Chapter 3

# RESEARCH AND TECHNOLOGIES FOR EVACUATION SYSTEMS

# Research and Technologies for Evacuation Systems

The aircraft evacuation system has three key elements: exits and slides, efficient means of reaching the exits, and the crew and passengers who use them. To be able to leave one's seat, move toward an exit door or hatch, and escape from the aircraft depends on the passenger's physical and mental condition, and tolerance to crash and fire hazards. These hazards, in turn, depend on the strength of seat attachments and restraints, airframe energy absorption, and the fire resistance of the cabin lining and seating materials.

Evacuation performance thus requires enhanced cabin safety to preclude incapacitation from impact, smoke, heat, and toxic gases before egress can be achieved. Evacuation performance also depends on the design and operation of emergency equipment and flight attendant training. Cabin safety research and evacuation testing are essential elements of any effort to assess and improve evacuation safety.

## CABIN SAFETY RESEARCH AND TECHNOLOGIES

The Federal Aviation Administration (FAA) researches and regulates several facets of cabin safety for transport airplanes, rotorcraft, and general aviation aircraft. The majority of the research and testing is accomplished at the Technical Center and the Civil Aeromedical Institute (CAMI). FAA also relies on the National Aeronautics and Space Administration and the National Institute of Standards and Technology (NIST) for contract or cooperative work in crashworthiness and fire safety, respectively. In passenger transport, after the United States, the United Kingdom is the second largest contributor to cabin safety research and technology (R&T). Other foreign investigators in fire safety research include Canada, Germany, the Nordic countries, Japan, and Australia.[1]

In 1980, FAA's Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee published several recommendations to improve fire safety and survivability.[2] FAA used the committee's recommendations to direct its research and development (R&D) efforts, and produced new and modified regulations in a number of areas.[3] The success of FAA's programs rests primarily on the development of representative fire scenarios and test methods. Currently, research is concentrated in two categories: in-flight fires, where safety is measured by the ability to prevent, detect, and contain a fire in the immediate vicinity of ignition as well as discriminate from false alarms; and postcrash fires, which in turn involve either making the environment inhabitable for a longer time or evacuating passengers more quickly.[4] The key programs relating to cabin materials, emergency equipment, and training are discussed below.

### Cabin Materials

According to FAA, the most important recent improvement in cabin safety was the addition of fire-blocking layers to seat cushions.[5] FAA, with NIST participation, established in the mid-1980s the methodology for determining the rate at which hot gases are emitted from burning seat cushions. The fire blocking has been shown to extend evacuation and survival time by at least 40 seconds in one representative

1 Richard Bukowski, senior researcher, Building and Fire Research Laboratory, National Institute of Standards and Technology, personal communication, Apr. 8, 1992.

2 Federal Aviation Administration, *Find Report of the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee, vol.* 1, Report FAA-ASF-80-4 (Washington, DC: June 26, 1980).

3 R.G. Hill et al., "Aircraft Interior Panel Test Criteria Derived From Full-Scale Fire Tests," DOT/FAA/CT-85/23 (Atlantic City, NJ: Federal Aviation Administration Technical Center, September 1985), p. 1.

4 Constantine p. Sarkos, manager, Fire Safety Branch, FAA Technical Center, personal communication, Apr. 22, 1992.

5 U.S. Department of Transportation, Federal Aviation Administration, *Aircraft Safety Research Plan* (Atlantic City, NJ: Federal Aviation Administration Technical Center, November 1991), p. 123.

postcrash fire scenario by delaying the onset of material ignition and reducing the spread of flames and toxic products of combustion.[6]

The FAA Technical Center developed the standard test protocol for assessing cabin material flammability through comparison of laboratory studies and fill-scale fire testing (using a reconfigured C-133 fuselage). In simulated postcrash fires, evaluation of combustion gas and temperature profiles indicated that the occurrence of cabin flashover[7] dictated survivability, and that flashover can be best characterized by heat release levels.[8] This prompted the development of the current heat release standard instead of limits on specific combustion products.[9] Today FAA continues to investigate fire behavior, smoke toxicity, the behavior of composite materials, and the effectiveness of potential safety improvements using the FAA Technical Center's DC-10 and B-707 test craft.[10]

CAMI has extensively studied the effects of fire on aircraft interiors, supporting rulemaking for crew member protective breathing equipment (PBE). Continuing fire safety research topics include smoke release and relative toxicity of materials used in cabin finishings, and methods to improve evacuation under toxic smoke conditions.

Over the years, FAA's Technical Center contracted out portions of its materials safety, fire performance, and toxicology research to NIST. NIST conducts in-house research at the Building and Fire Research Laboratory and funds additional research through its University Grants Program.[11] According to NIST staff, recent gains in scientific knowledge and the advent of measurement technology will shift fire safety regulation toward performance standards rather than design criteria.

The measurement technology required for quantitatively assessing evacuation system performance, including human factors, has not been developed to the same degree. The Aviation Rulemaking Advisory Committee efforts to replace evacuation design criteria with performance standards suffer from the lack of sophisticated analytic tools and human performance data.

## Emergency Equipment

Analysis of the 1985 Manchester aborted takeoff and subsequent fuel-fed fire prompted several recommended design changes, including improved access to overwing exits and cabin interior hardening, most of which have been implemented.[12] The accident also renewed interest in cabin water sprays and passenger protective breathing equipment. The relative merits and disadvantages of these proposals are discussed below, along with the topic of risk/risk assessment.

### *Protective Breathing Equipment*

Time and the thermo-toxic environment are two critical aspects of survival in aircraft accidents involving fire.[13] Based on R&D done at CAMI, criteria for PBE for air transport crew

6 John J, Petrakis, "FAA Occupant Protection and Cabin Safety Overview, " in *Proceedings of the Flight Safety Foundation/Federal Aviation Administration International Aircraft Occupant Safety Conference and Workshop,* DOT/FAA/OV-89-2 (Washington, DC: U.S. Department of Transportation, August 1989), p. 43.

7 Flashover is the sudden, rapid, and uncontrolled growth of fire throughout the cabin, generating high temperatures and toxic gases and robbing the cabin atmosphere of oxygen.

8 Constantine P. Sarkos, manager, Fire Safety Branch, FAA Technical Center, personal communication, Jan. 15, 1993.

9 Also known as the 65/65 rule, which refers to the maximum allowable rate of heat release, in kW/m2, and the total heat release, in kW-min/m2, under specified test criteria.

10 Alan S. Brown, "Fire Rule Changes Aircraft Materials Mix, " *Aerospace America,* March 1991, pp. 20-24.

11 Bukowski, op. cit., footnote 1.

12 Arthur Reed, "Technology Safety . . . For Cabin-Fire Survival, " *Air Transport World*, October 1991, pp. 101-106.

13 Garnet A. McLean et al., Civil Aeromedical Authority, *The Effects of Wearing Passenger Protective Breathing Equipment on Evacuation Times Through Type III and Type IV Emergency Aircraft Exits in Clear Air and Smoke, Final Report*, *DOT/FAA/AM-89/12* (Washington, DC: U.S. Department of Transportation, November 1989), p. 1

members were issued in June 1983.[14] Consisting of a full-face oxygen mask or combination smoke goggles and oxygen mask, crew member PBE is required equipment for all aircraft operating under 14 CFR 121.

Although the investigation of the Manchester accident resulted in a recommendation for provision of passenger PBE, or smokehoods, rules mandating their installation on transport aircraft have not been issued.[15] Two general types of smokehoods, filter and oxygen-generating, have been proposed. The lightweight filter type is susceptible to carbon monoxide contamination and becomes ineffective when cabin oxygen is depleted. Either type can delay evacuation because passengers stop moving toward the exits to don the masks. Smokehoods can also impede egress through smaller doors, prevent passengers from hearing crew instructions, and reduce vision.[16]

In addition, while the Civil Aviation Authority (CAA) of the United Kingdom issued a draft specification for passenger smokehoods in 1986, it rejected requiring smokehood equipment after a joint review of regulatory policy by U. K., U. S., French, and Canadian authorities showed that the implementation of other safety measures (e.g., seat fire blocking and cabin material improvements) has improved survivability to the extent that smokehoods have become less useful.[17] Because the time available to evacuate an aircraft is the most critical element of survival, the additional time spent donning smokehoods during the period when conditions permit the fastest egress reduces their potential to save lives and may even result in more deaths.[18]

### *Water Spray*

FAA commissioned an early cost/benefit study of fire management systems and safety improvements, completed in 1983. CAA reviewed worldwide accidents involving fire-related deaths over the 1966 to 1985 period, and concluded that the benefit attributable to having an onboard cabin fire suppression capability (e.g., a water spray system) is likely to be substantial and exceeds the benefit attributable to systems that do nothing to delay the onset or progress of fire.[19] In June 1989, FAA began working with CAA and Transport Canada to develop and evaluate a cabin water spray system (CWSS).[20]

The present heat release standard has driven technology to the point where it is unlikely that further cabin materials research and improvements over the near term will lead to appreciable delays of flashover.[21] Water spray works independently of fire origin and has more potential to delay flashover under a variety of fire scenarios; its benefits include cooler cabin temperatures, suppressed ignition of cabin materials and delay of flashover, absorption of combustion gases, and the washout of smoke particles.[22] Full-scale tests of one cabin sprin-

14 Federal Aviation Administration Technical Standard Order, TSO-C99, June 27, 1983.

15 The aviation industry first concentrated On the role of smoke and toxic gases in hindering evacuations after the November 1965 aircraft accident at Salt Lake City, Utah. FAA published a summary of CAMI studies related to passenger smokehoods performed during the period of November 1965 to February 1987. See E.A. Higgins, *Summary Report of the History and Events Pertinent to the Civil Aeromedical Institute's Evaluation of Providing Smoke/Fume Protective Breathing Equipment for Airline Passenger Use, DOT/FAA/AM-8715* (Washington, DC: U.S. Department of Transportation, Federal Aviation Administration, June 1987).

16 Helen Gavaghan, "Aircraft Fires: Living Through the Smoke," New *Scientist*, Aug. 6, 1987, pp. 54-57.

17 Reed, op. cit., footnote 12.

18 Louise Speitel and Richard G. Hill, *Study of Benefits of Passenger Protective Breathing Equipment From Analysis of Past Accidents, Final Report*, DOT/FAA/CT-88/03 (Atlantic City, NJ: FAA Technical Center, March 1988), p. 4.

19 Lionel Virr, "The Feasibility of Improved Fire Protection Systems for Aircraft Occupants," in *Proceedings of the Flight Safety Foundation/Federal Aviation Administration International Aircraft Occupant Safety Conference and Workshop*, DOT/FAA/OV-89-2 (Washington, DC: U.S. Department of Transportation, August 1989), p. 200.

20 Water spray is targeted because the use of foams and Halon-based suppression systems present health and/or environmental obstacles.

21 Sarkos, op. cit., footnote 8; and Kent Porter, contributing engineer, New Large Airplane Payload Systems, Boeing Commercial Airplane Group, personal communication, Aug. 11, 1993.

22 Sarkos, op. cit., footnote 4.

kler concept (the SAVE system) have suggested that survival times can be extended by 2 to 3 minutes.[23] By comparison, fire blocking and improved cabin interior materials provided extensions on the order of 40 seconds and 17 seconds, respectively .24

The possibility of inadvertent system discharge during flight, the weight/cost of system implementation, and reduced visibility during evacuation are key drawbacks. At FAA's request, manufacturers participated in a disbenefit study (i.e., estimating the consequences of both commanded and accidental use). Estimated weight penalties for narrow- and wide-body aircraft were on the order of 600 and 2,100 pounds, respectively.[25] Boeing estimated the costs of installing SAVE CWSS to be approximately $800,000 for a 757 airplane, and nearly $1.7 million for the newest model 747.[26] Estimated costs of retrofitting the world's fleet of current production aircraft exceeded $6 billion.[27]

Recognizing that these penalties and risks must be reduced before system implementation is feasible, FAA has explored zoned use of the sprinklers, or spraying water only in the immediate vicinity of the fire, to decrease the amount of water required. Full-scale effectiveness tests with the zoned CWSS showed that, along with improved visibility, temperature and gas concentration levels were lower, and the survival times greater than those in a fully sprayed cabin.[28] The optimal amount of water and its distribution requirements have yet to be determined. The drawbacks associated with using a system with a small fraction of the water required by the original concept should be reassessed.

FAA is also evaluating the effectiveness of another CWSS concept, one which employs sheets of water to act as curtains between sections of the aircraft and contain the fire within a small region of the cabin. Using nozzles fashioned by British Petroleum and sensor/activation systems developed by GEC Avionics, the BP/GEC system would function similarly to the first design (see figure 3-l). Relative system effectiveness for equivalent water supplies has not yet been determined. Other options for minimizing the weight penalty of CWSS include the use of potable water and, in the long term, water reclamation systems.

A CAA study of turbine-engine aircraft accidents involving fire deaths compared the potential benefits of five improvements to cabin safety .29 Assuming each improvement was applied uniquely, CAA found that the expected saving of life was much higher for water spray and smokehoods than the other options. Industry has argued that the study was biased toward water spray because the majority of the aircraft included in the assessment were first- and second-generation models that lacked many of today's fire safety improvements and had higher accident rates.[30] Changing demographics indicate that the average age of airplane passengers will be increasing, suggesting that the ability of passengers to move about and

23 Richard G. Hill et al., "Evaluation and Optimization of an On-Board Water Spray Fire Suppression System in Aircraft," paper presented at the Twelfth Meeting of United States-Japan Panel on Fire Research and Safety, Tsukuba and Tokyo, Japan, Oct. 27-Nov. 2, 1992, p. 1.

24 Petrakis, op. cit., footnote 6, p. 43; and U.S. General Accounting Office, *Aviation Safety: Slow Progress in Making Aircraft Cabin Interiors Fireproof,* GAOIRCED-93-37 (Washington, DC: U.S. Government Printing Office, January 1993), p. 26.

25 Thomas L. Reynolds, "Study of the Disbenefits Created by the Installation of Water Spray Systems for Fire Protection of Aircraft Cabins," Final Report and Industry Concerns Preface, December 1992, p. iv. Figures cited for systems installed aboard Boeing 757-200 and 747-400 airplanes, respectively. For the 747, the corresponding revenue loss, based on $1 million and 200 lbs. per passenger seat, would be roughly $10 million per year.

26 Ibid.

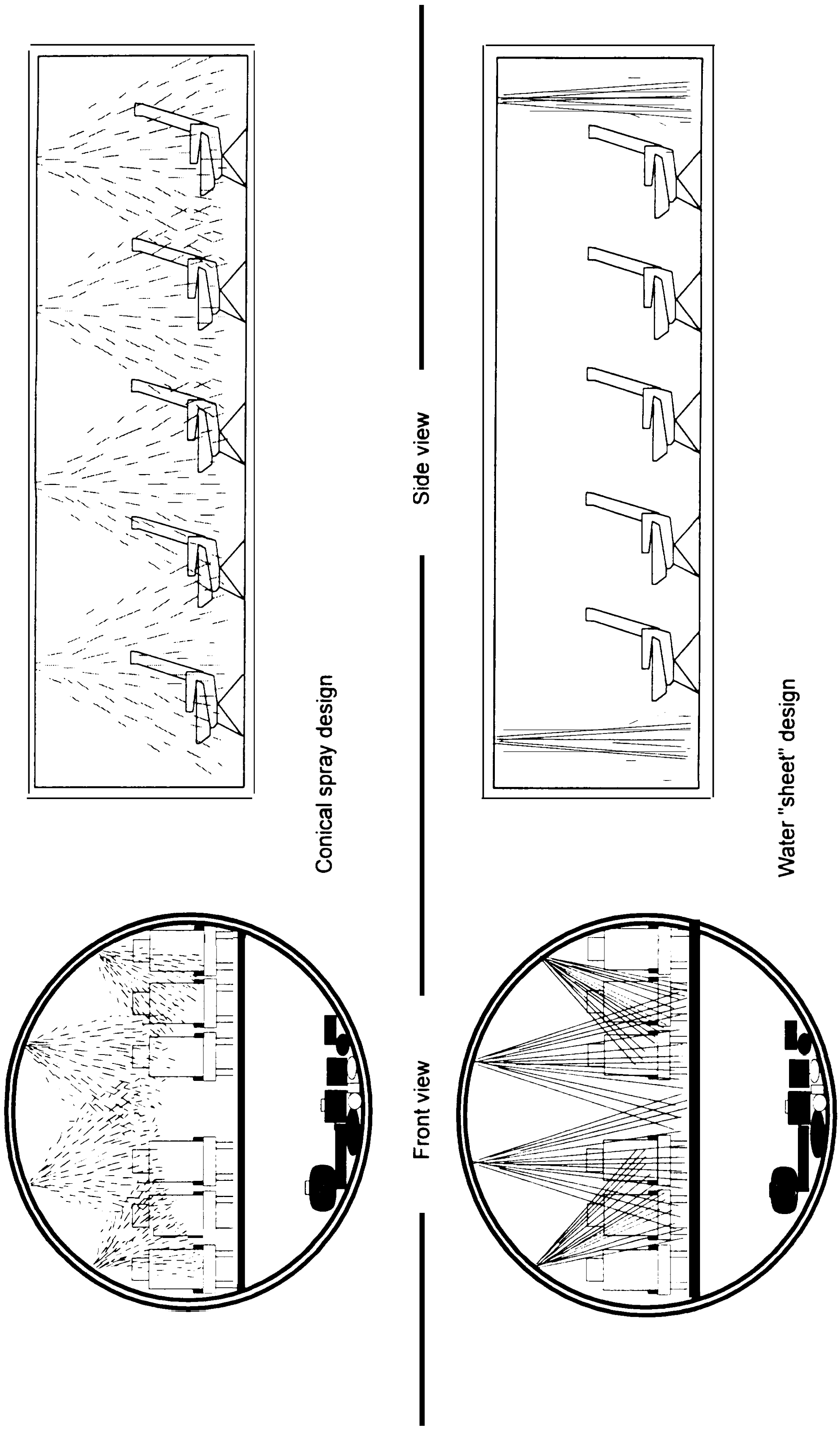
27 Ibid., p. vii.

28 Hill et al., op. cit., footnote 23, p. 1.

29 The five proposed improvements were: smokehoods, CWSS, improved access to overwing exits, more fire-retardant cabin lining materials, and minimum spacing requirements for seats. Ron Ashford, "Air Safety Regulation and Its Commercial Impact," *The Aeronautical Journal, vol. 95, No. 943,* March 1991, p. 85.

30 Thomas L. Reynolds, "Study of the Disbenefits Created by the Installation of Water Spray Systems for Fire Protection of Aircraft Cabins," draft report, July 1992, p. 63.

Figure 3-1--Two Configurations of Cabin Water Spray System Designs




SOURCE: Office of Technology Assessment, 1993.

rapidly exit the aircraft if necessary will be diminished. In general, then, technologies that further mitigate the thermo-toxic effects and extend cabin survivability periods would have greater benefits than attempts to further speed the evacuation rate.

## Risk/Risk Assessment

When the interactive effects of introducing a new technology are considered, the overall result may be less rather than more safety. Water spray systems may reduce the risk of fire-related fatalities but could contribute to an overall increase in risk to passenger safety-for example, inadvertent discharge during takeoff or landing phases of flight may distract pilots or cause critical avionics to fail. Similarly, while smokehoods could extend survivable conditions for a fraction of passengers, other passengers who might also have survived may, by delaying their escape in order to don smokehoods, be overcome by fire and smoke despite the breathing assistance.

In addition to technical feasibility and cost/benefit analyses, risk/risk assessments must be an essential part of the decisionmaking process when the likely safety improvement afforded by new technology is marginal. This is especially true of commercial aviation, where the overall fatality risk to passengers is already less than 1 in 10 million per flight.

## Training and Operations

The ability of flight attendants to quickly assess and respond to an in-flight or ground emergency affects passenger safety as much as the design of the aircraft and the performance of emergency equipment. The National Transportation Safety Board (NTSB) believes that as the crashworthiness of aircraft and survivability continues to improve, flight attendants ". . . are assuming a more critical role for ensuring passenger safety. "[31]

Flight attendants' spokespersons cite fatigue from lengthy duty times as providing potential for diminished capability during emergencies. However, the quality of their initial and recurrent training is perhaps more crucial. Flight attendants rely heavily on this training in emergency situations because real emergencies are rarely encountered in commercial aviation, providing little opportunity to practice the necessary skills. [32] Technologies assuming a larger role in training flight attendants include motion-based cabin simulators, fill-scale cabin/cockpit evacuation trainers, cabin evacuation simulators, and actual aircraft.[33] Some operators also use computer-assisted instruction.[34] However, the training provided in mockups does not test the flight attendants' ability to manage passenger flow, which has become increasingly important as seat density has increased.[35]

NTSB recommends that FAA require evacuation drills and group exercises during recurrent training, and that flight attendants demonstrate proficiency in managing passenger flow with verbal commands when competitive behavior is displayed.[36]

No matter how well-designed an aircraft or well-trained the flight attendants, passengers can undermine the safety capability by bringing on board excessive or inappropriate carry-on baggage, damaging safety equipment, or drinking to the point of becoming unable to respond to emergency instructions. In the 1992 evacuation from an L-1011 (see box 3-A), one passenger insisted on keeping a set of large animal horns while he exited the plane. [37] More

31 National Transportation Safety Board, *Flight Attendant Training and Performance During Emergency Situations,* Special Investigation Report NTSB/SIR-92/02 (Washington, DC: June 9, 1992), p. 37.

32 Ibid., p. 1.
33 Ibid., p. 18.
34 Ibid., p. 19.
35 Nora Marshall, senior accident investigator, National Transportation Safety Board, personal communication, Nov. 16, 1992.
36 National Transportation Safety Board, *Flight Attendant Training and Performance During Emergency Situations, Special Investigation Report,* NTSB/SIR-92/02 (Washington, DC: June 9, 1992), p. 31.
37 Independent Federation of Flight Attendants, "Recommendations to the National Transportation Safety Board Concerning Trans World Airlines Flight 843, " July 30, 1992, p. 3.

## Box 3-A–TWA Flight 843 Evacuation

On July ***30, 1992,*** shortly before 6 pm, TWA Flight 843 from New York to San Francisco aborted a takeoff from JFK airport. The plane quickly came to rest to the left of the runway and caught fire. Despite having but three of eight operable exit doors, there were no fatalities, in part due to the presence of off-duty flight attendants.

According to preliminary National Transportation Safety Board (NTSB) investigations, the Lockheed L-101 1 took off as normal and rose 50 to 100 feet before returning to the ground. Some passengers and flight attendants commented that something felt amiss with the plane prior to and during liftoff, but they could not be any more specific. Crew members and witnesses indicated that the aircraft landed very hard, causing the wings to flex excessively. A crew member in a plane awaiting takeoff reported that he saw and smelled jet fuel emanating from the plane immediately after it came down.

A fire quickly ensued and engulfed the aft portion of the plane, preventing the evacuation of passengers from all but three forward exits. By all accounts, the flight attendants responded swiftly, and evacuation was complete in approximately 2 minutes. Of the 273 passengers, 10 were injured, only 1 seriously. Flight attendants aboard the L-1011 stated that some passengers panicked and left their seats before they were told to do so and before the plane completely stopped. Investigators noted that a significant number of passengers climbed over the seat backs in order to exit the plane.

Nine flight attendants were assigned to flight 843, three more than the six required by Federal Aviation Regulations, and five off-duty flight attendants were on board as passengers. According to an Independent Federation of Flight Attendants report, the eight additional flight attendants played a significant role in the safe evacuation of the passengers. For example, the on-duty flight attendant assigned to the L-2 exit could not see if there were flames outside through the door's prismatic window. When she moved to a passenger seat window to get a better view, an off-duty flight attendant took over her post and prevented passengers from crowding the exit. The off-duty attendant then opened the hatch when the on-duty flight attendant verified that it was safe to do so. Subsequently, passengers became jammed at L-2, and the on-duty attendant instructed them to proceed to the L-1 exit.

SOURCES: National Transportation Safety Board, Office of Aviation Safety, "Factual Report of Investigation, " unpublished report, 1992; and Independent Federation of Flight Attendants, "Recommendations to the National Transportation Safety Board Concerning Trans World Airlines Flight 843, " July 30, 1992.

thorough enforcement of carry-on luggage rules has also been sought by flight attendant unions.

In 1985, the Training and Operations Working Group, established for the FAA's technical conference on emergency evacuation, recommended that FAA conduct research in communication techniques, behavioral sciences, and optimum learning situations to further improve comprehension and retention of safety instructions by passengers. FAA responded that the number of passenger-initiated unwarranted evacuations may in fact indicate that additional passenger training could have a negative effect on overall passenger safety .38 Rather than withhold information that may assist passengers in surviving a real emergency, crew coordina-

38 Federal Aviation Administration, Emergency Evacuation Task Force, "Report of the Training and Operation Working Group Meeting, December 3-4, 1985, Washington, DC, " *Task Force Report on* Emergency Evacuation *of Transport Airplanes,* DOT/FAA/VS-86/1,II (Washington, DC: U.S. Department of Transportation, July 1986), p. 18.

tion and communication could be improved to reduce the potential for unwarranted evacuations. Other technologies and training aids, including computer simulation, that may foster better communication between the flight crew and attendants should be explored. In addition, some operators use videos (on newer model aircraft) to heighten passengers' attention to the airline's safety briefing.[39]

Passenger education is only briefly mentioned in the National Plan for Aviation Human Factors; flight attendant training is not. According to FAA, a forthcoming revision to the National Plan is expected to address the cabin environment.

## EVACUATION RESEARCH AND TECHNOLOGIES

Little information is available on the behavior of evacuation systems and passengers in real accidents except for data recounted by witnesses and survivors after the fact. It is impossible to realistically simulate an emergency environment without exposing participants to considerable danger. To study the effects of various human behaviors on overall evacuation performance, researchers have used controlled and carefully staged emergency scenarios. In addition, researchers have developed and implemented complex evacuation models whose results depend on pre-set values or random variables representing human behavior. A number of persons interviewed for this paper felt that more "realistic" evacuation tests that attempt to introduce panic by exposing test participants to significant hazards would be unethical.[40]

In the United Kingdom, CAA has attempted to introduce competition among passengers during evacuation testing by offering financial incentives to limited numbers of test participants. Additional work using smoke and cabin water spray has been recently completed. According to Lionel Virr of Europe's Joint Aviation Authority: ". . . the issue of competitive behavior must be resolved to allow harmonization of future evacuation standards. "[41] CAMI investigators are considering initiating cooperative research with the United Kingdom's Cranfield Institute of Technology (CIT) to compare motivational techniques.[42]

Building evacuation research has included the design and development of several computer models to predict egress under various fire scenarios. These have some application to the development of models for aircraft. FAA has supported evacuation model development in previous years. In 1991, the Air Transport Association (ATA) began funding research by the Southwest Research Institute (SwRI) into simulation of passenger behavior in aircraft accidents.

This section discusses evacuation R&T programs, including testing to support rule changes (e.g., CAMI test of seat row separation standard for overwing Type III exit), from which an improved understanding of evacuation issues may be derived. It also discusses developments in computer modeling and simulation of passenger response during an emergency evacuation.

### Evacuation Testing

In 1986, CAMI studied flow rates through the overwing exits and exit preparation times under the following four different seating configurations:

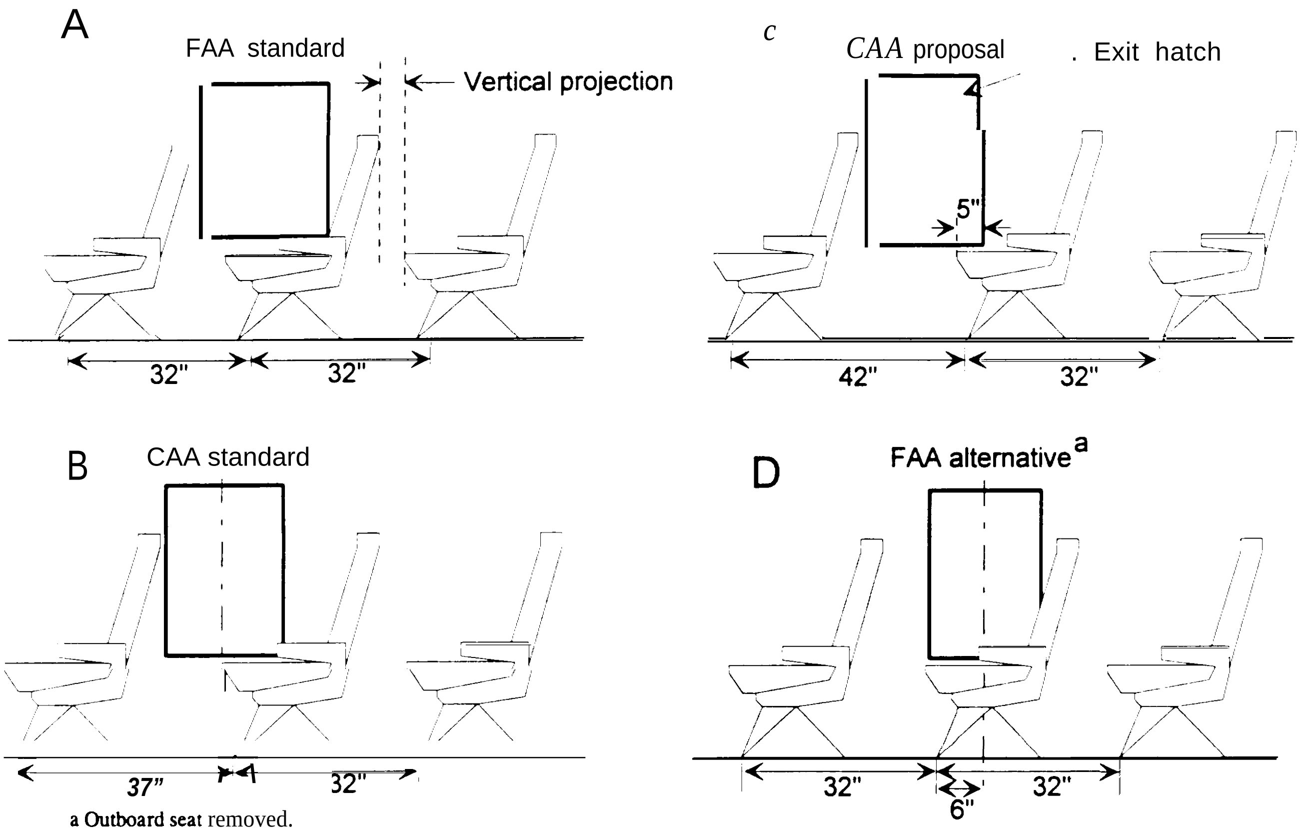
39 The Southern California Safety Institute, a spinoff of the University of Southern California's Safety Science Department, produces aviation safety videos and conducts training programs, audits airlines' safety programs, and so forth.

40 All Federal biomedical and behavioral research utilizing human test subjects is governed by a common rule for the protection of human subjects. See 14 CFR Part 11, June 18, 1991.

41 Advanced Rulemaking Advisory Committee, Emergency Evacuation Subcommittee, minutes of the Jan. 24, 1992, meeting, Washington, DC.

42 Jeffrey H. Marcus, manager, protection and Survival Laboratory, Civil Aeromedical Institute, personal communication, Jan. 13, 1992.

**Figure 3-2-- Schematic Representation of the Four Evaluated Seating Configurations**




a Outboard seat removed.

KEY:
FAA= Federal Aviation Administration
CAA=United Kingdom, Civil Aviation Authority

SOURCE: Federal Aviation Administration, 1992.

- the existing CAA minimum requirements;
- the minimum requirements of the CAA airworthiness notice (see section on "Exits" in chapter 1);
- the existing Federal Aviation Regulations (FAR) minimum requirements; and,
- an alternative proposed by FAA, in which the seat adjacent to the exit is removed.

Observed egress rates were faster for the proposed CAA configuration and FAA's alternative arrangement than for the configuration specified in the existing FAR (see diagrams in figure 3-2).[43] FAA observed no statistically significant difference in exit preparation times for the various configurations.

After releasing a notice of proposed rulemaking for improved access to overwing exits in April 1991, the Regulations Branch of the Transport Airplane Directorate requested that CAMI conduct a second study of egress efficiency for different seating arrangements.[44]

43 Paul G. Rasmussen and Charles B. Chittum, *The Influence of Adjacent Seating Configurations on Egress Through a Type III Emergency Exit, Final Report, DOT/FAA/AM-89/14* (Washington, DC: December 1989).

44 Garnet A. McLean et a]., Civil Aeromedical Institute, *Effects of Seating Configuration and Number of Type III Exits on Emergency Aircraft Evacuation, Final Report,*

Test results indicated that, of the total time required to evacuate through a single Type III exit, the amount of time a passenger needs to move from the center aisle through the seats and out the exit depends greatly on the ergonomic restrictions encountered at the exit opening (i. e., increasing the pathway width or decreasing the restricted distance to be traversed results in shorter egress times) .45

Based on the results from evacuation trials with a dual Type 111 exit configuration, FAA hypothesized that arranging the seat rows such that only one pathway leads to each exit would maximize the flow rates to and through the hatches. Aircraft with exit centerlines 29 inches apart (e.g., the Fokker 100) would have difficulty achieving this configuration.[46] In May 1992, FAA issued a final rule revising seat spacing standards for rows that lead to overwing exits; the implementation deadline was December 1992.[47]

In 1987, CIT commenced a CAA-sponsored program of research into passenger behavior during emergency evacuations. Analyses of aircraft accidents indicated significant congestion occurred during some emergency evacuations at galley entrances and overwing (Type III) exits.[48] CIT research sought to determine whether an optimum aisle width through the cabin divider (bulkhead) near the Type I exit or an optimum seating configuration adjacent to Type III exits existed. Two independent series of evacuation trials using different bulkhead apertures and seating configurations were performed, with one series employing financial incentives to foster competitive behavior among test participants.

CIT efforts to introduce as much realism as possible during the test included:

- using an actual aircraft, a Trident Three;
- training and dressing researchers as cabin staff; and
- providing pre-flight briefings and playing back a sound recording of an aircraft starting up and taxiing to a runway, experiencing an aborted takeoff, and being shut down.[49]

On comparing evacuation rates between the series, CIT researchers concluded that increasing the width of the bulkhead aperture leads to an increase in passenger flow rates through the adjacent Type I exit. CIT researchers also concluded that changes to the distances between seat rows on either side of an overwing exit influence flow rates; however, complete removal of the seat row adjacent to the Type 111 exit allowed passengers to pool together and resulted in slower evacuation rates than those measured for vertical projections between seat rows in the range of 13 inches to 25 inches (see figure 3-2).5°

A preliminary investigation into effects from the presence of nontoxic smoke was initiated in 1989, during which CIT again conducted a series of evacuations using varying bulkhead apertures and distances between seat rows next to overwing exits. CIT found that the presence of smoke significantly reduced the rate at which test volunteers were able to orderly evacuate the aircraft. At CAA's request, CIT also investigated the effects of nontoxic smoke and cabin configuration using competitive behavior. CIT found significant differences in egress rates for four alternative seat spacings adjacent to Type III overwing exits, but observed no statistically significant differences for evacuations through various bulkhead apertures.[51]

After comparing the results of these tests with data from the earlier noncompetitive evacuation trials involving nontoxic smoke, CIT research-

DOT/FAA/AM-92/27 (Washington, DC: U.S. Department of Transportation, August 1992), p. 1.
45 Ibid., p. 5.
46 Ibid., p. 6.
47 57 *Federal Register* 19220 (May 4, 1992).
48 Helen C. Muir and Trevor J. Gilpin, "Egress Update," paper presented at the Eighth Annual International Aircraft Cabin Safety Symposium, Costa Mesa, CA, Feb. 4-7, 1991, p. 2.

49 Ibid., p. 8.
50 Ibid., p. 12.
51 H.C. Muir et al., Cranfield Institute of Technology, Applied Psychology Unit, *Aircraft Evacuations: Competitive Evacuations in Conditions of Non-Toxic Smoke,* CAA paper 92005 (London, England: Civil Aviation Authority, March 1992), pp. 9, 11.

ers determined that the presence of a competitive element had a significant impact on egress rates for evacuations through the bulkheads, but did not affect the rate of evacuation through the Type III exit.[52] In the latter case, the difference in seat spacing (vertical projection) was the dominant factor in egress rates.

CAA also commissioned a study of human factors aspects of water spray system use during cabin evacuations. Using a 707 aircraft frame, CIT conducted eight full-scale evacuations, half in dry conditions. Mean evacuation times for the two conditions were virtually identical, suggesting the operation of the CWSS did not affect evacuation rates.[53] CIT researchers identified no significant visibility problems or hazards from wet cabin furnishings and floor surfaces.

Human behavior in actual emergency evacuations or even demonstrations for FAA certification cannot be extrapolated from the results of these series of CIT/CAA tests (e.g., because of the differences in participant demographics and small sample sizes). However, the data have provided insight into the effects of changes in human motivation and the cabin environment on evacuation capability.

## Computer Modeling and Simulation

The mathematical models used by aircraft manufacturers to predict evacuation times are simple calculations of total escape times based on empirical relations for equipment preparation and deployment times and the average throughput of exits. (These relations are derived from the results of research experiments and demonstrations for evacuation certification, not from actual emergency evacuations. )

More complex network and queuing models have been used to represent the characteristics of evacuation systems.[w] Network models, graphic representations of paths by which objects may move from one point to another, are useful for minimizing the time or distance of point-to-point travel but can quickly grow too complex for efficient use on computers .55 Queuing models describe the dynamics of . waiting lines, time-dependent processes that obey the laws of probability.[56] The initial population distribution and the probability of a person moving from one station in an evacuation system to another determine the waiting times and exit throughput.

Simulation relies on computer-generated random numbers to represent processes whose values cannot be approximated analytically. Parameter variability can be modeled with probability distributions; step-by-step and item-by-item, the simulation predicts what is likely to happen by running the model through several conditions.[57] For example, the influence of various hesitation times in the face of a growing fire threat could be observed using combined simulation models of aircraft evacuation and fire performance.

"A model is only as good as the parameters which describe the system . . . any evacuation models developed and used will need an extensive program of parameter determination and sensitivity analysis, and an equally extensive validation effort. "5[8] For example, if the presence of passengers with disabilities is assumed, simulation results are of little use unless good approximations (distributions) of seat exit and aisle flow rates are incorporated. Both general evacuation models and simulation efforts specific to aircraft are discussed below.

52 Ibid., pp. 18-19.

53 Researchers *noted* that the sample sizes were small and that the test results are not as statistically reliable as those derived from a larger sample. D.M. Bottomly and H.C. Muir, Cranfield Institute of Technology, Applied Psychology Unit, "Aircraft Evacuations: The Effect of a Cabin Water Spray System Upon Evacuation Rates and Behaviour, " report prepared for the Civil Aviation Authority, February 1993, p. 5.

5 4 John M. Watts, Jr., "Computer Models for Evacuation Analysis, " *Fire Safety Journal, vol. 12, 1987,* p. 241.

55 Ibid., pp. 237-238.

56 Ibid., p. 240.

57 Ibido, pp. 242-243.

58 Marcus, op. cit., fOOtnOte 42.

### General Models and Assessment

Assessment and modeling of flow problems involving people began in the early 1980s. Several models were developed to estimate the time required for groups of people to evacuate a given space or building. Building evacuation was modeled for situations in which the number of people inside a lobby affected the rate of exit from the lobby,[59] and where inhabitants may or may not be alerted before beginning egress.[60] In each case, the network flow solution method assumed egress occurred through well-defined passageways.[61] Other critical assumptions typical of the general approaches to solving related flow problems included:

- Any congestion will occur at doorways, and flow through vertical and horizontal passageways will be relatively free flowing;
- Doors serve to meter flow to about one person per second per door.[62]

The building models do not consider damage to exits as flow obstructions.[63] Implicit assumptions about nonvarying door and passageway dimensions and stairwell and hallway flow rates do not apply to cabin evacuation, and the models are inappropriate for conditions involving aisle congestion. None of the models attempted to incorporate human decisionmaking into the process, particularly in response to changing fire conditions. Neither panic, pushing, nor falling was assumed.

Certain methodological problems limit the study of human behavior in fires: experimental subjects cannot be placed in real fire (or crash) situations; testimony obtained after the fact from participants in fires may contain errors; and conclusions must be drawn cautiously where sample data are limited or not representative.[64]

In general, egress research (to fill models' data gaps) has fallen into three main categories: field studies of circulation facilities in nonemergency conditions; laboratory studies (e.g., sign visibility in smoke); and post-incident surveys of human behavior in emergencies.[65] The nature of case studies has progressed from mainly descriptive to more complex, analytical ventures that attempt to identify typical behavior patterns or correlate behavior and fire development .[66]

Despite the frequent use of the term "panic" to describe human response to emergency situations, particularly fire, researchers have concluded that ". . . people generally respond to emergencies in a 'rational, ' often altruistic manner, in so far as is possible within the constraints imposed on their knowledge, perceptions, and actions by the effects of the fire. "[67] Continued research into the reasoning and motivation behind individuals' actions, altruistic or not, is necessary. Existing models typically do not represent the perception of cues, investigative behavior (e.g., looking for the fire), and general coping behaviors.[68]

These data have limited application to aircraft evacuation. For example, some of the indeci-

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59 R.L. Francis, *A Negative Exponential Solution to an Evacuation Problem,* Report NBS-GCR-84-482 (Gaithersburg, MD: National Bureau of Standards, December 1984).

60 D.M. Alvord, *The Fire Emergency Evacuation Simulation for Multifamily Buildings,* Report NBS-GCR-84-483 (Gaithersburg, MD: National Bureau of Standards, December 1984).

61 T.M. Kisko and R.L. Francis, *Network Models of Building Evacuation: Development of Software System,* Report NBS-GCR-82-417 (Gaithersburg, MD: National Bureau of Standards, December 1982).

62 Harold E. Nelson, *'Fireform'-A Computerized Collection of Convenient Fire Safety Computations,* Report NBSIR 86-3308 (Gaithersburg, MD: National Bureau of Standards, April 1986), p. 27.

63 Matthew McCormick, chief, Survival Factors Division, National Transportation Safety Board, personal communication, Nov. 16, 1992.

64 R.L. Paulsen, "*Human Behavior and Fire Emergencies: An Annotated Bibliography,* " Report NBSIR 81-2438 (Gaithersburg, MD: National Bureau of Standards, December 1981), p. 3.

65 Hamish A. MacLennan, "Towards an Integrated Egress/Evacuation Model Using an Open Systems Appreach, " in Proceedings of the First International Symposium of Fire Safety Science, n.d., pp. 581-590.

66 Paulsen, op. cit., footnote 64, p. 5.

67 Ibid., p. 4.

68 MacLennan, op. cit., footnote 65.

sion attributable to not knowing for certain if a fire has broken out is often absent, time scales are different, and escape modes differ from the well-defined hallway model typically used. However, data on how smoke and the sight of fire affect decisionmaking skills, sex- or age-related effects, and so forth likely would be transferable.

Computer-based models that incorporate both human performance parameters and system characteristics are being developed. Simulation requirements include: assessment of risk from, for example, crash-related injury, smoke/gas toxicity, and fire; typical human behavior under stress, darkness, and smoke; basic response times under best conditions; and decision-making parameters. The generality and validity of these models must be determined. Models must address performance in dynamic large-scale, multiperson systems, as well as the effects of stress and emergencies.

In addition, the NIST Building and Fire Research Laboratory has developed the HAZARD1 model of evacuation from burning buildings using fire survivor psychological data to construct human behavior parameters.[69] HAZARD1 analyzes the fire environment for allowable egress time and demonstrates evacuation of building occupants based on behavioral rules obtained from interviews with fire survivors. NIST staff acknowledge the data are skewed in favor of successful behavior; those who did not survive cannot be interviewed. The software can be modified to do probabilistic branching for non-universal behavioral patterns; the current version uses only a deterministic approach, Other work at NIST relates to congestion in large buildings. University of Florida/Gainesville researchers have developed a version of HAZARD1 that allows optimization of building and fire safety designs.

### *Aviation-Specific Models*

In the early 1970s, FAA developed a computer model of aircraft evacuation using General Purpose Simulation System (GPSS) language, developed by IBM.[70] To estimate and analyze the escape process, the model used statistical functions to control passenger movements and to advance time related to each event.[71] First applied to evacuation tests in two single-aisle, narrow-body aircraft configurations,[72] FAA further developed the model to represent evacuations from wide-body aircraft.[73] The model provided for passenger reassignment to equalize the length of queues before exits. An average of 20 runs was used to evaluate each scenario.

FAA executed simulations of evacuations from DC-10, L-101 1, and B-747 aircraft during the same period the wide-body aircraft were undergoing evacuation certification tests. The simulation results correlated well with full-scale demonstration times.[74] However, the simulation model could not assess a priori the effects of human behavior. Although FAA's model predicted the total evacuation time for 527 passengers aboard a 747 would be 84 seconds, in a demonstration for certification participants exited the aircraft in under 67 seconds.[75] FAA attributed the difference to the motivation of passengers and crew.

**Recent and Continuing Efforts.** Under a FAA/CAMI-sponsored contract initiated in 1987, Gourary and Associates developed a clock-driven simulation model of the aircraft evacuation process for use on a computer. Each cycle, the model recalculates the position of each passenger subject to initialized variables: exit preference; endurance, or probability of surviving heat or smoke; agility; and "wake-up

69 Bukowski, op. cit., footnote 1.

70 J.D. Garner et al., *GPSS Computer Simulation of Aircraft Passenger Emergency Evacuations, FAA-AM-78-23* (Washington, DC: U.S. Department of Transportation, Federal Aviation Administration, June 1978), p. 1.

71 Earl D. Folk et al., *GPSS/360 Computer Models To Simulate Aircraft Passenger Emergency Evacuation,* FAA-AM-72-30 (Washington, DC: U.S. Department of Transportation, Federal Aviation Administration, September 1972), p. 1.

72 Ibid., p. 8. Comparison of test results fOr 134- and 234-passenger loads showed that larger exits used in the latter case allowed higher flow rates through the doors,

73 Garner et al., op. cit., footnote 70, p. 1.

74 Ibid., p. 5.

75 Ibid., p. 6.

time, " or the time it takes for a passenger to begin to move purposefully (reflects shock and the capability of opening one's lap-belt).[76] Increases in heat or smoke, passenger "fatalities," and disabled exits affect the flow rates through aisles and doorways (i.e., transitional probabilities).

The Gourary model is not comprehensive in terms of the human behavior assumptions, but it does portray passenger evacuation under a variety of crash/fire scenarios described by 40 crash characteristics and narrow-body aircraft cabin layouts.

None of the simulation models described above directly addressed psychological factors. Manufacturers and researchers lack the data to determine how much of a role these factors have in the overall success of evacuation. With development and validation of adequate parameters, the simulation may closely approximate an emergency evacuation.[77]

ATA-sponsored research by the Southwest Research Institute seeks to simulate passenger egress under a variety of evacuation conditions and passenger characteristics. ATA hopes to develop safety requirements that are sufficient for all passengers, including persons with disabilities, in all evacuation circumstances. The SwRI four-phase effort aims to create an aircraft evacuation (AIREVAC) computer model to simulate passenger behavior during emergency evacuations. Phase 1, completed in September 1991, entailed a literature search to identify variables, mathematical relations, and other information necessary to construct the model, scheduled for Phase 2 of the project. The model validation will be based on either archival evacuation data or on data from a new evacuation exercise .78

SwRI's literature search yielded no systematic overview of the evacuation process; rather, the effort produced references to work on specific issues and concerns.[79] The SwRI model variables address situational characteristics; passengers' physical and psychosocial characteristics, including motivational variables; and behavioral outcome variables. The latter includes initial response, helping another passenger, panic, and competitive behavior.[80]

**Data Issues.** Although FAA's simulation model provided for variations in passenger mix, seating and exit configuration, door-opening delay, time on the escape slide, and slide capacity, insufficient data were available to establish appropriate variables representing the different influences on evacuation rate.[81] Also, the lack of data on the effects of adverse conditions (e.g., smoke and debris) prevented their simulation.[82]

Boeing said that its own simulation effort in the 1980s was dropped in the belief it would not significantly improve the evaluation of evacuation systems and procedures, given the lack of evacuation data to substantiate the simulation model and the reliability of its existing mathematical models,[83]

Today, as in the 1970s, no central clearinghouse for evacuation data exists.[84] The largest collection of data published to date, the Aerospace Industry Association's report on its yearlong evacuation system study, was completed prior to the conduct of most wide-body aircraft certification tests.[85] Phase 3 of the SwRI

76 Gourary Associates, Inc., "Evacuation of passengers From Transport Aircraft: A Microcomputer-Based Model, " *User's* Manual *for Evacuation Simulator Demonstration Diskette,* Version 7.03, May 31, 1991, pp. *7-9.*

*77* Marcus, op. cit., footnote 42.

78 James E. Schroeder and Megan Tuttle, Development *of an Aircraft Evacuation (AIREVAC) Computer Model,* SwRI Project No. 12-4099 (San Antonio, TX: Southwest Research Institute, Sept. 30, 1991).

79 Ibid., p. 8.

80 Ibid., pp. 9-11.

81 Gamer, et al., op. cit., footnote 70, p. 2.

82 Ibid., p. 11.

83 George Veryioglou, senior manager, *747/767* Payload Systems, Boeing Commercial Airplane Group, personal communication, Dec. 12, 1991.

84 Garner et al., op. cit., footnote 70, P. 4.

85 Ibid., p. 4. See also Aerospace Industries Association of America, Inc., "Evacuation, " Technical Group Report AIA CDP-4, July 1968.

simulation task, designated for filling data "holes," is yet unfunded by ATA.[86]

Studying events related to single-aisle, narrow-body aircraft is possible with test beds in the United States and elsewhere. However, there is no research facility in the world that can be used for investigating wide-body, dual-aisle aircraft evacuation issues .87 The fiscal year 1995 FAA capital budget contains funding for such an evacuation facility. (A 747-100 has been offered to CAMI--the difficulty lies in getting it to Oklahoma City.) Just as certification of the 747, with its dual-aisle configuration, introduced more complexity into analytical methods, the proposed super jumbo aircraft (seating 550 to 800) will also stretch the capability of existing models and facilities.

The need for more data to extend the utility and reliability of the simulation technique is apparent. Improved accident data analysis, passenger demographics information, thermo-toxic environment information, parameterization of flight attendant and passenger behaviors, and a test bed for evaluating wide-body aircraft scenarios are required to validate evacuation simulations.

Even augmented, validated simulations may have their detractors. One passenger advocacy group has expressed alarm at the possibility that the SwRI computer simulation models sponsored by ATA will be used to rationalize limiting the number of passengers with disabilities allowed on board transport aircraft.[88] One can expect that this or any other test or analysis of evacuation performance is likely to produce slower egress times as the percentage of older passengers, children, or persons with disabilities on board aircraft increases. This fact of life, along with equity and other issues, will affect those finally making policy decisions.

86 James Schroeder, president, Applied Human Factors, Inc., personal communication, Oct. 28, 1992.

87 Marcus, op. cit., footnote 42.

88 Fred Cowell, executive director, Paralyzed Veterans of America, statement before the Emergency Evacuation Subcommittee of the Aviation Rulemaking Advisory Committee, May 14, 1992.