Aircraft Evacuation Testing: Research and Technology Issues

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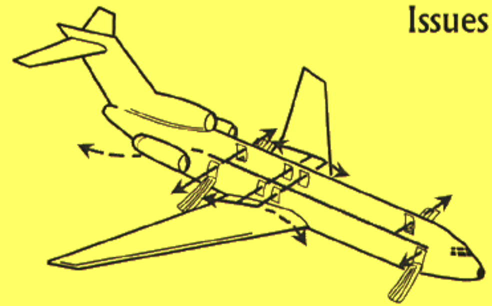

BACKGROUND PAPER

Office of Technology Assessment
Congress of the United States

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EXECUTIVE SUMMARY

The U.S. air transportation industry has an outstanding safety record. Yet passenger safety aboard U.S. airlines remains a continuing issue for the public, the Federal Aviation Administration (FAA), and the U.S. Congress. One concern is that aircraft be evacuated quickly and safely in an emergency.

FAA certification criteria and test methods are integral to evaluating the evacuation capabilities of new aircraft. In November 1991, the Subcommittee on Government Activities and Transportation of the House Committee on Government Operations requested that the Office of Technology Assessment (OTA) ". . . study the prospects for improving existing methods of evacuation testing in light of the need to balance realism against the safety of test participants. "[1] For this study, OTA examined regulatory, research, and technology issues related to passenger safety and evacuation testing.

Pursuant to Federal aviation regulations, aircraft manufacturers conduct full-scale demonstrations to show an airplane's basic evacuation capability and to evaluate crew training. FAA full-scale evacuation demonstration criteria include the following requirements:

- All passengers and crew must be evacuated from the aircraft to the ground within 90 seconds;
- The demonstration must be conducted during the dark of night or with the dark of night simulated, so that the airplane's emergency lighting system provides the only illumination of exit path and slides;
- specified mix of passengers "in normal health" must be used;
- Not more than 50 percent of the emergency exits may be used.

FINDINGS AND CONCLUSIONS

Benefits and Limitations of Evacuation Demonstrations

- Full-scale demonstrations are costly and expose participants to significant hazards. The cost of conducting a full-scale demonstration can exceed $1 million. On average, approximately 6 percent of participants are injured during full-scale tests. While most injuries have been minor, broken bones and paralysis have occurred. Fewer and less severe injuries than average occurred in the December 1992 MD-1 1 certification test in which slides were replaced with ramps.
- A full-scale demonstration simulates evacuation for only a narrow range of emergency conditions-an aborted takeoff at night involving no structural damage, cabin fire, or smoke, for a distinct subset of potential passengers (i. e., no children, persons with disabilities, or non-English speaking passengers).
- Demonstrations provide only a benchmark for consistent evaluation of various seating and exit configurations. The requirement to demonstrate complete evacuation within 90 seconds is not an adequate performance standard for measuring actual evacuation capabilities.
- Present evacuation certification rules do not encourage new technology development for extending the period of survivability in post-crash fires. The evacuation demonstration criteria are inflexible, regardless of the availability of technologies that could extend the period of survivability within the cabin.

1 Barbara Boxer, chair, Subcommittee on Government Activities and Transportation, House Committee on Government Operations, letter to John Gibbons, director, Office of Technology Assessment, Nov. 19, 1991.

Models and Simulations for Evacuation Certification

- At present, neither certification by full-scale demonstration nor by purely analytical certification methods is acceptable to all segments of the aviation community.
- The certification process will likely continue to rely on human test subjects in the foreseeable future. However, a combination of analysis and partial demonstrations or component tests can be developed to minimize the risk of injury and provide more comprehensive data on aircraft performance than full-scale demonstrations.
- Using aircraft manufacturers' analytical models, passenger egress rates through existing aircraft components are predictable. The results of industry analyses typically correlate well with observed rates through doors, aisles, slides, and other components under consistent test conditions.
- Human behavior in certification tests may be empirically modeled using data from prior demonstrations, but cannot yet be reliably "simulated." Estimates for average reaction times and egress rates are known for evacuation during controlled conditions. Because few reliable data exist on human behavior during accidents, the variations in human judgment and decisionmaking that might be expected for changing hazardous conditions cannot be predicted. These data cannot be obtained from current demonstration requirements, which do not address motivational effects or other behavioral factors that often exist in a real emergency.
- Recent computer simulation efforts may provide the technology base for a dynamic aircraft evacuation simulation capability, but the additional psychological data required for validating behavioral assumptions will be difficult to attain.

Data Issues

- FAA and industry could collect additional experimental data to support and validate evacuation models/simulations. Although FAA's present test fuselage is adequate for studying evacuation scenarios in single-aisle, narrow-body airliners, neither FAA nor any other regulatory agency has a facility that can be used to analyze egress from double-aisle, wide-body transports.
- Data on injuries related to aircraft evacuation testing are not readily available, nor are they classified by severity. Data from actual emergency evacuations are unevenly collected and analyzed. Neither FAA nor the National Transportation Safety Board collect information on precautionary evacuations.

Aircraft Evacuation Performance and Safety

- Survivability in commercial air transports is improving, largely through the introduction of highly fire-retardant materials and more crashworthy seats, restraints, and overhead bins. Though still a significant threat, fire has become less of a risk in survivable accidents. In the early 1980s, FAA attributed 40 percent of fatalities in survivable accidents, approximately 20 percent of total fatalities, to fire effects.[2] Between 1985 and 1991, approximately 10 percent of fatalities aboard U.S. airlines were related to fire.[3]
- Crew training and passenger motivation are as crucial to successful evacuations as the aircraft's design and equipment.

2 Constantine P. Sarkos, manager, Fire Safety Branch, FM Technical Center, personal communication, June 3, 1993.

3 Office of Technology Assessment, based on FAA and National Transportation Safety Board data.

Flight attendant training, done in cabin mockups without passengers, may not provide crew members with sufficient skills for assessing flow control problems and motivating passengers to evacuate more efficiently. Simulation technologies may enhance training in passenger management and use of emergency equipment.

Passenger safety may be better improved by extending the period of survivability than by attempting to reduce the time required for evacuation. New technologies intended to delay deadly heat and toxicity levels after a crash would save more lives than feasible configuration changes intended to speed evacuation, according to a British analysis of aircraft accidents. Furthermore, demographic trends indicate that the average mobility of aircraft passengers will decrease in the future.

Chapter 1

BACKGROUND AND REGULATORY CONTEXT

Background and Regulatory Context

Air travel, for business or pleasure, is an indispensable part of American life. The integrity of the aircraft and air traffic management systems, and the vigilance and skill of those who operate them, are the cornerstones of safe air travel. Should an emergency occur, passenger survival depends on the ability of the aircraft and its contents to withstand impact and the post-crash environment, on the design and effectiveness of escape routes and equipment, and on the crew's ability to help passengers evacuate the aircraft as quickly as possible. Ensuring crashworthiness, prolonging survivable conditions within the cabin, and providing quick egress are major thrusts of Federal safety programs. One of the final measures of an aircraft's readiness for operation is the full-scale evacuation demonstration.

Pursuant to existing Federal aviation regulations, aircraft manufacturers must demonstrate that a new or substantially revised type of aircraft can be completely evacuated under specified conditions in less than 90 seconds. Manufacturers have conducted more than 20 full-scale evacuation demonstrations since 1969, involving over 7,000 volunteers and airline crew personnel.[1] On average, 6 percent of full-scale demonstration participants receive injuries, which typically range from scrapes and bruises to broken bones. In October 1991, a test participant became permanently paralyzed after being injured during a McDonnell Douglas evacuation demonstration test for certification of an MD-11 airplane.[2] This renewed concern on the part of Congress, manufacturers, and passenger, pilot, and flight attendant groups about the safety of the certification process. The air transportation community is striving to find ways to reduce the likelihood of injuries in future tests.[3] At the same time, the community is considering the net benefits of full-scale demonstrations as a requirement for type certification.

The Federal Aviation Administration's (FAA) Aviation Rulemaking Advisory Committee (ARAC) is studying options for the development of performance standards to replace evacuation safety design criteria. Recent congressional Activity includes 991 hearings by the subcommittee on Government Activities and Transportation of the House Committee on Government Operations,[4] and a request for the General Accounting Office (GAO) to assess both the implementation of recent cabin materials regulations and the adequacy of the 90-second evacuation test criterion. GAO's investigation of evacuation demonstration issues is on hold, pending completion of the ARAC Subcommittee's efforts.

In November 1991, the Subcommittee on Government Activities and Transportation of the House Committee on Government Operations requested that the Office of Technology Assessment (OTA) ". . . study the prospects for improving existing methods of evacuation testing in light of the need to balance realism

1 Webster C. Heath, manager, Technical Liaison, Industry Regulatory Affairs, Douglas Aircraft Co., personal communication, Sept. 24, 1992.

2 At the time of the unsuccessful demonstration, the MD-1 1 was certificated to carry 390 passengers. The Douglas Aircraft Company again attempted to certificate the aircraft for 410 passengers on December 11, 1992, employing ramps instead of slides to minimize the potential for injury to test participants. The second, revised demonstration satisfied FAA's requirements for certification. See section on evacuation demonstrations in chapter 2.

3 In 1993, Boeing and Airbus will attempt full-scale demonstrations with their respective B-767 and A-330 aircraft.

4 See Us. Congress, House Committee on Government Operations, "Issues in Aircraft Cabin Safety and Crash Survivability: The USAir-Skywest Accident, " House Report 102-501, Apr. 22, 1992.

5 See U.S. Genera] Accounting Office, *Aviation Safety: Slow Progress in Making Aircraft Cabin Interiors Fireproof*, GAO/RCED-93-37 (Washington, DC: U.S. Government Printing Office, January 1993).

against the safety of test participants."[6] The safety and utility of testing methods are two primary concerns. Investigating the evacuation performance of an aircraft under actual emergency conditions would subject test participants to significant risk of injury. Computer simulation has emerged as a potential tool for evaluating numerous evacuations in changing fire and cabin configurations, trials too hazardous to conduct with human participants.

OTA examined a range of regulatory, research, and technology issues related to passenger safety and evacuation testing, including the scientific validity of the full-scale demonstration as a measure of evacuation capability. While this document describes alternatives to and the relative merits of current full-scale demonstration requirements, it does not provide research or regulatory policy options for Congress. Key issues this background paper does discuss include:

- the current evacuation standards and the role of evacuation testing;
- data collection and analysis to evaluate performance of evacuation systems in actual accidents or incidents;
- potential near-term improvements to demonstration tests that may reduce the likelihood of injury to participants;
- the role of mathematical modeling and/or computer simulations in reducing the need for human participation in the evaluation of evacuation procedures and equipment; and,
- economic concerns.

Federal authority for aircraft safety and evacuation standards lies with FAA. The National Transportation Safety Board (NTSB) investigates aviation accidents or incidents and makes recommendations regarding safety improvements, Outside the United States, the Civil Aviation Authority (CAA) of the United Kingdom is most active in improving the evacuation capability of the aircraft and crew under its authority. This section describes the roles of the U.S. agencies and CAA, along with requirements for emergency equipment, cabin safety operations, and crew training.

FEDERAL AVIATION ADMINISTRATION

FAA responsibility for cabin safety encompasses the development and enforcement of the Federal Aviation Regulations (FAR);[7] FAA conducts and sponsors research and development (R&D) programs related to cabin safety to support its rulemaking activities.

Cabin safety certification and compliance authority rests primarily with FAA's Aircraft Certification Service, which manages airworthiness offices throughout the United States and sets airworthiness standards, and the Flight Standards Service, which regulates air carrier operations and crew training and standards. The Certification Service establishes minimum standards for the design and manufacture of all U.S. aircraft and certifies that all aircraft meet these standards prior to introduction into service.[8] Certification authority for large commercial aircraft rests with FAA's Transport Aircraft Directorate in Seattle, Washington.

Under the Executive Director for System Development, the FAA Technical Center in Atlantic City supports regulatory development through in-house and contracted R&D, particularly in the areas of crashworthiness and fire safety. FAA's Civil Aeromedical Institute (CAMI) in Oklahoma City, under the purview of the Office of Aviation Medicine, is another contributor to crashworthiness research and evacuation standards evaluation. CAMI conducts pilot training research and, along with the

6 Barbara Boxer, chair, Subcommittee on Government Activities and Transportation, House Committee on Government Operations, letter to John Gibbons, director, Office of Technology Assessment, November 19, 1991.

7 Title 14, Chapter I Of the Code of Federal Regulations.

8 U.S. Congress, Office of Technology Assessment, *Safe Skies for Tomorrow: Aviation Safety in a Competitive Environment, OTA-SET-381* (Washington, DC: U.S. Government Printing Office, July 1988), p. 56, available from OTA's Science, Education, and Transportation Program.

Technical Center, supports accident investigation.

To obtain type[9] certification, manufacturers of aircraft having more than 44 passenger seats must conduct emergency evacuation demonstrations that test the following:

- basic aircraft design;
- the efficiency with which passengers can safely be evacuated from the aircraft;
- the emergency evacuation system; and
- the manufacturer's FAA-approved emergency evacuation procedures.[10]

Manufacturers typically elect to conduct the demonstration to serve both the type and operating certification requirements. Figure 1-1 shows the procedure for aircraft type certification, including airframe, seats, and evacuation demonstration.

The number, duties, and location of flight attendants are specified in 14 CFR 121. Flight attendants perform numerous safety-related duties before, during, and after each flight. The individual air carriers provide flight attendants with their initial emergency procedure training, and additional training each year thereafter. Current regulations require 1 flight attendant for every 50 passenger seats.

The description and demonstration of emergency evacuation procedures are integral parts of the operating certificate application procedure.[11] Once all application and demonstration requirements have been satisfied, FAA issues an air carrier operating certificate, specifying the terms, conditions, and limitations of operation.[12]

Recent History

Flight and cabin safety comprises a significant portion of FAA's rulemaking and research duties. In 1979, FAA formed the Special Aviation Fire and Explosion Reduction Advisory Committee to assess related research and regulatory needs. For several years, following the committee's final report in 1980, FAA emphasized the development of improved fire test methods and cabin interior material criteria.[13] Several of the projects and rules related to improving fire safety are identified in table 1-1.

On August 22, 1985, as a Boeing B-737 attempted to take off from Manchester International Airport (England), its left engine disintegrated, causing a fuel spill and a subsequent fuel-fed cabin fire. Of the aircraft's 137 occupants, 55 died aboard the burning aircraft. Most were later found to have been incapacitated from smoke and toxic gas inhalation. Accident analysis indicated that limited access to overwing exits and competition among passengers delayed evacuation of the plane.

In September 1985, FAA convened a public technical conference related to emergency evacuation from transport aircraft.[14] Discussion centered on emergency exits and slides, full-scale evacuation demonstrations, and crew training. FAA formed an Emergency Evacuation Task Force to coordinate activities of three working groups established during the conference--Design and Certification, Training and Operations, and Maintenance and Reliability.[15] In 1986, FAA agreed to develop and issue rulemaking and/or advisory material on

9 Type, as defined in 14 CFR 1.1, means those aircraft that are similar in design (e.g., DC-10 Series 30 and Series 40, B-747-200 and B-747-400).

10 Federal Aviation Administration, "Evaluate FAR Part 21 Emergency Evacuation/Ditching Procedures/ Demonstration," *Airworthiness Safety Inspectors Handbook, vol. 2* (Washington, DC: November 1988), ch. 77-1.

11 U.S. General Accounting Office, *Aviation Safety: Procedures for Registering and Certifying Air Carriers,* GAO/RCED-87-1 *15FS* (Washington, DC: May 5, 1987), p. 15.

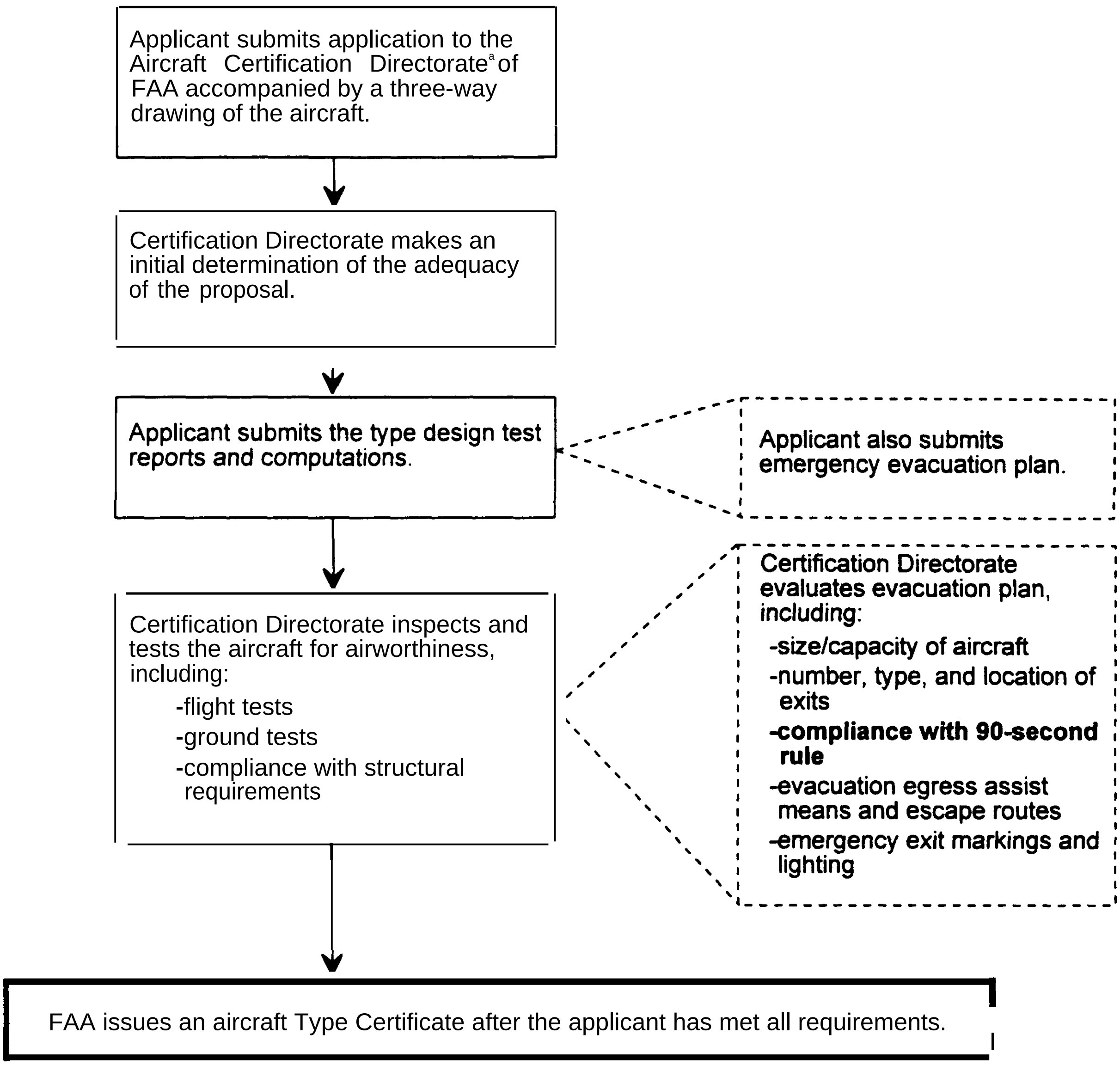
12 Ibid., p. 18.

13 Constantine Sarkos, Federal Aviation Administration, "Full Scale Test Results and Status of FAA's Cabin Safety Program," *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. 179.

14 50 *Federal* Register 32087 (Aug. 8, 1985).

15 For further description of the conference and its working groups, see U.S, Department of Transportation, Federal Aviation Administration, *Task Force Report on Emergency Evacuation of Transport Airplanes, vol. 1, Summary Report,* DOT/FAA/VS-86/1,I (Washington, DC: July 1986).

Figure I-I--Federal Aviation Administration Procedures for Issuing an Aircraft Type Certificate



[a]The FAA office responsible for evaluating compliance with certification requirements for a given class of aircraft.

SOURCE: Office of Technology Assessment, 1993.

Table 1-1—Federal Aviation Administration Fire Safety Program

	Project/subject	Action	Issued (compliance)
1.	Seat cushion fire blocking 14 CFR Part 135 extension	Final Rule Final Rule	10/26/84 (11/26/87) 11/25/87 (12/1/88)
2.	Floor proximity lighting	Final Rule	10/26/84 (11/26/86)
3.	Lavatory smoke detectors	Final Rule	3/26/85 (10/29/86)
4.	Lavatory automatic fire extinguisher	Final Rule	3/26/85 (4/29/87)
5.	Halon fire extinguishers	Final Rule	3/26/85 (4/29/86)
6.	Class E cargo compartment fire extinguishers	Final Rule	3/26/85 (10/29/85)
7.	Class C & D cargo or baggage compartments	Final Rule	5/16/86 (6/16/86)
8.	Improved cargo liners	NPRM	10/28/87 (2 years)
9.	Crew member PBE for flight attendants	Final Rule	5/26/87 (7/6/89)
10.	Heat release-interior materials	Final Rule	7/21/86 (8/20/88 and 8/20/90)
11.	Smoke density-interior materials	Final Rule	8/19/88 (8/20/90)
12.	Fuel system crash resistance	NPRM	4/26/89
13.	Small airplane crash resistant fuel systems	NPRM	2/14/90
14.	Passenger PBE	Rulemaking dropped	
15.	Cabin water spray system	R&D	
16.	Class C & D cargo compartments	R&D	

KEY: NPRM = Notice of Proposed Rulemaking; PBE=protective breathing equipment.

SOURCE: John J. Petrakis, “FAA Occupant Protection and Cabin Safety Overview,” *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. 56; and Office of Technology Assessment, 1993.

29 specific proposals recommended by the working groups. All but 2 of the 29 recommendations resulted in FAA action by the beginning of 1992. [16]

Of the numerous elements of an aircraft's emergency evacuation system, exit and slide design, flight attendant training, and full-scale evacuation demonstrations required for type certification have engendered the most attention and public debate. The key design and training requirements and related areas of contention are discussed below; full-scale demonstrations are described in a subsequent section.

Exits

Since 1967, FAA has regulated the location of emergency exits on airplanes with the fol1owing requirements:

- Specific types and numbers of exits must be provided for given numbers of passengers;
- Exits must be located to provide the most effective means of passenger evacuation; and
- Exits must be distributed as uniformly as practical with respect to passenger seating.

Exit arrangement, deployment, and marking, and emergency lighting must meet specific criteria. [17] See box 1-A for a description of various types of aircraft exits.

In 1986, after analysis of the Manchester accident indicated congestion at the overwing exit contributed to slow evacuation, CAA issued an airworthiness notice for alternate minimum requirements for seating next to overwing exits. [18] FAA, in turn, authorized CAMI to evaluate the proposed changes under conditions that would enable comparison with the minimum requirements delineated in the FAR.[19] CAMI conducted the evacuation tests in 1986 and 1991. In May 1992, FAA issued a final rule requiring transport aircraft having 60 or more passenger seats[20] to make Type III overwing exits more accessible (e.g., provide wider passageways between seats or remove the seat adjacent to the exit) .21 With compliance required by December 1992, the rule also mandated that all aircraft with Type III exits display placards that describe how to open and stow the exit, and state the exit door's weight.

Slides

To prevent injury to passengers and crew escaping through floor-level exits located more than 6 feet above the ground, assist devices (e.g., slides or slide-rafts) are required. The rapid deployment, inflation, and stability of evacuation slides are critical elements of the evacuation system. Slide design and performance requirements are contained in technical standard orders, while general slide requirements are found in 14 CFR 25. In 1983, FAA revised the requirements to specify criteria for resistance to water penetration and adsorption,

16 U.S. Department of Transportation, Federal Aviation Administration, *Task Force Report* on *Emergency Evacuation of Transport Airplanes, vol. 3, Final **Report***, FAA/AIR-92-01 (Washington, DC: Jan. 23, 1992), p. 11.

17 14 CFR 25.807, Amendment 25-15, 32 ***Federal** Register 13263* (Sept. *20, 1967).*

18 Civil Aviation Authority, United Kingdom, "Access to and Opening of Type III and Type IV Emergency Exits, " Airworthiness Notice No. 79, 1986.

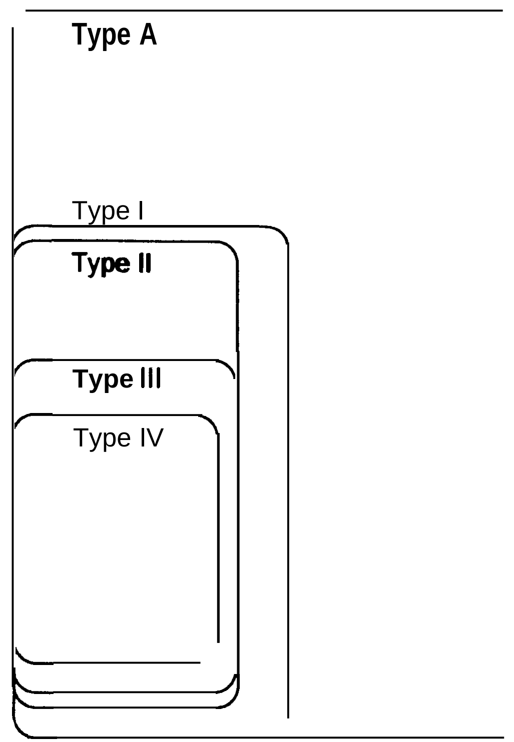
19 Paul G. Rasmussen and Charles B. Chittum, ***The** Influence of **Adjacent** Seating Configurations on Egress **Through** a Type III Emergency Exit, Final **Report**, DOT/FAA/AM-89/14* (Washington, DC: December 1989). Although the **final** report was not released until **1989**, the tests were authorized in 1986. Additional tests were conducted in 1991; see Garnet A. McLean et al., Civil **Aeromedical** Institute, ***Effects** of Seating Configuration and Number of Type III **Exits** on Emergency **Aircraft** Evacuation*, Final *Report*, **DOT/FAA/AM-92/27** (Washington, DC: U.S. **Department** of Transportation, August 1992).

20 **FAA** considers that a minimum of **60** passenger seats, which typically requires at least 15 rows, enables operators to provide the **additional** access through seat row adjustment without a loss of revenue. 57 *Federal Register 19239* (May 4, 1992).

21 57 ***Federal Register*** 19220 **(May 4. 1992)**.

Box 1-A—Description of Passenger Emergency Exits

Type A[a]	Rectangular opening at least 42 inches wide by 72 inches high, with specified dimensions for passageways to main and cross aisles. Floor-level Type A exits must be equipped with dual-lane emergency slide. Overwing Type A exits with step-downs[b] outside the airplane typically have automatically deployed and erected means of reaching the wing and ground.
Type I[a]	Floor level exit at least 24 inches wide by 48 inches high.
Type II	Floor level exit at least 20 inches wide and 44 inches high. May also be located over the wing, with step-up inside the airplane of no more than 10 inches and step-down outside the airplane not exceeding 27 inches.
Type III[a]	Rectangular opening at least 20 by 36 inches with step-up not to exceed 20 inches. Most often placed over the wing, having stepdown not exceeding 36 inches.
Type IV[c]	Over-the-wing exit no less than 19 by 36 inches, with step-up of no more than 29 inches and step-down no greater than 36 inches.
Tail[a]	Similar to the Type I exit in size, a *ventral* exit is a passage from the passenger compartment through the plane's fuselage down a set of stairs to the ground. Tail *cone* exits lead directly out of the airplane's tail onto an escape slide.



[a] Exit types most commonly used in large transport aircraft.

[b] *Step-down* is the actual distance between the bottom of the required opening and a usable foothold, extending out from the fuselage, that is large enough to be effective without searching by sight or feel. *Step-up* is the height from the floor of the cabin to the lower sill of the exit.

[c] Used in aircraft having fewer than 10 passenger seats.

SOURCE: Office of Technology Assessment, 1993, based on 14 CFR 25.807; Daniel A. Johnson, *Just in Case: A Passenger's Guide to Airplane Safety and Survival*, (New York, NY: Plenum Press, 1984), p. 148; and Mary Edwards and Elwyn Edwards, *The Aircraft Cabin: Managing the Human Factors* (Hants, England: Gover Technical Publishing Co., 1990), p. 140.

puncture strength, radiant heat resistance, and deployment as flotation platforms after ditching.[22]

Training and Operations

FAA requires operating certificate holders (airlines) to establish and maintain training programs for each crew member. FAA also regulates cockpit crew hours but not flight attendants' duty time. Activities required of flight attendants prior to takeoff include verifying that passengers' seat belts are fastened, briefing passengers on emergency equipment use, and ensuring all galley items and carry-on luggage are securely stowed. Flight attendants also administer first aid and cope with other in-flight emergencies.

During flight attendant *initial training,* required instruction topics include passenger handling, cabin and galley equipment use, airplane characteristics pertinent to in-flight emergency procedures, appropriate provisions of the FAR, and extensive emergency training. *Recurrent training* includes a review of the crew member's state of knowledge of the airplane and their duties, provides new instruction as necessary in subjects required for initial ground training, and requires a competence check in assigned duties and responsibilities.[23] Cabin crew members receive recurrent training every 12 months.[24]

Along with instruction in procedures and equipment use, the emergency training must provide at least one firefighting drill and at least one emergency evacuation drill.[25] During initial training and once each 24 months during recurrent training, crew members must perform and observe additional emergency drills, In general, this is accomplished using cabin mockups, in which flight attendants and other crew members operate exits and simulate the deployment, inflation, and use of slides. Hands-on training with the slides is provided only in initial training.[26]

NATIONAL TRANSPORTATION SAFETY BOARD

Created in 1966 under the U.S. Department of Transportation, NTSB became an independent executive branch agency in 1975. It investigates accidents[27] for all transportation *modes,* including general aviation, selected public-use aircraft, and commercial transports; conducts safety studies; and issues recommendations for changes in regulations and procedures. FAA is not bound to accept NTSB regulatory change suggestions.[28]

Aircraft operators must immediately notify NTSB whenever an accident occurs or an aircraft evacuation involves use of an emergency egress system.[29] The information provided to NTSB must include the number of persons aboard the aircraft, and the number killed or

22 John J. Petrakis, Federal Aviation Administration, "FAA Occupant Protection and Cabin Safety Overview," *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. 47. See also Federal Aviation Administration, "Emergency Evacuation Slides, Ramps, and Slide/Raft Combinations," TSO C-69B, unpublished report Aug. 17, 1988.

23 14 CFR 121.427; 35 *Federal Register* 90 (Jan. 3, 1970).

24 Flight deck crew training requirements are contained in 14 CFR 121, Subpart N.

25 The realism of the evacuation drills is of concern; e.g., United Airlines uses darkness in its flight attendant training. William Hathaway, U.S. Department of Transportation/Research and Special Programs Administration, Volpe National Transportation Systems Center, personal communication, Jan. 15, 1993.

26 Noreene Koan, chairperson, National Air Safety Committee, Association of Flight Attendants, personal communication, Dec. 12, 1992.

27 An aircraft accident is an occurrence associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage. *incident* means an occurrence other than an accident, associated with the operation of an aircraft, that affects or could affect the safety of operations. 49 CFR 830.2.

28 Office of Technology Assessment, op. cit., footnote 8, p. 53.

29 49 CFR 830.5.

seriously injured .30 NTSB then assesses the accident or incident and determines probable cause. However, NTSB is not required to keep track of the nature of passenger injuries (i.e., whether the injuries occurred as a result of a collision or during evacuation from the aircrafit.[31] Because existing accident/incident databases do not support assessment of the performance of evacuation systems during actual emergency conditions, this information must be painstakingly gleaned from investigator reports.

Accident/Incident Reports

FAA's Aviation Standards National Field Office maintains a database of accidents and incidents officially reported to NTSB and reports filed by FAA field inspectors.[32] NTSB admits it does not collect all relevant data because reporting requirements omit some types of evacuations (i. e., those in which no serious injuries occurred). According to NTSB staff, a significant number of occurrences are not monitored because of a shortage of personnel, variability in reporting efforts, and an emphasis on fatal accidents .33

The performance of evacuation systems has not been the focus of accident investigations. Reporting has improved over the years, according to Boeing staff, as investigators have begun to pay more attention to crashworthiness as well as airworthiness issues.[34] A Boeing paper presented at FAA's 1985 technical workshop on evacuation safety cited a total of 583 known inservice incidents in which aircraft were evacuated. FAA neither maintains nor requires manufacturers to maintain records of evacuation-related injuries. According to safety interest groups, the manufacturers share this safety data among themselves, but choose not to release it to the public.[35] Because the information is proprietary, Boeing admits a reluctance to share certification documents with pilot and flight attendant groups at the time FAA views them.[36]

UNITED KINGDOM CIVIL AVIATION AUTHORITY

Among other activities, CAA supports R&D related to cabin safety and evacuation. CAA's projects in the area of aircraft and safety regulation cover operational problems and airworthiness, including passenger survivability, and human factors in general .37

Currently, CAA efforts include:

- determine the feasibility of developing computer models to assess seating configuration in relation to the number of exits for both new aircraft and for aircraft operating without the full complement of exits available;
- develop models for predicting the behavior of fires in different aircraft cabin configurations; and
- assess the potential of cabin water spray systems (CWSS) to extend evacuation

30 *Serious injury* is defined as any injury: 1) requiring hospitalization for more than 48 hours, commencing within 7 days of receipt of the injury; 2) resulting in fracture of any bone (except simple fractures of nose, fingers, or toes); 3) causing severe hemorrhages, nerve, muscle, or tendon damage; 4) involving any internal organ; and 5) involving any second- or third-degree bums, or bums affecting more than 5 percent of the body surface.

31 Matthew McCormick, chief, Survival Factors Division, and Stan Smith, chief, Data and Analysis Division, National Transportation Safety Board, personal communication, Dec. 17, 1991.

32 U.S. Congress, Office of Technology Assessment, *Transportation of Hazardous Materials, OTA-SET-304* (Washington, DC: U.S. Government Printing Office, July 1986), p. 71, available from OTA's Science, Education, and Transportation Program.

33 Nora Marshall, senior accident investigator, National Transportation Safety Board, personal communication, Jan. 8, 1992.

34 George Veryioglou, senior manager, 747/767 Payload Systems, Boeing Commercial Airplane Group, personal communication, Jan. 25, 1993.

35 Matthew Finucane, director, Air Safety and Health, Association of Flight Attendants, personal communication, Dec. 18, 1991.

36 Veryioglou, op. cit., footnote 34.

37 Civil Aviation Research and Development Programme Board, *Programme of Research and Development for Civil Aviation Operations and National Air Traffic Services,* Issue 23 (Cheltenham, England: Civil Aviation Authority, April 1992), p. iii.

time and save lives, and to study the feasibility of CWSS implementation on transport aircraft.[38]

The United Kingdom's Accident Investigation Board assumes many of the same responsibilities and investigation activities as NTSB.

[38] *Ibid., pp. 15-18.*

Chapter 2

EVACUATION DEMONSTRATIONS FOR CERTIFICATION

Evacuation Demonstrations for Certification

Beginning in 1965, the Federal Aviation Administration (FAA) required each air carrier operating under Part 121 of the Federal Aviation Regulations to perform full-scale evacuation demonstrations under simulated emergency conditions prior to receiving operating certification for new aircraft or seating configurations.[1] The air carrier demonstration was designed to evaluate crew training and the adequacy of evacuation procedures.[2] FAA initially imposed a 120-second egress time limit for evacuating all passengers and crew. See box 2-A on evacuation regulation chronology.

FAA attributed a 1967 change in maximum egress time to 90 seconds to advances in slide technology that had occurred since the initial standard was released. g In 1982, after study of actual and demonstrated emergency evacuations, FAA allowed certificate holders, under specified conditions, to use the results of a successful demonstration conducted by either the manufacturer or another airline rather than conduct a new test.[4]

The stated goal of requiring the full-scale demonstrations is to provide a benchmark by which FAA can consistently evaluate evacuation capability using various seating and exit configurations.[5] FAA claims that a consistent measure of success is achieved by requiring all manufacturers to strive for the same 90-second limit. According to FAA, the demonstration . . . is not an acceptable evacuation performance standard.“G That is, manufacturers must also comply with specific equipment and minimum configuration requirements in addition to successfully demonstrating complete evacuation within 90 seconds. Performance standards, on the other hand, are expressed using objective performance goals alone--no specific design or operating criteria are established.

In addition to the 90-second time limit, FAA full-scale evacuation demonstration criteria include the following:

- The demonstration must be conducted during the[6] dark of night or with the dark of night simulated--the airplane’s emergency lighting system can provide the only illumination of exit paths and slides;
- A specified mix of passengers “in normal health” must be used--for example, at least 30 percent must be females and at least 5 percent must be over 60 years of age;
- The passengers may not have participated in a demonstration in the previous 6 months; and
- Not more than 50 percent of the emergency exits may be used.

In a 1989 advisory circular (AC), FAA provided guidance to manufacturers on how to determine whether analysis and tests might be used in place of full-scale demonstration.[7] The AC also provided guidelines for set-up and conduct of the demonstration. Among other things, the AC identified two equivalent age-sex distributions, shown in table 2-1. Under the 1989 FAA guidelines, manufacturers may replace participants in the highest age category (i.e., the one most susceptible to injury) with greater numbers of persons aged 51 to 60 years and need not use minors.

1 29 *Federal Register 18291* (Dec. 24, 1964).

2 Anthony J. Broderick, associate administrator for regulation and certification, Federal Aviation Administration, testimony at hearings before the House Committee on Government Operations, Subcommittee on Government Activities and Transportation, Apr. 11, 1991.

3 31 *Federal Register* 10276 (July 29, 1966).

4 Walter S. Coleman, director, operations, Air Transport Association, “Emergency Evacuations, Career *Training,* and Passenger Briefings, ” paper presented at the FAA Technical Conference on Emergency Evacuation of Transport Category Airplanes, Sept. 3-6, 1985, Seattle, WA, p. 3.

5 54 *Federal Register 26692* (June 23, 1989).

6 Ibid.

7 U.S. Department of Transportation, Federal Aviation Administration, Advisory Circular 25.803-1, Nov. 13, 1989.

Box 2-A–Chronology of Changes to Evacuation Regulations

June 1965	Amendment 121-2 required all transport-category aircraft operators to conduct demonstrations, to be completed in less than 120 seconds, for all previously built and new aircraft.
October 1%7	Amendment 25-15 required manufacturers to conduct a 90-second demonstration, and required that aircraft be equipped with automatically deployed egress assist devices.[1]
	Amendment 121-30 revised the operators' demonstration time limit from 120 seconds to 90 seconds, and required *retrofit* of automatically deployed egress assist devices within 2 years for all previously built aircraft.
December 1978	Amendments 25-46 and 121-149 revised requirements to permit manufacturers and operators to concurrently demonstrate compliance with evacuation certification requirements, and allowed evacuation certification to be substantiated by a combination of analysis and tests at the discretion of the FAA Administrator.
January 1982	Amendment 121-176 required, if an aircraft is certified to FAR 25.803 per Amendment 25-46, the airline operator to demonstrate crew proficiency by showing that crew members can open half the exits and achieve usable slides within 15 seconds.
March 1990	Amendment 121-124 established criteria for passengers seated in exit rows.

1 Egress assist devices include slides, slide raft combinations, and overwing escape routes. At certain exits, slides must be automatically erected as well.

KEY: FAR = Federal Aviation Regulations, Title 14, Chapter 1 of the CodC of Federal Regulations.

SOURCES: Federal Aviation Administration Advisory Circular No. 25-803-1. Nov. 13, 1989; and Aviation Rulemaking Advisory Committee, Emergency Evacuation Subcommittee, Performance Standards Working Group, "Emergency Evacuation Requirements and Methods That Would Eliminate or Minimize the Potential for Injury to Full-Scale Evacuation Demonstration Participants, " unpublished report, January 1993.

LIMITATIONS OF FULL-SCALE DEMONSTRATIONS

Full-scale demonstrations of evacuation systems are both hazardous and costly. Intended to serve as a benchmark for functional ability of emergency equipment and procedures, the test is not useful for system optimization.

The emergency evacuation scenario used in fill-scale demonstrations does not represent most accident conditions, where impact forces and fire effects frequently impair passengers' abilities to escape the aircraft. Participants in demonstrations know they face no such danger in their efforts to quickly exit the aircraft, so panic is not present. However, the test still exposes participants to a range of injuries, from bumps and bruises to serious, permanent injury. During seven full-scale demonstrations conducted by manufacturers between 1972 and 1980, 166 of 2,571 total participants received injuries, or 6.5 percent. Of the 3,761 participants in 12 demonstrations conducted between

Table 2-l-Equivalent Passenger Age-Sex Distributions for Evacuation Certification Participants, 1989 Federal Aviation Administration Advisory Circular

Passenger distribution 1:

Age	Percent of total	Percent of females
21-50	80	30
51-59	15	40
>60	5	30

Passenger distribution 2:

Age	Percent of total	Percent of females
18-50	75	30
51-60	25	40

NOTE: Minors are precluded from participating in evacuation demonstrations under many state child labor laws. Distribution 2 eliminates the need for participants older than age 60, who are most susceptible to injury. **In August 1993, relying on Civil Aeromedical Institute and industry data on the relative evacuation rates of different age and sex mixtures, FM amended the age/sex distribution requirement for evacuation demonstration participants as follows: (1) at least 40 percent of the passenger load must be female; (2) at least 35 percent must be over 50 years of age; (3) at least 15 percent must be female and over 50 years of age.**

SOURCE: U.S. Department of Transportation, Federal Aviation Administration, Advisory Circular 25.803-1, Nov. 13, 1989, and 58 *Federal Register 45230* **(Aug. 26, 1993).**

1981 and 1991, 212 received injuries (5.6 percent),8

The cost of conducting full-scale evacuation demonstrations, including test set-up, payments to volunteers, analysis, and so forth, reaches upward of $2 million for wide-body transports.[9] The cost of evacuation demonstration is insignificant compared to overall program and airplane construction; manufacturers assert it is the hazard of serious injury, not test costs, that generated their interest in modifying the existing certification criteria and developing alternative testing and assessment methods.

Since FAA first imposed the evacuation test on airlines and airframe manufacturers, there have been only two major changes. First, improvements in slide technology prompted FAA to reduce the maximum evacuation time in 1967. Second, Federal and State occupational safety and healh laws proscribe the use of children under 18 years of age in the demonstrations.[10]

As with other safety standards, the demonstration for certification relates to a minimum level of safety; airline economics dictate that manufacturers strive for maximum seating capability, not optimal safety for a given number of passenger seats. Both cost and the potential for injury make manufacturers reluctant to conduct any more than the minimum number of tests required of the industry.

The utility of FAA's "benchmark" for evacuation capability hinges on the comparability of test conditions and test results. The benchmark enables FAA to determine only if an aircraft achieves the same minimum level of performance as other aircraft before it; the benchmark does not permit quantitative assessment of overall safety or the relative performance of elements within the aircraft's evacuation system. The subjective nature of some of the test criteria (e.g., the maximum level of illumination possible to simulate the dark of night) introduces variability. Controlling variability is a key factor in the statistical validity of any test, as discussed below.

Test and Data Validity

In order to assess the validity of a test or its data, one must judge both the quality of the test procedure and the measurement methodology. The identification of major variables and how they affect the outcome of a test lends credibility to the process, as does the repeatability of results. Achieving consistent test conditions is fundamental to limiting variability. FAA and industry use the benchmark of 90 seconds to gauge whether different cabin seating and exit configurations provide a minimum level of aircraft evacuation safety. Human performance, a dominant variable in successful evacuations under real or imagined emergency situations, is not easily controlled. The following factors may greatly affect the outcome of an actual emergency evacuation performance:

- cabin and flight crew capabilities (e.g., training, experience, and physical/mental condition);
- aircraft integrity and evacuation technologies;
- passenger demographics, percent of seats occupied, and amount and mix of carry-on luggage;
- ambient lighting; and,
- actual accident conditions.

One potential problem with the test procedure is that the mix of test participants required by FAA is often not representative of the flying public on a given flight. In general, passenger demographics vary from region to region and seasonally. Tests conducted using passenger loads with higher percentages of women and

8 Aviation Rulemaking Advisory Committee, Emergency Evacuation Subcommittee, Performance Standards Working Group, "Emergency Evacuation Requirements and Compliance Methods That Would Eliminate or Minimize the Potential for Injury to Full-Scale Evacuation Demonstration Participants, " unpublished report, January 1993, p. 10.

9 Webster C. Heath, manager, Technical Liaison, Industry Regulatory Affairs, Douglas Aircraft Co., personal communication, July 8, 1992.

10 William H. Shook, senior principal technical specialist, Douglas Aircraft Co., personal communication, Dec. 16, 1992.

elderly persons, or with children and persons with disabilities, would likely generate longer average evacuation times. See box 2-B on FAA tests with persons with disabilities and figure A-1 in the appendix.

An unrealistic passenger mix, combined with the absence of surprise, trauma, fright, and panic, produces optimistic indications of an aircraft's evacuation safety capability.[11] However, industry and many others are understandably loathe to subject demonstration participants to the presence of fire, smoke, and additional debris, for fear of increasing the likelihood of injury. On the other hand, any changes to the certification process designed to reduce the risk of injury require analysis of the comparability of results.

In addition, without the benefit of repeated trials, one cannot be confident that a single certification test result truly represents an aircraft evacuation system's capability. Neither a margin of error or confidence level can be determined (see figure A-2 in the appendix). By comparison, use of anthropomorphic dummies allows auto manufacturers to conduct realistic crash response tests repeatedly and with high validity, without threat to human safety, and to determine performance relative to government standards. [12] FAA and the aviation community struggle to achieve agreement on whether the value of but one full-scale evacuation demonstration for certification warrants the risk. A formal vehicle for this discussion was the Emergency Evacuation Subcommittee established by the FAA Aviation Rulemaking Advisory Committee (ARAC).[13] The following section describes the subcommittee's progress and potential changes to the demonstration requirement.

DEVELOPMENT OF ALTERNATIVES

In February 1991, ARAC formed a subcommittee to address a slate of regulatory reforms in the evacuation area--reforms recommended during the conferences and workshops of the mid-1980s--and charged it with giving advice and recommendations to the FAA Flight Standards and Aircraft Certification offices on regulatory standards for evacuation and passenger safety. In turn, the subcommittee chartered a working group to address the potential for using performance standards in place of or in addition to design criteria for certification. [14] The Performance Standards Working Group (PSWG--members are drawn from the various elements of the aviation community) is charged with making a recommendation concerning whether new or revised standards for emergency evacuation can and should be stated in terms of safety performance rather than as specific design requirements. The working group must consider two questions:

- Can standards stated in terms of safety performance replace, supplement, or be an alternative to any or all of the current combination of design and performance standards that now address emergency evacuation found in Federal Aviation Regulations Parts 25 and 121?
- If a performance standard is recommended, how can FAA evaluate a minor change to an approved configuration, or a new configuration that differs in either a minor or a major way from an approved configuration?

In November 1991, PSWG expanded its mission to include making a recommendation to the Emergency Evacuation Subcommittee con-

11 S.M. Vanstone, Vice chairman, Aircraft Designs and Operations Committee, International Federation of Air Line Pilots Association (IFALPA), "Emergency Evacuation and Cabin Safety, " paper presented at the FAA Public Technical Conference on Emergency Evacuation of Transport Airplanes, Sept. 3-6, 1985, Seattle, WA, p. 1.

12 Jeffry H. Marcus, manager, Protection and Survival Laboratory, Civil Aeromedical Institute, personal communication, Jan. 13, 1992.

13 Created February 5, 1991, ARAC is comprised of FAA officials and representatives from 58 aviation groups.

14 AS part of the 1993 renewal of ARAC's charter, the subcommittees were redesigned as interest areas (e. g., Emergency Evacuation Issues) and working groups now report directly to ARAC. Steve Erickson, assistant chair, Aviation Rulemaking Advisory Committee, Emergency Evacuation Issues, personal communication, Aug. 16, 1993.

Box 2-B–Evacuation of Persons With Disabilities

Because the need for assistance in emergency situations has limited the access of nonambulatory persons to commercial air transportation, in the early 1970s, the Federal Aviation Administration (FAA) commissioned the Civil Aeromedical Institute (CAMI) to study aircraft evacuation using passengers with disabilities.[1]

CAMI testing showed that, when occupying window seats, passengers with disabilities spent 50 percent of the total time required for egress in moving from their seats to the aisle. The data suggested that persons with disabilities should be seated along the aisle. However, this may compromise the safety of the passengers in the outboard seats. CAMI's evacuation trials also showed that total evacuation times were shorter when nonambulatory passengers were seated away from the exits. Other observations from the study included:

- Aide width and seat row pitch affect the ability of other passengers to assist nonambulatory persons.
- Passengers with disabilities may need to be reoriented before entering the slides.

The desire to ensure accessibility to all forms of transportation led to a 1982 Civil Aeronautics Board ruling that all passengers, regardless of impairment, should be given reasonable access to air travel and the opportunity to use ordinary, unaltered airline services.[2] While it may be technically feasible to derive optimum seating conjurations for different percentages of passengers with disabilities, political and ethical considerations likely preclude the implementation of any such plans.

Rule changes adopted in 1991, and revised in 1992, limit seating adjacent to exits to those passengers who are proficient in the English language and do not have mobility, sensory (e.g., hearing and vision), or cognitive (e.g., schizophrenia) impairments.

1 J.G. Blethrow et al., Civil Aeromedical Institute, *Emergency Escape of Handicapped Air Travelers*, FAA-AM-77-11 (Washington, DC: Federal Aviation Administration, July 1977), pp. 1-2.

2 Mary Edwards and Elwyn Edwards, *The Aircraft Cabin: Managing the Human Factors* (Hants, England: Gover Technical Publishing Co., 1990), pp. 45-46.

cerning new or revised emergency evacuation requirements and compliance methods that would eliminate or minimize the potential for injury to fill-scale demonstration participants. PSWG released its report on methods of reducing risk of injury to participants in emergency evacuation demonstrations for certification in January 1993. Table 2-2 lists the working group's conclusions and recommendations.

Despite months of effort to reach consensus, the report failed to satisfy the group as a whole.[15] Three letters of dissent, submitted with the working group's report, described dissatisfaction with the process and report conclusions. Key concerns were the perceived failure of the group to ". . . undertake a systematic analysis of the procedures used in conducting full scale evacuation demonstrations, " and the loss of valuable crew performance information incurred by eliminating the requirement for full-scale demonstrations.[16] The Air Line Pilots Association expressed concern that the absence

[15] ARAC was intended to speed the rulemaking process by including constituents at the front end of regulation development (i.e., before notice of proposed rulemaking and request for comments are released). However, the length of time required by the Performance Standards Working Group to address its first mission caused some concern on the part of the subcommittee's chairman and members of Congress that the process is itself unwieldy.

[16] Association of Flight Attendants "Comments on Performance Standards Working Group Report, " unpublished report, Jan. 15, 1993, p. 1.

Table 2-2-Conclusions and Recommendations of the Performance Standards Working Group, 1992 Report

Conclusions:

- The nature of the full-scale evacuation demonstration, as currently defined in FAR 25.803(c), is such that injuries can occur.
- The full-scale evacuation demonstration can be a useful tool for comparing the evacuation capability of a new, unique airplane configuration with the current FAR 25.803 standard.
- The full-scale evacuation demonstration test conditions can and should be revised to minimize the potential for injuries to test participants.
- Steps must be taken to ensure that testing with humans is strictly limited and controlled. Only after all alternative means of obtaining necessary data have been deliberated should limited exposure of test subjects to the evacuation demonstration test conditions of FAR 25.803(c) be considered.
- Full-scale evacuation demonstrations should be conducted for only those airplane configurations where regulatory authority-approved test data are not available to support analysis.

Research recommendations:

- CAMI, or another source FAA deems appropriate, carry out a study to determine which age and sex group(s) are least susceptible to injury and develop an appropriate age and sex mix for full-scale demonstration tests while maintaining the validity of the 90-second criterion.
- Initiate a research program to develop a new, two-part emergency evacuation test protocol for escape slide testing and airplane flow rate tests without the use of escape slides.
- Institute a high-priority research and development program to develop long-term revisions to the evacuation demonstration test protocol so as to further minimize injuries to test participants.
- Develop a system or process for FAA to collect data on injuries sustained during emergency evacuation demonstration testing.
- Establish an FAA escape slide research and development program designed to further minimize injuries.

KEY: **CAMI = FAA's Civil Aeromedical Institute; FAA= Federal Aviation Administration; FAR = Federal Aviation Regulations, Title 14, Chapter I of the Code of Federal Regulations.**

SOURCE: **Aviation Rulemaking Advisory Committee, Emergency Evacuation Subcommittee, Performance Standards Working Group, "Emergency Evacuation Requirements and Compliance Methods that Would Eliminate or Minimize the Potential for Injury to Full Scale Evacuation Demonstration Participants," unpublished report, January 1993.**

of data on injury rates for alternatives to the two extremes of certification (analysis only or fill-scale demonstrations) made the working group report biased toward FAA approval based solely on analysis.[17]

Analysis

Injuries sustained over the years by demonstration participants became the basis for the 1978 rule change[18] providing that the demonstration requirement may be waived if the Administrator finds that a combination of analysis and component testing[19] will provide data equivalent to that obtainable through full-scale demonstration.[20] In 1982, Boeing Aircraft presented to FAA an analysis approach that relied on a timeline summation of evacuation activities from exit preparation to the arrival of the last evacuee on the ground. All segments of the timeline were derived using data from FAA-witnessed tests and tests verifiable from video or film records .21 Boeing's model approach is outlined in figure A-3. The time of exit flow is equal to the time elapsed between the first evacuee and last evacuee reaching the ground; this time is a function of the anticipated number of passengers and crew and the flow rate permitted by exits.[22] Critical to the analysis (and evacuation performance) is the balanced loading of passengers with respect to exit size and location. To address the issue of passenger management (flow control), Boeing includes a discussion of passenger distribution; exit performance capability, both preparation and egress; and crew member performance elements (e.g., time of travel to duty position).[23]

The Douglas Aircraft Company adopted a similar approach for predicting evacuation performance, using data from prior demonstrations and component tests, along with "industry-accepted averages, " to estimate total evacuation time. Douglas Aircraft Company staff believe the analytical model is more credible than a full-scale demonstration, which is affected by numerous human factors.[24] Industry in general supports testing of component performance, emergency procedures, and crew training to avoid exposing crew and demonstration volunteers to the risk of injury, but there is some political sensitivity to certification by analysis, as discussed in box 2-C.

Demonstrations With Platforms

One suggestion for reducing the likelihood of injury to demonstration participants entails replacing the slides with level platforms or gently sloped ramps. Slide performance data would thus be obtained with more controlled demonstrations that present fewer risks to participants.

On December 11 and 12, 1992, for its second attempt to certificate the MD-11 for 410 passenger seats, McDonnell Douglas adopted such a phased approach.[25] McDonnell Douglas first developed the analytic methodology to equate the existing 90-second test with slides to a ramp-based test of an unknown time limit. To fill in data gaps, McDonnell Douglas conducted component tests to establish average opening times for doors with and without slides, and the flow rates (passengers per minute) through doors without slides.

McDonnell Douglas completed 10 tests with 100 persons each to establish rates for Type A

17 Ricky R. Davidson, chairman, Air Line Pilots Association, Accident Survival Committee, letter to Jay Anema, chairman, Performance Standards Working Group, Jan. 19, 1993.

18 See FAR amendments 25-46 and 121-149.

19 Component tests and partial demonstrations examine the performance of isolated elements within the evacuation system.

20 George Veryioglou, engineer, Airframe Systems Technology, Boeing Commercial Airplane Group, "Emergency Evacuation System Certification via Analysis and Tests, " paper presented at the FAA Technical Conference on Emergency Evacuation of Transport Airplanes, Sept. 3-6, 1985, Seattle, WA, p. 5.

21 Ibid., p. 10.

22 Ibid., p. 11.

23 Ibid., pp. 11-12.

24 Douglas Aircraft Co., "MD-11 Evacuation Demonstration: Analysis and Changes Overview With Analytic Model, " paper submitted to the Federal Aviation Administration, n.d., p. 6.

25 According to McDonnell Douglas staff, the California Occupational Safety and Health Agency would not allow the manufacturer to repeat the full-scale demonstration with slides in total darkness.

Box 2-C–Political Sensitivity to Use of Analysis in Evacuation Certification

In 1984, Boeing proposed to deactivate one of five pairs of overwing exits on inservice passenger 747s.[1] Maximum passenger density would be reduced to 440 from 550, commensurate with the new number of Type A exit pairs.[2] However, the distance between doors would exceed 60 feet. (Existing regulations did not specify the maximum distance between exit doors.) The Federal Aviation Administration (FAA) Transport Aircraft Certification Office (Northwest Mountain Region) approved Boeing's request based on analysis.

Flight attendant unions protested the decisions and certification process, and called on Congress to intervene on grounds of diminished safety.[3] A June 1985 hearing conducted by the House Committee on Public Works, Subcommittee on investigations and Oversight brought public attention to both the potential impact of allowing large distances between exits and the unscrutinized process in which the deactivation was approved. At the hearing, FAA Administrator Donald Engen announced his disapproval of sealing off the overwing exits. Subsequently, Admiral Engen appointed an Emergency Evacuation Task Force to examine the issue and reassess related emergency evacuation regulations.[4]

In October 1987, FAA published a notice of proposed rulemaking relating to new standard limits on transport category airplanes for the distance between any passenger seat and the nearest exit and the distance between exits.[5] Under the rule, type certification for the new 747-400 with only eight exits would not be approved, and operation within the United States of oreign-owned 747s having eight exits would not be allowed.[6] In 1989, FAA issued a final rule prohibiting airplane manufacturers and air carriers from increasing the distance between emergency exits beyond 60 feet.[7] Boeing maintains the rule was specifically applied to the 747 but not the Lockheed L-1011, which also had distances greater than 60 feet between exits.[8] Mathematical analysis of evacuation times for the different configurations (i.e., 440 passenger seats with 8 exits or 550 passenger seats with 10 exits) would yield the same results because flow rates and door opening times were insensitive to variations in internal configurations.

1 At the time, Boeing offered the 747 in various configurations, including a passenger model with 10 Type A main deck exits; convertible and combi 747s with 10, 8, or 6 main deck Type A exits; and the special performance 747, with 8 such exits. George Veryiglou, senior manager, 747/767 Payload Systems, Boeing Commercial Airplane Group, personal communication, Jan. 25, 1993.

2 14 CFR 25.807 rates each Type A exit pair at 110 passengers.

3 U.S. Congress, Office of Technology Assessment, *Safe Skies for Tomorrow: Aviation Safety in a Competitive Environment*, OTA-SET-381 (Washington, DC: U.S. Government Printing Office, July 1988), p. 57, available from OTA's Science, Education, and Transportation Program.

4 Scott Imus, director of staff for Congressman James L. Oberstar, "Keynote Address." *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. 12.

5 NPRM 87-10,52 *Federal Register* 39190 (Oct. 20, 1987).

6 Off&of Technology Assessment, op. cit., footnote 3, p. 57.

7 14 CFR 121.310, Amendment 121-205, 54 *Federal Register* 26696 (June 23, 1989).

8 Veyioglou, op. cit. footnote 1. The L-1011 is still operated under Part 121 with these distances.

and Type I doors. Based on the test results, McDonnell Douglas proposed a maximum time limit of 62 seconds for the modified certification demonstration.[26] Additionally, after three evacuations using different procedures and flight attendant stations, McDonnell Douglas staff concluded that the cabin could be effectively managed with 9 (the minimum number required by FAA) instead of 10 flight attendants.

The evacuation test was completed in 56 seconds; a time margin analysis like that espoused by the Working Group for future certifications by analysis yielded 51 seconds, well above the

26 Shook, Op. cit., footnote 10.

10 percent factor.[27] The entire testing program resulted in only four minima1 injuries, although past experience suggested one or two fractures would occur.[28] FAA held the test to be sufficient for certification. Boeing and Airbus will likely adopt use of component tests and analysis when possible. However, this approach tells little about the system effects of new slide configurations, a major factor in evacuation performance and one that has often changed.[29]

Limitations to Analysis

The analytical models provide only estimates of flow rates under ideal conditions; the models do not take into account the effects of passenger motivation or the presence of fire, smoke, and injuries. The results of the October 1991 evacuation test for the MD-1 1 evacuation certification, in which test conditions were appreciably harsher,[30] illustrate this limitation. In addition, flow control is difficult to analyze mathematically because the calculations are insensitive to architectural changes within the cabin or differences in passengers' decision-making abilities.[31] Another concern over relying on analysis and component tests for certification is that, without full-scale demonstrations, it will be difficult to acquire information on passenger management strategies.

Industry asserts that its mathematical analysis methods are valid and that demonstrations using volunteers are no longer necessary. Boeing and McDonnell Douglas provided OTA incomplete data to perform a statistical analysis of the parameters used in their models.

Other Alternatives

In addition to the combination of analysis and component testing, the use of "professional" demonstration participants has been suggested (i.e., reduce the chance of injury by replacing the "naive" volunteers required for full-scale demonstrations with trained professionals).

The Civil Aeromedical Institute employs two different test protocols for its evacuation studies. In the first, participants repeat evacuation drills several times to gain experience before experimental variables are changed. Experimentation begins after no significant difference in evacuation times is reached. The second protocol entails exposing participants to the same combination of experimental variables in different orders to average the experience factor between subjects[32] (Latin square or counterbalanced experiment design).

Begging the question of whether or not the certification test represents reality, a ". . . systems test with naive subjects allows the evaluation of design factors such as cabin lighting, tactile clues for exit locations, etc., whose influence would be lost or minimized with experienced test subjects. "3[3] Tests with young participants with similar athletic abilities could minimize the risk of injury but provide only optimistic estimates of evacuation performance. The comparability of test results with those of earlier demonstrations would be suspect.

Continuing research and technology development have been integral to improving the overall evacuation capability of an aircraft as well as developing new methods of assessing evacuation performance for certification purposes. The next chapter describes the major research and technology issues and programs related to evacuation performance.

27 The time margin analysis sums over all exits the difference between maximum allowable egress time (e.g., 90 seconds) and that achieved during the demonstration. The PSWG-recommended margin of 10 percent of the maximum equaled 6.2 seconds for the December 12, 1992, McDonnell Douglas evacuation test.

28 Shook, op. cit., footnote 10.

29 George Veryioglou, senior manager, 747/767 Payload Systems, Boeing Commercial Airplane Group, personal communication, Dec. 14, 1992.

30 FAA interpretation of the simulated dark of night requirement resulted in a pitch-black environment outside the aircraft; even the light from video monitors used for data collection was shielded from passengers' view. Additionally, a combination of cabin crews from different countries was used, contributing to poor coordination of flight attendant actions.

31 Shook, op. cit., footnote 10.

32 Marcus, op. cit., footnote 12.

33 Ibid.

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.

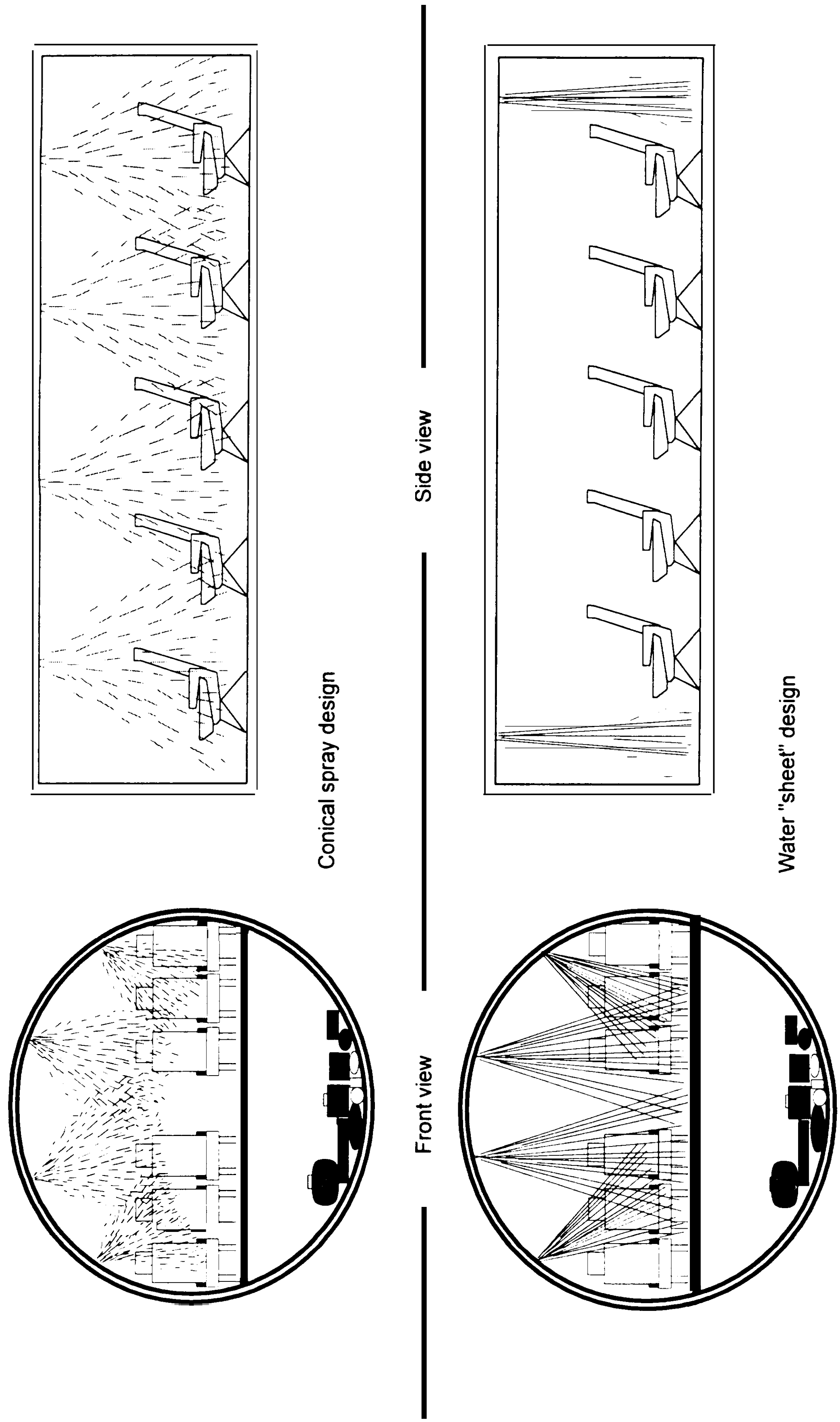
27 Ibid., p. vii.

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:

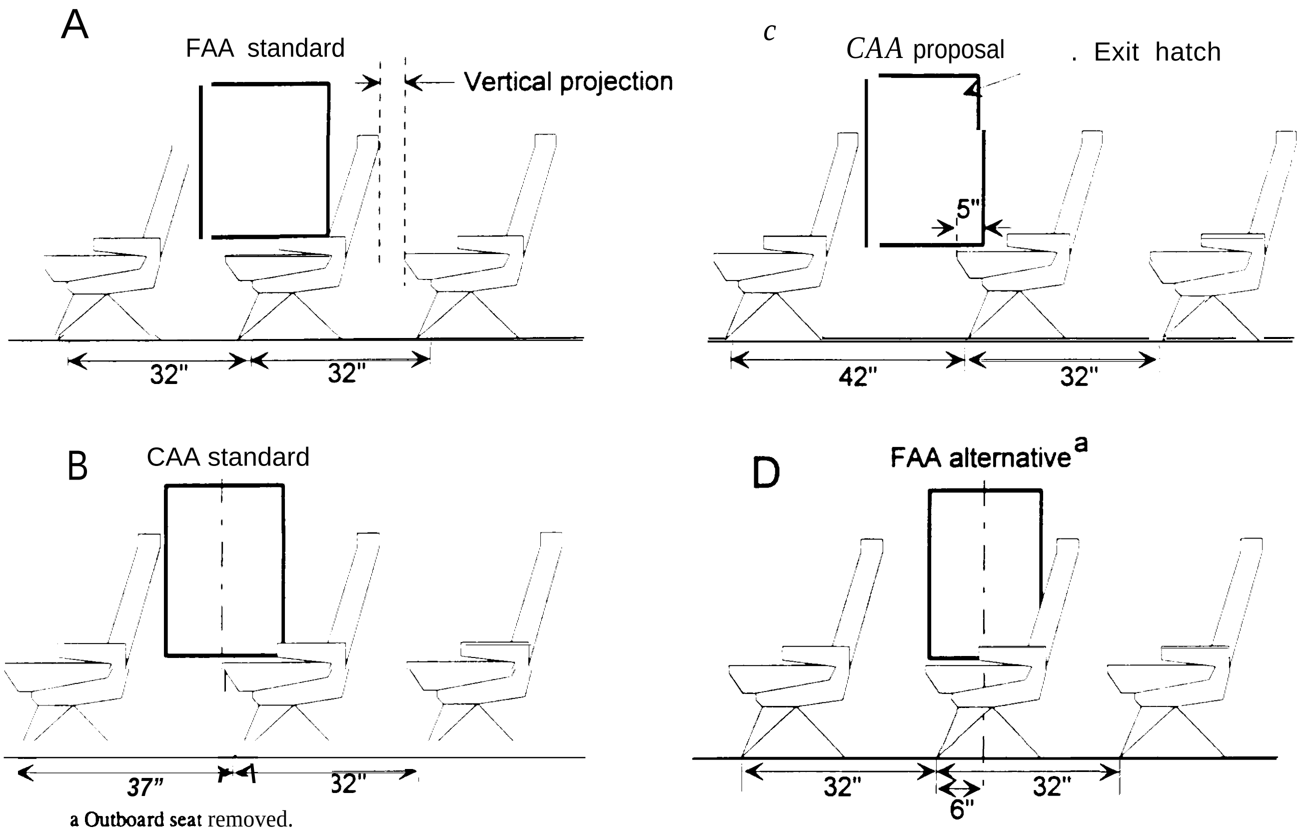
39 The Southern California Safety Institute, a spinoff of the University of Southern California's Safety Science Department, produces aviation safety videos and conducts training programs, audits airlines' safety programs, and so forth.

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).[50]

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-

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 year-long 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.

Chapter 4

FINDINGS AND CONCLUSIONS

Findings and Conclusions

An aircraft's evacuation capability is one of many safety issues the Federal Aviation Administration (FAA) reviews before the aircraft is permitted to enter service. Evacuation equipment is one of a long line of measures intended to improve passenger safety in the event an emergency occurs aboard an aircraft. However, technology alone does not ensure that a passenger escapes the cabin under adverse circumstances. The abilities and actions of flight attendants and the passengers themselves factor greatly into the success of an evacuation.

BENEFITS AND LIMITATIONS OF EVACUATION DEMONSTRATIONS

- **Full-scale demonstrations are costly and expose participants to significant hazards.** The cost of conducting full-scale demonstrations can exceed $1 million each. For example, the cost for the first attempt to certificate the MD-1 1 aircraft with 410 passenger seats was approximately $1.3 million.[1] On average, approximately 6 percent of participants are injured during full-scale tests. Participant injuries were the basis for the 1978 rule change allowing analysis and partial/component tests to replace full-scale demonstrations when conditions warranted. While most injuries have been minor, broken bones and paralysis have occurred. Less severe injuries than expected for traditional demonstration formats occurred in the FAA-approved December 1992 MD-11 certification test in which slides were replaced with ramps and the exterior of the aircraft was lighted.

- **A full-scale demonstration simulates evacuation for only a narrow, optimistic range of emergency conditions.** The certification requirements represent an aborted takeoff at night (i.e., no structural damage, cabin fire, or smoke) with a distinct subset of potential passengers (i.e., no children, persons with disabilities, or non-English speaking passengers).

  There are major weaknesses with using FAA full-scale demonstrations as measures of evacuation performance: 1) only one data point is provided for a measurement that could have a broad probability distribution; 2) the selection criteria for test "passengers" do not reflect actual passenger demographics; and 3) tests do not encompass many of the conditions in actual accidents.

- **Successful evacuation in an actual emergency depends on more than the flow rates demonstrated for certification.** Factors in the outcome of a real emergency evacuation include: cabin and flight crew capabilities; aircraft integrity and seating technologies; passenger and baggage characteristics; and actual accident conditions, such as fire and smoke.

Adding "realism" (e.g., smoke and fire) to full-scale demonstrations as they are currently configured increases the risk of injury to test participants without guaranteeing reduced risk of injury to the flying public. The variability of actual accident conditions cannot be represented with only a few approximations of emergency settings.

The Performance Standards Working Group of FAA's Aviation Rulemaking Advisory Committee, charged with developing revised emergency evacuation requirements and compliance methods for reducing the risk of injury to full-scale demonstration participants, was not able to reach consensus on its proposal to modify the certification test to rely more heavily on analysis. Recommendations and a final report were submitted in January 1993. The working group has since begun to consider whether design standards for emergency evacuation can and should be converted to performance standards.

1 Webster C. Heath, manager, Technical Liaison, Industry Regulatory Affairs, Douglas Aircraft Co., personal communication, July 8, 1992.

- **FAA acknowledges that demonstrations provide only a benchmark for consistent evaluation of various seating and exit configurations; the** requirement to demonstrate complete evacuation within 90 seconds is not an adequate performance standard for measuring evacuation capabilities.[2] Nor is the one-time demonstration useful for system optimization; it provides manufacturers a single opportunity to observe flaws and take corrective actions. After a second attempt to attain certification, one cannot be confident that differences in test results are statistically significant.

Because compliance with some of the test conditions is subjectively determined, variability in the test conditions can occur. During the October 1991 certification test for the MD-11 aircraft, the simulated "dark of night" and crew mix requirements were thought to be more rigorous than for prior tests.

- **Present evacuation certification rules do not encourage development of new technology for extending the period of survivability in postcrash fires.** FAA has emphasized the development of technologies that can speed evacuation rates and reduce total evacuation time (e.g., faster deploying slides, floor-level path lighting). But FAA rules give no credit for technologies that, in real life, could extend the period of survivability within the cabin.

MODELS AND SIMULATIONS FOR EVACUATION CERTIFICATION

- At present, neither certification by fill-scale demonstration nor by purely analytical methods is acceptable to all segments of the aviation community. Manufacturers feel existing data from prior evacuation certification tests have validated their mathematical models such that full-scale demonstrations can often be replaced by combinations of component/system tests and analysis, but statistical analysis of data and model sensitivity have not been explored. Passenger, flight attendant, and pilot groups have expressed concern with reliance on analysis to demonstrate compliance with evacuation standards.
- **The aircraft certification process will likely continue to rely on human test subjects in the foreseeable future.** However, a combination of analysis and partial demonstrations or component tests can be developed to minimize the risk of injury and provide more comprehensive data on aircraft performance than fill-scale demonstrations.
- **Human behavior in certification tests may be empirically modeled using data from prior demonstrations, but cannot yet be reliably "simulated."** Estimates for average reaction times and egress rates are known for evacuation during controlled conditions. Because few reliable data exist on human behavior during accidents, the variations in human judgment and decisionmaking that might be expected for changing hazardous conditions cannot be predicted. These data cannot be obtained from current demonstration requirements, which do not address motivational effects or other behavioral factors that often exist in a real emergency. Manufacturers' mathematical models are insensitive to age, sex, and other characteristics of demonstration participants.

Evacuation models developed for buildings include some human behavioral factors but are not fully transferable to aircraft. For example, there are many configurational differences. The psychological data used in these models are limited to that obtained in interviews of building fire survivors.

Computer simulations, creating repeated and varied evacuation trials, may be more valid as measures of an aircraft's evacuation performance than a single full-scale demonstration would be. At the very least, the simulations can suggest a range of outcomes for given test conditions. Recent computer simulation efforts may provide the technology base for an improved simulation capability. The additional psychological data

2 54 *Federal Register* 26692 (June 23, 1989).

required for validating behavioral assumptions will be difficult to attain.

- **Evacuation rates for existing aircraft components are predictable.** The results of industry analyses typically correlate well with observed rates through doors, aisles, slides, and other components under consistent test conditions. What is not known or predictable is the performance of the emergency evacuation system in an actual emergency (i.e., how many doors/slides will be inoperable or blocked by fire/smoke, how quickly will smoke or flames enter the cabin if a post-crash fire occurs, what interactions will take place between passengers to speed or slow the evacuation?). OTA notes that evacuation trials with human test subjects measure none of these events. Factors that greatly affect the outcome of a real emergency evacuation include: cabin and flight crew capabilities; the integrity of the aircraft and cabin furnishings; passenger and baggage characteristics; and hazardous conditions.

DATA ISSUES

- Additional experimental data are required to validate models/simulations. Earlier industry simulation efforts stalled due to the lack of human factors data. The data collection phase of a current simulation development project has been delayed for lack of funding. Although FAA's present test fuselage is adequate for studying issues related to single-aisle, narrow-body airliners, there is no facility, worldwide, that can be used to analyze egress from double-aisle, wide-body transports.

- Data on injuries related to evacuation testing are not readily available, nor are they classified by severity. Neither FAA nor the National Transportation Safety Board (NTSB) collect information on precautionary[3] evacuations. Data from actual emergency evacuations are unevenly collected and analyzed. With current database structures, evacuation performance data must be painstakingly gleaned from accident reports.

- Recommended changes to FAA fire safety test objectives in the 1980s helped FAA to develop improved test procedures and obtain more comprehensive data for rulemaking. The National Institute of Standards and Technology and the United Kingdom's Civil Aviation Authority are two excellent sources for complementary evacuation and fire data.

AIRCRAFT EVACUATION PERFORMANCE AND SAFETY

- **Survivability in commercial air transports is improving,** largely through the introduction of technologies that mitigate impact forces and delay incapacitation from smoke, heat, and toxic gases.[4] Though still a significant threat, fire has become less of a risk in survivable accidents. In the early 1980s, FAA attributed 40 percent of fatalities in survivable accidents to fire effects. A review of U.S. airline accidents that occurred between 1985 and 1991 showed that approximately 10 percent of fatalities were related to fire. Two central elements of evacuation systems are heat-resistant slides that inflate and deploy automatically and floor-level path lighting.

- **Crew training and passenger actions are as crucial to successful evacuations as are the aircraft's design and equipment.** According to NTSB, as the crashworthiness of aircraft improves, flight attendants assume a more critical role in ensuring passenger safety. Flight attendant training, done in cabin mockups without passengers, may not provide crew members with sufficient skills for motivating passengers to evacuate more efficiently and assessing flow control problems. Because simulation could rapidly show the potential results of different commands and crew actions on the outcomes of emergency evacuations, simulation technologies could

3 Evacuations in cases where the threat of fire or harm later disappeared.

4 By delaying the onset of smoke, the presence of fire retardant materials augments passenger vision as well as improves the potential for survival.

enhance training in passenger management and use of emergency equipment.

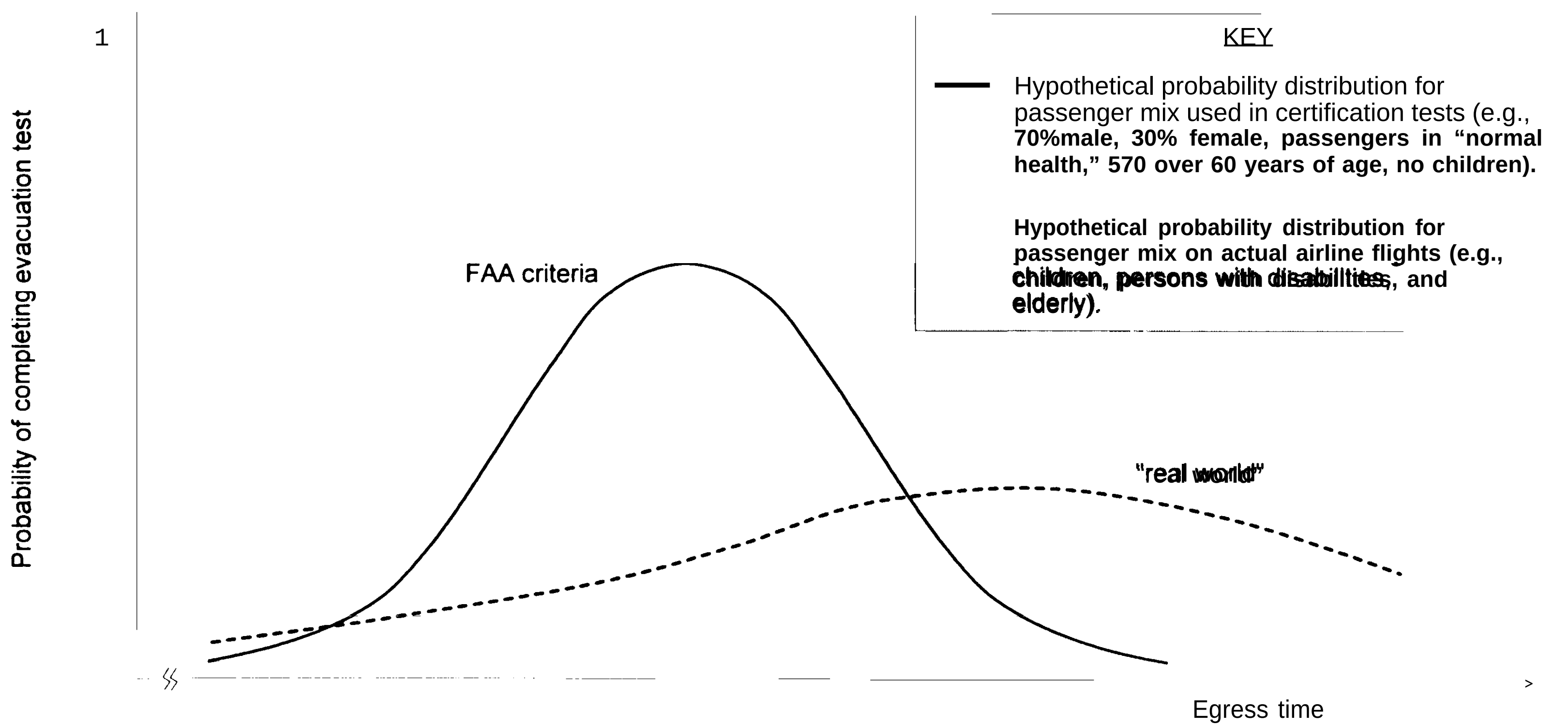
- There is wide variation in the mobility, strength, and perceptive capabilities of aircraft passengers. Under existing aviation regulations, airline operators restrict seating in exit rows to those persons willing and able to read, hear, and understand emergency instructions and to operate evacuation equipment.[5]
- Another factor is the presence and type of carry-on baggage. Some increase in cabin safety could be expected from further restrictions on carry-on baggage, which in an accident can impede passenger movement from seat to aisle and aisle to exit. In addition, passengers often stop to retrieve carry-on items, which flight attendants must remove before the passengers use the slides.
- **Technology efforts to suppress or mitigate thermo-toxic conditions will likely aid passenger survivability more than efforts to further speed evacuations.** Changing demographics suggest passenger evacuation rates will be, on average, slower in the future. To achieve significant reductions in evacuation times from typical seating configurations would require more doors (which add weight and reduce seating capacity, resulting in revenue losses) or fewer passengers (more lost revenue). Speeding evacuation through small changes in technology would be difficult. British analysis of fire deaths in international accidents during the 1980s indicated that new technologies intended to delay deadly heat and toxicity levels after a crash are likely to save many more lives than would efforts to further speed evacuation.[6]

5 *55 Federal Register 8072* (Mar. 6, 1990).

6 Ronald Ashford, "Air Safety Regulation and Its Commercial Impact," *Aeronautical Journal, vol. 95, No. 943*, March 1991, p. 85.

APPENDIX

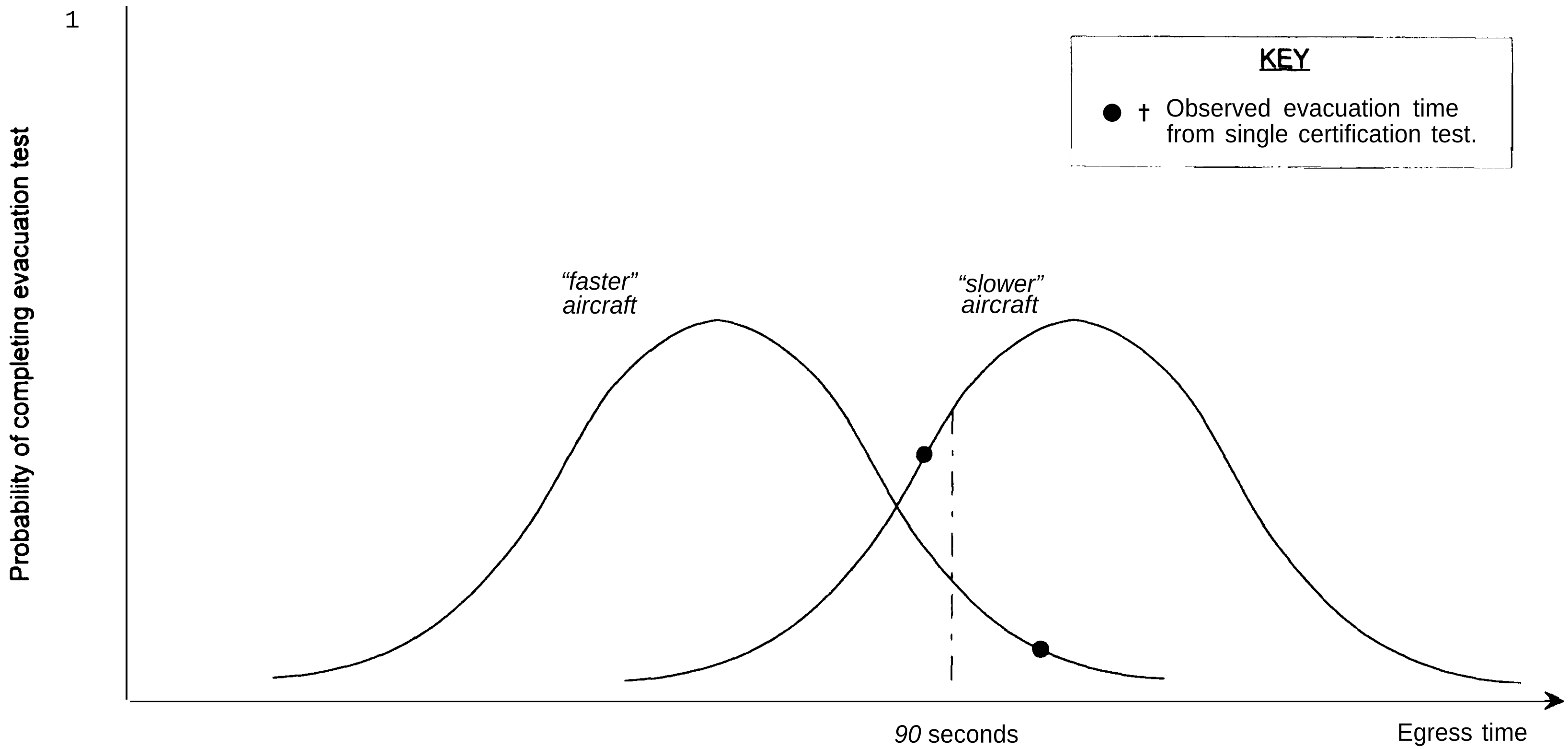
Figure A-1 -- Comparison of Hypothetical Test Results Using “Real World” vs. Certification Test Passenger Mixes



NOTE: This figure shows a rough estimate of sample distributions that might be produced if repeated evacuations were conducted: 1) under existing FAA criteria; and 2) with passenger loads representative of the real world. The estimated distribution of egress times under the real world conditions is much broader and its mean is greater.

SOURCE: Office of Technology Assessment, 1993.

Figure A-2 -- Comparison of Hypothetical Sample Distributions for Aircraft Evacuation Times



NOTE: This figure illustrates the problem of assuming a single test will indicate which is the better or more acceptable of two aircraft tested for compliance with evacuation certification requirements. It represents two theoretical sample distributions of egress times for a "slower" and a "faster" aircraft, as might be obtained from repeated evacuation tests of the two configurations. As shown in the figure, it is quite possible for the faster aircraft (having a shorter average egress time) to fail and the slower aircraft to pass, based on single tests.

SOURCE: Office of Technology Assessment, 1993.

Figure A-3 --- Boeing Evacuation Analysis Method and Mathematical Model

A. Analyze configuration and assign evacuation zones

B. Calculate tota evacuation time (T_{total}) for each exit of each exit pair

C. Verify $T_{total} \leq 90$ seconds

$$T_{total} = T_{exit\ prep} + T_{hesitation} + T_{traverse} + T_{exit\ flow}$$

$T_{exit\ prep}$ = [(Flight attendant reaction time) + (door opening time) + (assist means deployment/inflation time)]

$T_{hesitation}$ = Time from escape device ready for use to first evacuee on device

$T_{traverse}$ = Time for evacuee to descend to the ground after entering the device

$$T_{exit\ flow} = \frac{(\text{Evacuees} - 1) * 60\ (\text{seconds/minute})}{\text{exit flow rate (evacuees/minute)}}$$

SOURCE: Boeing Commercial Airplane Group, 1992.