircraft exits, and then use graph theory and "combinatorial analysis" to simulate an evacuation.

Most current aircraft-evacuation models are what experts call stochastic-queuing models. A stochastic process is an event occurring over time and following the laws of probability. In such models, each passenger is represented and his or her behavior is governed by a set of rules that relate to the probability that they will take certain action. That probability is generated by a random-number generator.

At each tick of the model's simulation clock, the model determines the actions of each hypothetical passenger, based on three factors: the rules governing behavior, the probabilities for action generated by the random-number generator and the area of the cabin where the passenger is situated.

The Marcus report considered three main computer cabin-evacuation models, each with its own set of strengths and limitations.

The GA model. In the 1970s, CAMI experts developed the first computerized cabin-evacuation model. CAMI researchers devised a more advanced model in the 1980s, called the Gourary Associates (GA) Model, that can be run on a personal computer and has an easy-to-understand visual display. But the Marcus report says that the GA Model "is limited by a crude cabin environment model, and by the inability to simulate a widebody, dual-aisle aircraft."

The AIREVAC model. Another evacuation model, called AIREVAC, was developed under the sponsorship of the Air Transport Association of America (ATA), mainly to assess how the presence of passengers with impaired mobility affects the evacuation process.

The CAMI report said the AIREVAC model "has a detailed simulation of a passenger's psychosocial responses to an evacuation, but as presently constructed, it can only represent a single model of an aircraft, and cannot simulate a fire." Therefore, it is suitable for certification tests, but not for trying to reconstruct the evacuation patterns that occurred in real aircraft accidents.

The EXODUS model. A third evacuation model, developed in England, EXODUS is capable of performing detailed simulations of the toxic effects of an aircraft fire.

The report says EXODUS simulations have been used successfully to simulate conditions in a widebody aircraft; to aid in a series of evacuation tests; and to reconstruct the fire that followed the aborted takeoff of a British Airtours Boeing 737 at Manchester Airport, England, in 1985. [Of the B-737's

137 occupants, 55 died in the accident, which included evacuation difficulties.]

The Marcus report suggests three possible sources for validating those and future cabin-evacuation models:

- Reconstructing accidents, to determine how close the model's predictions come to the actual event. But the report cautions that "exact agreement is not expected, only a general agreement in the location and number of fatalities."

- Simulating a certification test is a simpler process, and "certification tests may have more information available for the modeler."

- Using evacuation tests that are designed explicitly to serve as validation tools for computer models. The Marcus report calls this the best option for validating such models.

Two practical steps that might enhance the chances for surviving an aircraft fire are the present use of "fire-blocking layers" in aircraft polyurethane seat cushions and the possible use of cabin water-spray systems (CWSS).

"Currently used fire-blocking layers," the Chaturvedi/Sanders report said, "now improve the fire resistance of polyurethane seat cushions in aircraft." That report suggested that "proposed cabin water-spray systems exhibit considerable potential for slowing the spread of cabin fires. These water-spray systems have also proved valuable for scrubbing water-soluble fire gases, such as hydrogen cyanide and hydrogen chloride, from smoke atmospheres."

Although such water-spray systems offer benefits, some critics have cited two potential drawbacks: that steam created from the contact of the water spray with fire might cause respiratory-tract injuries, and that steam might also change temperatures in parts of the aircraft cabin in a way that might increase the risk of thermal injury to occupants.

The FAA took such concerns seriously enough to ask CAMI researchers to look into those potential drawbacks of water-spray systems. That evaluation, presented in a recent CAMI report, *The Potential for Pulmonary Heat Injury Resulting From the Activation of a Cabin Water Spray System to Fight Aircraft Cabin Fires*, by Robert P. Garner, concludes that the risk of greater injury from such steam is relatively low.

Garner's analysis suggested that, when CWSS water-spray systems are used during an aircraft fire, the heat content would increase significantly in only a very small volume of the aircraft cabin. " ... [The] risk due to increased latent heat in the environment resulting from activation of a CWSS is relatively small," the Garner report found. "Although a potential hazard from steam and hot water vapor saturated air does exist, exposure to these conditions for more than a second or two is highly unlikely and could theoretically be avoided by maintaining the correct posture and quickly evacuating the aircraft."

Also, the Garner report found, the overall heat content in cabins during fires would be "significantly higher" without the water-spray system. "The water in the spray is absorbing heat which is, in essence, what produces a significantly lower rate of temperature rise in the cabin when a CWSS is activated."

Overall, the Garner report said, "the fact that a relatively small, potentially hazardous thermal environment may be produced seems inconsequential in comparison to an uncontrolled fire environment." ♦

Editorial note: The three FAA CAMI reports discussed in this article are: *Aircraft Fires, Smoke Toxicity, and Survival: An Overview*, Report no. DOT/FAA/AM-95/8, February 1995, by Arvind K. Chaturvedi and Donald C. Sanders, eight pages, with bibliography; *A Review of Computer Evacuation Models and Their Data Needs*, Report no. DOT/FAA/AM-94/11, May 1994, by Jeffrey H. Marcus, 14 pages, with bibliography; and *The Potential for Pulmonary Heat Injury Resulting From the Activation of a Cabin Water Spray System to Fight Aircraft Cabin Fires*, Report no. DOT/FAA/AM-95/17, May 1995, by Robert P. Garner, 11 pages, with charts and a bibliography. All are available from the National Technical Information Service, Springfield, Virginia, U.S. Telephone: (703) 487-4780.

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About the Author

Robert L. Koenig is a Berlin, Germany-based correspondent who specializes in transportation and science issues. He has written on aviation matters for Science *and the* Journal of Commerce*. Before his move to Germany, he was a Washington, D.C., newspaper correspondent for the* St. Louis Post-Dispatch, *for which he covered transportation issues. He won the National Press Club's top award for Washington correspondents in 1994. Koenig has master's degrees from the University of Missouri School of Journalism and from Tulane University in New Orleans, Louisiana.*

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