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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Methodologies for Calculating Firefighting Agent Quantities Needed to Combat Aircraft Crash Fires

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16. Abstract

The current method for determining required firefighting agent quantities at an airport is based on the concept of a "critical area" rectangular box defined by the aircraft length and fuselage width. Aircraft size and construction materials have evolved to an extent that the concepts of critical area, which consists of Theoretical Critical Area and Practical Critical Area need to be studied to ensure they are still valid methodologies for determining the firefighting agent requirements for airports. This analysis addressed various factors in assessing current aircraft rescue and firefighting (ARFF) agent requirements. These factors included the historical development of the existing methods and the recent fire-related loss history. The recent loss history includes the effectiveness of the ARFF response and a fire hazard analysis for threats to occupants in an aircraft and those who have escaped the aircraft. The National Fire Protection Association 403 methodology was found to be acceptable and appropriate for establishing agent quantities.

17. Key Words

Aircraft rescue and firefighting, AFFF, National Fire Protection Association, Aircraft survivability, Aviation jet fuel, Composites, Theoretical critical area, Practical critical area

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LIST OF ACRONYMS

AC	Advisory Circular
AFFF	Aqueous film-forming foam
AFRL	Air Force Research Laboratory
ALPA	Air Line Pilots Association, International
ARAC	Aviation Rulemaking Advisory Committee
ARFF	Aircraft rescue and firefighting
ARFFRWG	Aircraft Rescue and Firefighting Requirements Working Group
AvGas	Aviation gasoline
CAFS	Compressed air foam system
CAFFS	Combined Agent Fire Fighting System
CAT	Category (as in airport category)
CFR	Code of Federal Regulations
CFRP	Carbon fiber-reinforced plastic
FAA	Federal Aviation Administration
GLARE	GLAss-REinforced fiber metal laminate
HRET	High-reach extendable turret
ICAO	International Civil Aviation Organization
IR	Infrared
JP	Jet propellant
MD	McDonnell Douglas
MIL SPEC	Military Specification
NFPA	National Fire Protection Association
NPRM	Notice of Proposed Rulemaking
NTSB	National Transportation Safety Board
PCA	Practical Critical Area
PKP	Potassium bicarbonate
RFFP	Rescue and Firefighting Panel
SCBA	Self-contained breathing apparatus
TAU	Twin agent unit
TCA	Theoretical Critical Area
TO	Technical Order (United States Air Force)
UL	Underwriters Laboratory, Inc.
UHP	Ultra-high pressure
USAF	United States Air Force

EXECUTIVE SUMMARY

To improve the effectiveness of aircraft rescue and firefighting (ARFF) resources, the Federal Aviation Administration (FAA) reviewed the current methodology for calculating the total amount of firefighting agent required to combat aircraft fires. The purpose of this study was to determine whether the current concept of a rectangular, box-shaped critical area of fire protection is an applicable basis for a formula to determine firefighting agent quantities. The analysis addresses these factors in assessing current ARFF agent requirements. The basis of existing methodologies is documented. Recent loss history is summarized, including the effectiveness of the ARFF response.

An accident review indicated that ARFF personnel may use more agent than the Code of Federal Regulations (CFR) or National Fire Protection Association (NFPA) 403 requires, but the amount of agent generally used for initial fire control appears to be within the required amounts. There is no general fuel and passenger load correlation between aircraft within and across airport categories. The only notable trend is a general increase in these loads as the length and width of the aircraft increases.

A fire hazard analysis was performed for threats to occupants in an aircraft and those who have escaped. Since there is no quantitative method to predict how much fuel will spill, the fire hazard analysis assumed that the fire size of representative scenarios was unlimited. The agent required to protect occupants was calculated based on a radiation heat transfer model, as described in a companion report, "Analysis of Suppression Effects on Aviation Fuel Fires Around an Aircraft." This analysis was used to calculate agent quantities for two conditions.

1. Prevention of heat penetration to an intact aircraft and subsequent interior ignition, so ambulatory occupants are not exposed to untenable conditions

2. Prevention of a thermal threat to individuals who have exited the aircraft

Three representative aircraft lengths (Categories 9, 6, and 4) were assessed. Variables included aircraft fuselage thickness/material, ARFF response time, and wind conditions. Foam effectiveness was based on a conservative estimate of 0.13 gpm/ft^2 required for suppression using aqueous film-forming foam (AFFF). The agent requirement methodology in NFPA 403 was found to be an acceptable and appropriate method to establish agent quantities. The new FAA 4-minute burnthrough criteria dramatically reduced the chances of interior ignition for the intact aircraft crash scenario. As of this writing, these criteria are not fully implemented throughout the commercial aircraft fleet.

Data are lacking to fully understand the threat posed by the potential large-surface area involvement of composite material. There is insufficient data to make a clear determination of the agent requirements for advanced composite airframes that are used in new aircraft. Suppression of burning composites requires testing. Additionally, data regarding the potential for combustible materials in a debris field from larger aircraft and the new escape slide locations to add to the agent requirement is also insufficient and requires testing.

Since the fire threat is directly associated with the aircraft length, it is appropriate that this type of aircraft classification be retained. CFR requirements stop at Index E, which includes any aircraft that is at least 200 feet long. The NFPA categories, which essentially mirror the International Civil Aviation Organization categories, provide specific categories for aircraft up to 295 feet. Because of their increased volume, double-deck aircraft could be considered analogous to two aircraft on top of each other. Increasing the height by adding additional decks does not increase the overall length, which would increase the required amount of agent; therefore, a safety factor can be accommodated by considering all double-deck aircraft in the next-higher category until sufficient data is available to adequately characterize the hazard.

Since the hazard analysis is quantitative, the remission factor does not change the outcome. There is no technical basis to invoke a remission factor; the potential hazard is independent of the number of operations.

1. INTRODUCTION.

1.1 PURPOSE.

The Federal Aviation Administration (FAA) Airport Technology Research and Development Branch is responsible for developing and implementing technologies that maximize the potential of aircraft passenger survivability in a postcrash environment. To ensure the effectiveness of aircraft rescue and firefighting (ARFF) resources, the FAA reviewed the current methodology for calculating the total amount of firefighting agent required to combat aircraft ground fires. Aircraft size and construction materials have evolved to an extent in which traditional crash rescue firefighting concepts may be outdated. The size of passenger aircraft is increasing, with associated increases in fuselage size, wingspan, passenger capacity, and jet fuel load. In addition, widespread use of composite materials is becoming the norm. Firefighting technologies, aircraft construction methods, aircraft fuel tank locations, and aircraft with multiple passenger levels potentially affect agent requirements. The purpose of this study was to determine whether the current concept of a "critical area" rectangular box is an applicable basis for a formula to determine firefighting agent quantities. The analysis addresses these factors to assess the current ARFF agent requirements.

1.2 BACKGROUND.

The FAA, via Title 14 Code of Federal Regulations (CFR) Part 139; the International Civil Aviation Organization (ICAO); and the National Fire Protection Association (NFPA) all have different requirements for providing agent. The NFPA and ICAO have similar, yet slightly different, formulas for determining the quantities of firefighting agents and types of ground equipment necessary to achieve fire protection within an acceptable period of time. All formulas were based on a rectangular box designating a critical area of fire protection. The concept of a Theoretical Critical Area (TCA) and a Practical Critical Area (PCA), where firefighting agent has to be delivered to ensure occupant[1] evacuation, has been codified throughout the world. These formulas have evolved over time. Given the changes in aircraft and firefighting technology, it is appropriate to determine if they are still applicable.

ARFF agent quantities, application rates, flow rates, and number of vehicles were established more than 30 years ago, based on the aircraft of the early 1970s. The quantities of agent and number of vehicles were determined using formulas and judgment related to critical fire area, control time, agent application rate, and interior attack. These concepts were defined by the length and width of an aircraft fuselage, which was used to determine the area around an aircraft that must remain free of fire to safely permit the evacuation of the occupants. This concept was further refined based on the agent used in actual incidents and the potential need for an interior attack.

[1]In this report, the term occupant is used to denote all people on an aircraft, including passengers and crew.

1.3 RELATED DOCUMENTS.

The following three primary documents provide agent requirements for ARFF at airports.

- NFPA 403, "Standard for Aircraft Rescue and Fire-Fighting Services at Airports," 2009 Edition [1], hereafter referred to as NFPA 403.
  - NFPA 403 [1] is the principle document used in this report for comparative purposes. It is developed using a consensus standard-making process and provides the best-documented supporting rationale for the technical requirements of ARFF agents.
- 14 CFR Part 139, "Certification of Airports," Subpart D—Operations [2]
  - Title 14 CFR Part 139 [2] applies to those land airports serving passenger operations of an air carrier that are conducted with an aircraft having a seating capacity of more than 9 passengers, hereafter referred to as Part 139.
- ICAO "International Standards and Recommended Practices, Aerodromes—Annex 14 to the Convention on International Civil Aviation, Aerodrome, Volume 1 Aerodrome Design and Operations," Fourth Edition, July 2004 [3], hereafter referred to as ICAO Annex 14.
  - The ICAO requirements are promulgated internationally; signatory countries may adopt these requirements, with amendments. ICAO Annex 14 includes both standard language (necessary for safety, using "shall" language) and recommended practices (desirable in the interest of safety). Guidance is provided in supplementary manuals, such as the ICAO "Airport Services Manual, Part 1—Rescue and Firefighting," Third Edition, 1990 [4].

The FAA also issues recommended guidelines via FAA Advisory Circulars (AC) to provide an acceptable means of complying with the CFR. AC 150/5210-6D [5] covers ARFF suppression agents.

Agent requirements and associated calculation methodologies were previously evaluated by Cohn and Campbell of Gage Babcock & Associates, Ltd. [6], hereafter referred to as the Gage report. Internationally, a study of fire and rescue services was conducted for the United Kingdom (UK) Department of Trade and Industry in 1972 by EASAMS (Elliott Automation Space and Advanced Military Systems) Limited [7], hereafter referred to as the EASAMS report.

The FAA maintains an Aviation Rulemaking Advisory Committee (ARAC) to provide advice and recommendations to the FAA Administrator on the FAA rulemaking activities with respect to aviation-related issues. On March 22, 2001, the FAA announced the assignment of a new task to ARAC, specifically to develop a Notice of Proposed Rulemaking (NPRM) to implement any modifications, deletions, or additions identified in the review of Part 139, Subpart D. The ARAC was tasked with

- reviewing the existing ARFF requirements contained in Part 139, Subpart D and identifying ARFF requirements that should be added, modified, or deleted. This review was to include the current rule and any other documents the agency may have issued regarding Part 139, Subpart D and any ARFF standards issued by other organizations.

- developing an NPRM to incorporate the modifications, deletions, and additions identified in the reviews.

- recommending the disposition of any substantive comments the agency received in response to the NPRM.

As part of this task, ARAC was asked specifically to address the following ARFF issues:

- Number of trucks
- Amount of agent
- Vehicle response times
- Personnel requirements
- Airport ARFF Index

The ARAC accepted the task and assigned it to a newly formed Aircraft Rescue and Firefighting Requirements Working Group (ARFFRWG), which worked under the existing Airport Certification Issues Group. The ARFFRWG performed all analysis and documented the issues relating to the assigned task. Their findings are contained in the "Final Recommendation to ARAC Airport Certification Issues Group 14 CFR Part 139 Subpart D" report dated March 20, 2004 [8], hereafter referred to as the ARAC report. The ARFFRWG unanimously agreed that the current CFR quantities for firefighting agents were not appropriate. However, the ARFFRWG members had differing opinions as to the most appropriate adjustments to make. The consensus of the ARFFRWG concluded that the NFPA agent quantities were appropriate, while a dissenting opinion concluded that adjusted ICAO agent quantities (less than NFPA 403 requirements) were appropriate. No new methods for assessing agent requirements were proposed, although there was concern about the proximity of evacuation slides on new aircraft, which potentially lies outside the critical area. The final ARFFRWG recommendation essentially adopted the agent requirements of NFPA 403.

The analysis in this report may be considered an update to the Gage and EASAMS reports, with issues identified in the ARAC report specifically addressed from a technical basis. Potential new hazards associated with the Boeing 787 and Airbus A380 were addressed. Many of the findings are repetitive but, in the interest of completeness, are included in the report.

Because of the length and detail of the radiative-heat transfer model calculations used in the methodology analysis, this information is reported separately in a companion report, "Analysis of Suppression Effects on Aviation Fuel Fires Around an Aircraft" [9], hereafter referred to as the companion report.

2. DISCUSSION.

2.1 TECHNICAL APPROACH.

To assess firefighting agent requirements, the knowledge of the historical development of agent quantities, existing and anticipated airframe technologies, firefighting agent and vehicle performance, and the effectiveness of manual crash rescue firefighting efforts is needed. The basic approach was to fully document the historical basis of the TCA and PCA formulations. This provided insight on the assumption made on occupant evacuation. The fire loss record from the early 1970s up to this report was assessed since it provides valuable information on occupant survivability, fire hazards from aircraft accidents[2], and ARFF effectiveness. An assessment of hazards was performed, using the fire loss history and up-to-date airframe characteristics. Using updated fire hazard modeling techniques (flame radiation calculations) and associated test data, the threat to surviving occupants was assessed. The current agent calculation methodology was then compared to the updated hazard assessment and previous proposals. Finally, potential revisions to the current methodology were assessed consistent with the hazard assessment and new firefighting technologies not currently included in the baseline requirements.

2.2 SCOPE AND ASSUMPTIONS.

NFPA 403 was used for the baseline in the analysis, because most key national (FAA) and many international (ICAO) experts and representatives participate in this consensus standard process. Differences and variations between NFPA, CFR, and ICAO regulations and guidance were included in the analysis. AC 150/5210-6D references NFPA 403 agent requirements as acceptable to comply with Part 139.

While the scope of this analysis is applicable to all Part 139 airports, the emphasis was on Index Airports, which serve larger aircraft, and the challenges faced in providing protection for the revised B-747, the new B-787, and new A380 aircraft (NFPA Categories 5-10). Data is described in terms of both FAA airport indices and NFPA/ICAO categories, since there is a proposal from the ARAC to coordinate FAA/ICAO airport categories.

The ARFF response time directly relates to occupant survivability, so it has been included in this assessment. NFPA 403 addresses interior firefighting agent requirements, which traditionally have been implicitly outside the scope of ambulatory occupant evacuation embodied in Part 139 requirements. Since the task is to assess all agent requirements, NFPA interior agent requirements are considered. Secondary agents are de-emphasized, but addressed to the extent that they have been previously evaluated. Staffing, specifically the quantification of potential interior firefighting personnel requirements, is outside the scope of this study. This report

[2] The term accident and crash are used in the report to denote an event at or near an airport where ARFF responds to a fire or potential fire situation. In the fire loss review in section 4, the terms "incident" and "accident" have very specific definitions when they relate to NTSB data. NFPA 403 also includes a definition of aircraft accident.

focuses on passenger aircraft; however, when information regarding cargo aircraft was available, it was included.

To the maximum extent possible, the threats and associated agent requirements have been quantitatively derived. Probabilistic risk assessment or cost-benefit analysis techniques have not been used. However, not all rules and mitigation techniques can be absolutely quantified.

3. CURRENT METHODOLOGY.

3.1 OVERVIEW.

Currently, the stated objective of NFPA 403 is to save lives. The requirements to meet this objective are defined in Annex B, which states that the TCA is the area adjacent to an aircraft that must be controlled for the purpose of ensuring temporary fuselage integrity and providing an escape area for its occupants**.**

The level of fire protection to be provided at airports serving fixed-wing aircraft is expressed in terms of firefighting agent quantities and number of vehicles. According to Annex B of NFPA 403, regulatory requirements for this protection prior to 1970 were based on aircraft passenger capacity and fuel load. In the early 1970s, there were considerable activities related to revising the technical approach for determining the required level of protection. Key reports that document this development include:

- The first (1970) and second (1972) meetings of the ICAO Rescue and Firefighting Panels (RFFP) I and II [10 and 11]

- The Gage report [6], sponsored by the FAA, on the minimum needs for airport firefighting and rescue services

- Tests performed by the FAA, principally by George Geyer, to quantify the exterior fire threat to aircraft fuselages and firefighting agent performance required to control exterior fire threats to the aircraft. The key reports include evaluations of

    - crash fires on aircraft fuselage integrity [12].
    - firefighting agents and techniques [13].
    - protection levels for the U.S. Military [14].

  Geyer and other FAA researchers performed many associated tests related to firefighting agent performance.

- Follow-up tests by the FAA, primarily by Gus Sarkos [15] and Tim Marker [16], related to aircraft fuselage integrity, fire growth characteristics within the aircraft cabin, and fire hardening of the fuselage

The ICAO panel members concluded that the concept for determining the level of protection (i.e., calculating required agents) should be the critical area. This was defined in ICAO RFFP I as the area to be protected in any postaccident situation that would permit the safe evacuation of the aircraft occupants [10]. The length and width of the fuselage, along with the wingspan, were considered in developing the critical area.

The width of potential fire area on each side of the aircraft fuselage that would have to be secured to protect its integrity was assessed. This was used to establish the TCA that needed to be secured. The TCA was refined to a PCA, reportedly, based on fuel spill and fire size data from actual incidents [6].

In-service aircraft were categorized and grouped by their dimensions and associated TCA/PCA. The concept of using graduated aircraft categories (indices) as a means of assessing the level of protection continues to be in effect. Fire control and extinguishment times were considered; a control time of 60 seconds was established, which is the time required from the arrival of the first firefighting vehicle to the time the initial intensity of the fire in the PCA is reduced by 90%. The fire should be totally extinguished within 2 minutes after the crash vehicles arrive. Agent extinguishing application rates were developed for firefighting foam (protein, fluoroprotein, and aqueous film-forming foams (AFFF)). By multiplying the PCA times the rate of application and the required fire suppression time, the total agent quantity can be determined. The required foam/water solution required for control in the PCA, designated as Q_1, is

$$Q_1 = PCA \text{ x } R \text{ x } T \tag{1}$$

where

PCA = Practical critical area
R = Rate of application for a specific foam
T = Time of application (1 minute for control in the PCA)

Additional foam agent was necessary to affect total fire extinguishment, designated as Q_2. There has been no agreement on a quantitative method to determine Q_2; quantities have been developed for Q_2 as a function of the aircraft PCA based on expert judgment. A third agent component for potential postcrash interior firefighting, designated as Q_3, has recently been established in NFPA 403.

Summarizing, the quantity of agent required by NFPA 403 is based on a PCA established by the size of the aircraft to be protected. Agent quantities are based on three components, so the total agent required, Q_T, is

$$Q_T = Q_1 + Q_2 + Q_3 \tag{2}$$

It is difficult to establish the quantitative basis of the current approach on a step-by-step basis from the literature. A simple summary has been provided by Tom Lindemann, a past member of the NFPA 403 Technical Committee [17], which states that FAA research indicates that when an aircraft is involved in a fuel spill fire, the aluminum skin will burn through in about 1 minute. If the fuselage is intact, the sidewall insulation will maintain a survivable temperature inside the cabin until the windows melt in approximately 3 minutes. At that time, the cabin temperature rapidly increases beyond a survivable temperature of 400°F. The ARFF equipment and agents can control a fire in 1 minute. Therefore, ARFF personnel and equipment must reach the scene in 2 minutes to meet the anticipated burnthrough scenario.

The following sections provide detailed discussion of the development of the agent requirements, the source and justification of these requirements, and the limitations to the current approach, including the assumptions stated by Lindemann [17].

3.2 THE CRITICAL AREA CONCEPT.

3.2.1 Initial Establishment of the Critical Area.

NFPA 403 summarizes the development of the critical area concept. ICAO RFFP I was convened by ICAO in Montreal, Canada, from March 10 to 20, 1970. At that time, the method contained in ICAO Annex 14, Attachment C (Fourth edition), for the determination of the level of protection (agent quantities and number of vehicles) to be provided at airports for fixed-wing aircraft was based on the fuel load and passenger capacity of the aircraft. As a result of exchanged correspondence, the panel members were in general agreement that a new or revised method for specifying the quantity of provided firefighting agents and rescue equipment was needed.

The panel members unanimously agreed that the concept for determining the level of protection should be the critical area, which is the area to be protected in any postaccident situation that would permit the safe evacuation of the aircraft occupants. The purpose of the critical area concept was to serve as the basis for calculating the quantities of firefighting agents necessary to achieve protection within an acceptable period of time (which was not defined), not to define fire attack procedures.

Based on the logic that passenger capacity is related to length, the panel members also unanimously agreed that the critical area should be a rectangle with as one dimension the length of the fuselage. However, a difference of opinion existed as to what width should be used. The RFFP report documents five proposed means of defining the width of the critical area [10].

It was finally agreed that no single system could be used to express the area to be protected for all sizes of aircraft. In the end, the panel members agreed that the critical area should be a rectangle with one dimension based on the overall length of the aircraft. The other dimension should be the overall width (wingspan) of the aircraft for aircraft with wingspans of less than 30 m (100 ft). For aircraft with wingspans of 30 m (100 ft) or more, the second dimension should be 30 m (100 ft). A standard fuselage width of 6 m (20 ft) was assumed. Using this approach, the aircraft in service at that time were grouped into a series of eight categories. Beginning with Category (CAT) 1, each successive CAT represented a logical progression in aircraft length [10].

The concept of using graduated aircraft categories to assess fire protection needs is still in effect with only minor revisions that reflect changes in the operating aircraft fleet. This general concept has been adopted worldwide by both consensus standard-writing organizations and national regulatory authorities. Today, NFPA and ICAO use the term Category, whereas the FAA uses the term Index.

Following ICAO RFFP I, the panel members agreed that the use of the area concept for determining the level of firefighting agents and equipment needed to combat an aircraft accident fire was based on the following facts:

- The quantity of agent necessary to control or cover the fire area could be relatively accurately determined.

- The rate of application of the agents to control the fire in the most effective time period could also be determined.

3.2.2 Quantitative Basis of the Critical Area.

During 1969, Geyer performed fire tests on aircraft fuselage integrity [12]. Experiments were performed at the FAA William J. Hughes Technical Center. The fire environment was comprised of three 10-ft-wide by 30-ft-long rectangular pits filled with JP-4, located equidistant from the ends and parallel to a 40-ft-long, stainless steel-covered fuselage section of a four-engine commercial jet aircraft. It was found that this fire would penetrate the skin within 40 seconds after fuel ignition when the wind velocity was between 10 and 12 mph. The maximum temperature of 880°F was reached within 40 seconds; all the thermocouples embedded in the fuselage skin on the upwind side reached 900°F within 116 seconds after fuel ignition. An extrapolation of the available data indicated that an aluminum fuselage would be subject to fire damage if the separation distance upwind, between the fuselage and the fire, was less than 80 ft during prolonged fire exposure, resulting from flame “trailing” caused by the 10- to 12-mph wind. Other tests in the 1969 Geyer experiments were performed to determine the effect of JP-4 fuel fires located on the downwind side of the fuselage. When the fire was 20 ft from the fuselage and the wind velocity was between 10 and 12 mph, there was no resultant damage to the aluminum skin. Geyer concluded that, with a wind velocity of 10 to 12 mph, the critical dimension perpendicular to the fuselage, which defines the critical fire area, is the 80-ft distance upwind of the aircraft fuselage. Geyer considered this method for estimating the critical fire area around an aircraft valid when the fuselage length was in excess of 60 ft.

Geyer found the critical fire area around aircraft involved in smaller fires to be somewhat more difficult to establish because “of the greater affect that wind had in disrupting the fire plume from relatively small spill fires upwind from the fuselage.” The 1969 experiments indicated that if a 10-ft-wide and 40-ft-long JP-4 pool fire was placed parallel to and 20 ft from the upwind side of the fuselage, a fire exposure time of 100 seconds was required after fuel ignition before the aluminum skin reached the incipient melting temperature of 900°F.

Geyer concluded that an estimation of the dimension perpendicular to the aircraft fuselage (60 ft or less) involved in small fires, which is considered to define the critical fire area, should include a 20-ft distance on both sides of the fuselage plus an allowance for the width of the fuselage. The rationale for the final smaller aircraft critical area remains unclear.

During this same time period, the Gage report was being prepared. There was considerable discussion and analysis related to the crash fire rescue scenario. The Gage report noted that the primary function of aircraft crash fire and/or rescue services is the preservation of life, with the preservation of property a secondary but important function. They considered that the use of the term "rescue" for these functions as unfortunate, because the common connotation of rescue implies the physical guidance or removal of an individual from a position of danger. Further clarification of life safety was provided by the Gage report.

- Guide, remove, or transport occupants from an endangered aircraft.
- Reduce the fire intensity to permit the occupants to escape.
- Extinguish the fire to remove the danger.
- Establish a path through the fire for escape.

NFPA 403 [1] defines aircraft rescue as the firefighting action taken to prevent, control, or extinguish fire involving, or adjacent to, an aircraft for the purpose of providing maximum fuselage integrity and an escape area for its occupants. Rescue and firefighting personnel, to the fullest extent possible, will assist in evacuation of the aircraft using normal and emergency means of egress. Interior evacuation actions were later added to this definition (see Section 3.3.4 of NFPA 403).

The Gage report [6] cited a detailed survey of aircraft accidents up to 1963, which indicated that the conventional rescue concept was applicable to crew-only aircraft. In passenger transports, the occupants either escaped themselves or, unless the fire was extinguished, they perished. This escape, however, may have been aided or made possible by fire suppression activities. An updated survey by the Gage report of accidents did not indicate any significant variation from this conclusion. The Gage report goes on to cite specific incident data related to the effectiveness of ARFF, which is reviewed in section 4 of this report.

The Gage report deviated from the Geyer approach in analyzing the thermal threat to occupants. Geyer considered protection of the occupants within the aircraft (i.e., by preventing hazardous conditions from occurring within the cabin), but the Gage report considered the thermal threat to occupants who have already evacuated the aircraft. For this threat, the fire had to be kept sufficiently clear of the escape path to enable the occupants to reach safety. The Gage report stated that the version of NFPA 403 current at the time of the study was based on fire suppression activities to provide a clear area the full length of the fuselage and 100 ft wide. The Gage report assumed a no-wind condition of a clear space 40 ft wide on each side of the aircraft, with a 20-ft allowance for the fuselage width, as equivalent to the wind-aided fire threat analyzed by Geyer. Thus, the no-wind and wind scenarios resulted in the same critical areas.

To test this theory, in the Gage report, a simplified fire model was used to analyze the radiant exposure to an occupant escaping from a fire-exposed aircraft. The exposing fire was assumed to be represented (as viewed by the occupant) by a rectangular plume. The length of the plume was 80% of the fuselage length and its height was 1.20 times the fuselage height. The width of the fire was assumed sufficient; the plume had an emissivity of 1 and a radiant intensity of 10 Btu/ft^2 sec. This was analyzed for an occupant who exited from the aircraft opposite the center of the plume and escaped along the fuselage until the occupant was beyond the plume by 25% of its length. At that time, escape was assumed to be complete. This fire model and the escape path (total length = 0.6 L) is shown in figure 1. The radiant exposure was computed for a clear path of widths equal to 20%, 40%, and 60% of the fuselage length (0.2, 0.4, and 0.6 L).

The analysis did not consider the fire on the opposite side of the aircraft since the individual would be partially shielded by the fuselage. The escape path was analyzed for two aircraft: a small transport, the 83-ft-long Fairchild 227; and a large transport, the 232-ft-long B-747.

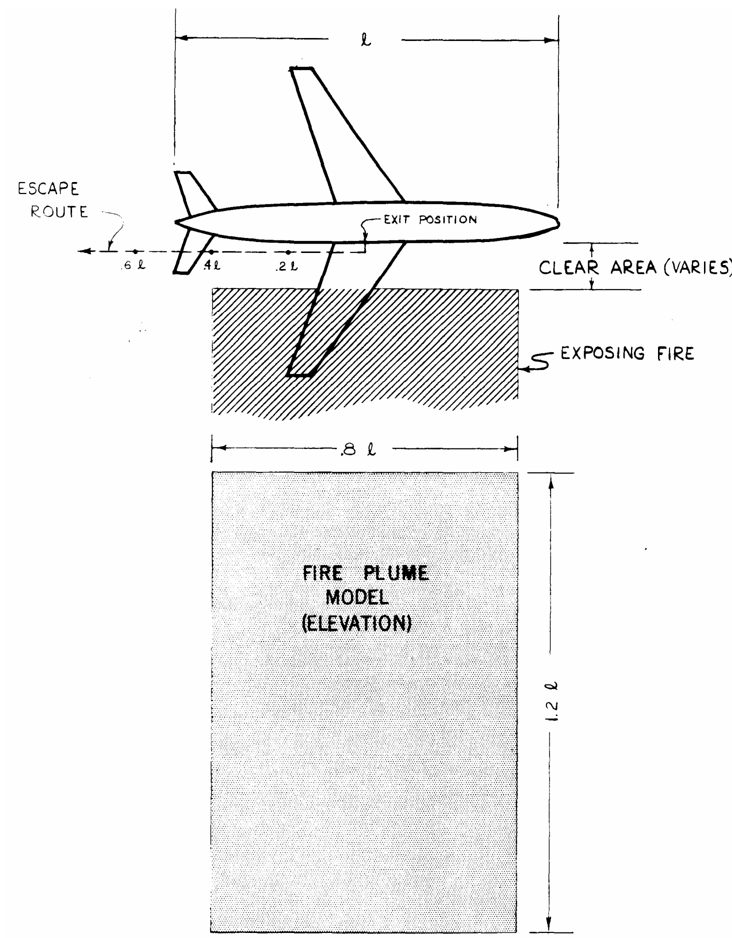

Figure 1. Fire Model Used for Escape Analysis [6]

It was found that an escaping passenger from a small aircraft would be subject to unbearable pain while exiting the aircraft, and the exposed flesh would have third-degree burns prior to reaching a safe distance from the fire. With a larger aircraft, the situation becomes even worse. When applied to a B-747 aircraft, the model predicted that at clear path occupant fire separations of 46 and 92 ft (0.2 and 0.4 L), the escapee would suffer third-degree burns while exiting the aircraft. At a separation of 128 ft (0.6 L) from the fire, the occupant would be able to traverse a short distance along the escape path before receiving third-degree burns.

The Gage report analysis showed the practical limitations of the escape path concept as applied to the critical fire area concept of maintaining fuselage integrity. In other words, the TCA/PCA, where the fire area is intended to be controlled very quickly (60 seconds) by the first arriving vehicles, is not necessarily a clear rescue path for ambulatory occupants. Rather, the intent (as emphasized in Annex B of NFPA 403) is to protect the aircraft skin from melting under severe fire conditions.

3.2.3 Establishment of the PCA.

When ICAO RFFP II convened in 1972, the panel members confirmed the critical area concept where one area dimension would be the length of the aircraft. The methodology based on the 1969 Geyer tests [12], as documented in a subsequent report by Geyer related to suppression effectiveness [13], was made available to the panel members. However, there was no consensus as to length of the other side. The panel members also concluded that there was a need to distinguish between the TCA within which it might be necessary to control a fire, and a PCA that was representative of actual aircraft accident conditions. The TCA was explicitly defined in the ICAO RFFP II report as "the theoretical area adjacent to an aeroplane in which fire must be controlled for the purpose of ensuring temporary fuselage integrity and providing an escape area for its occupants." The panel members agreed that the TCA should be a rectangle, with one dimension, based on the overall length of the aircraft, and the other dimension determined by the following:

- For aircraft with an overall length of less than 20 m (65 ft): 12 m (40 ft) plus the width of the fuselage.
- For aircraft with an overall length of 20 m (65 ft) or more: 30 m (100 ft) plus the width of the fuselage [11].

The ICAO RFFP II decided that the TCA served only as a means for categorizing aircraft in terms of the magnitude of the potential fire hazard in which they might become involved. It was not intended to represent the average, maximum, or minimum spill fire size associated with a particular aircraft. The original formula for the maximum TCA, as presented in the ICAO RFFP II report, was given as follows [11].

$$A_T = L \text{ x } (12 \text{ m } (40 \text{ ft}) + w) \text{ for } L < 20 \text{ m } (65 \text{ ft}) \quad (3a)$$

or

$$A_T = L \text{ x } (30 \text{ m } (100 \text{ ft}) + w) \text{ for } L \geq 20 \text{ m } (65 \text{ ft}) \quad (3b)$$

where

A_T = TCA
L = overall length of the aircraft
w = width of the aircraft fuselage

The formula for the PCA developed by ICAO RFFP II for fixed-wing aircraft can be expressed as follows.

$$PCA = (0.67) \text{ x } (TCA) \quad (4)$$

There was a perception that actual crash fires were smaller than the TCA. The ICAO RFFP II wrestled with the concept of reducing the TCA to a "practical" area, based on loss data. NFPA 403, Annex B notes that the ICAO RFFP II indicated that the PCA was approximately two thirds the size of the TCA. This was supposedly verified by a study of actual fire sizes and aircraft accidents. The amount of water used at actual accidents was also cited; it was reported that in 99 (93%) of 106 accidents for which this data was available, the amounts recommended by the panel members were in excess of those actually used.

Some have questioned the basis of these statements. The Gage report [6] provides crash fire incident area data, and the EASAMS report [7] provides water usage data (see sections 4.6 and 4.10, respectively). These data appear to support the rationale for a PCA, which is smaller than the TCA.

Based on this analysis, the ICAO RFFP II decided to use two-thirds of the TCA as the PCA (see figure 2).

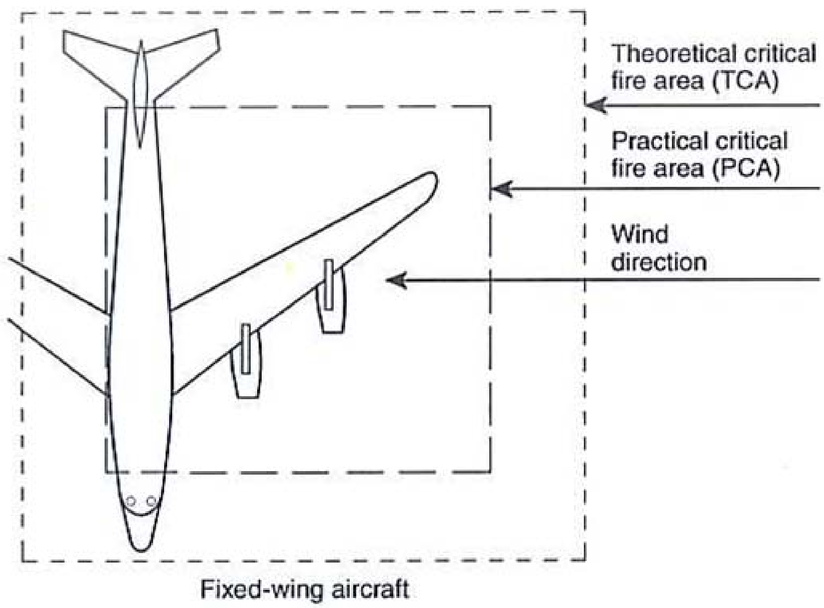

Figure 2. The TCA Relative to the PCA [1]

3.3 SUPPRESSION AGENT QUANTITIES.

3.3.1 Response Time and Fire Control.

After defining the critical area to be protected and developing a system of fire protection categories (indices) based on aircraft size and width (see section 3.4), the ICAO RFFP I panel members considered the issues of discharge rates and the firefighting agents to be applied to the critical area. The panel members concluded that fire control time and fire extinguishment time within the critical area should be considered individually and defined as follows.

- Control time: The time required from the arrival of the first firefighting vehicle to the time the initial intensity of the fire is reduced by 90%.

- Extinguishment time: The time required from arrival of the first firefighting vehicle to the time the fire is completely extinguished [10].

ICAO RFFP II originally stated that complete extinguishment in the critical area should occur within 1 minute after fire control.

The rationale from the RFFP and the commentary from NFPA 403 Annex B [1] are vague on explicitly establishing the link between the response time of vehicles, the control of the exterior fuel fire, and the onset of hazardous conditions to occupants. This relationship can quantitatively be expressed as

$$T_V + T_E \leq T_B \tag{5a}$$

where

T_V = vehicle response time
T_E = time to extinguish exterior pool fire threat (90% control)
T_B = time occupants are exposed to life threatening conditions

By establishing this metric, performance measures can be assessed.

The ICAO RFFP I [10] noted that the existing 3-minute vehicle response time specified in Annex 14 was considered an acceptable upper limit, though it was recognized that, under many instances, airport authorities could improve (lower) this limit. ICAO RFFP II considered that a 2-minute response time to any part of the airport movement area should be an objective. Their official recommendation was that response time to any part of the airport movement area under optimum conditions of visibility and surface conditions should be not more than 3 minutes, but preferably, not more than 2 minutes.

Gage [6] noted that quick response and quick knockdown of the fire by airport fire equipment offer the best chance of passenger survivability in an aircraft crash situation. They recommended a maximum response time of 3 minutes, recognizing that "this time period is considered by most authorities to be longer than can actually be tolerated to assure survivability of all passengers." They asserted that the effectiveness of an airport crash fire/rescue service diminishes rapidly with response times to the scene of a crash in excess of 2 minutes, based on their thermal analysis as described in section 3.2.2. They indicated that a desirable response time would be 90 seconds (0-second response time would be the goal, but it is obviously not practical), with a 2-minute response as optimum. Even these response times, they noted, will not be adequate for major crash fires, in which fuselage openings are directly exposed to fire or in which the cabin interior is involved.

The vehicle response time aspects described here and in section 3.6.2, are revisited in the current threat analysis, section 5.2.3. As a means of describing the historical basis of protection criteria, a return to the Lindemann approach [17] is sufficient, where 3 minutes is stated as the time when occupants will be exposed to threatening conditions for an unabated fire. If the ARFF resources arrive at the scene within 2 minutes, fire control must be achieved in 1 minute. Thus, equation (5a) is met.

$$T_V\,(2\text{ min}) + T_e\,(1\text{ min}) \leq T_B\,(3\text{ min}) \tag{5b}$$

Currently, the 1-minute fire control time for the PCA is considered a reasonable minimum. New technologies may be developed to reduce this time (see section 7). Any gradation of control times below this order of magnitude currently fall within the realm of experimental error, variability of conditions, and imposition of safety factors (see section 7).

3.3.2 Control Time in the PCA—Q_1.

The ICAO RFFP II panel members confirmed the fire control and extinguishment definitions, and based on an analysis of accident data furnished by the member's countries, the equipment and techniques to be used should be capable of controlling the fire in the PCA within 1 minute. The ICAO RFFP I (March 1970) and ICAO RFFP II (June 1972) agreed that the amount of foam agent should be quantified based on the largest aircraft supported at each airport. Members of both panels agreed that Q_1 could be quantified based on the critical area concept—the area around the fuselage that needs to be protected to ensure fuselage integrity and to provide a safe area for passenger escape. The time within which specific amounts of agent needed to be applied could also be estimated based on melt times of aircraft exterior skin exposed to radiant heat from an adjacent pool fire. By knowing the area involved, the time during which the agent has to be applied, and the expected performance of the individual foam agents (as measured by foam application rates and densities derived from large-scale tests), it was possible to calculate specific amounts of Q_1 for various fuselage dimensions.

As discussed in section 3.1, in NFPA and ICAO standards, Q_1 is the calculated amount of agent necessary to control a pool fire of a specific size (the PCA) within 1 minute. Both NFPA and ICAO use the same agent application density for the three foam agents: 0.13 gal/ft^2 for AFFF, 0.18 gal/ft^2 for fluoroprotein, and 0.20 gal/ft^2 for protein foam. Since Q_1 by definition is the amount of agent that must be applied to the PCA in 1 minute, Q_1 is both a quantity (gallons) and a flow rate (gpm) of foam agent that must be applied to the PCA to achieve control.

The application densities cited above have been used by NFPA and ICAO for roughly 30 years. A considerable amount of research effort has been expended on establishing threshold application densities for flammable liquid pool fires. The relevant research, including extensive work done by Geyer, the Naval Research Laboratory, and others, is discussed and reviewed in depth in Section 4 of Chapter 4 of reference 18 and in Scheffey, et al. [19]. These summaries show that the NFPA/ICAO-assumed application rates for AFFF, fluoroprotein, and protein foam (0.13, 0.18, and 0.20 gpm/ft^2, respectively) are adequate to control a pool fire within 60 seconds. Figure 3, extracted from Geyer's work during the 1970-1980 time frame [13], shows the performance capability of the foam agents by showing the fire control time as a function of the agent application rate. Geyer's data were derived from extinguishment tests conducted on JP-4 pool fires of 70, 100, and 140 ft in diameter.

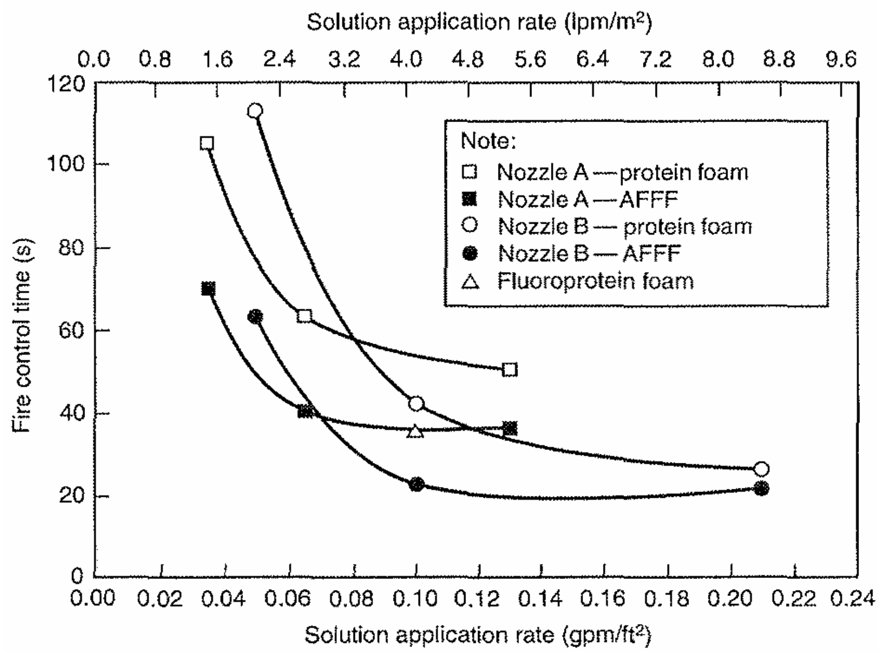

Figure 3. Fire Control Time as a Function of Solution Application Rate Using Protein Foam and AFFF on JP-4 Pool Fires [13]

Figure 3 shows that for a 60-second fire control time, the application rate for AFFF was on the order of 0.04 to 0.06 gpm/ft^2, while the application rate for protein ranged from 0.08 to 0.10 gpm/ft^2. The application rate curves tend to flatten for AFFF and protein at about 0.10 and 0.20 gpm/ft^2, respectively. Above those rates, the control times are not appreciatively improved. Likewise, critical application rates for fire control are indicated when control times increase dramatically. As expected, the single test with fluoroprotein foam fell between AFFF and protein. The application rates for AFFF were recently reverified in tests by the United States Air Force (USAF) [20].

Geyer [13] recognized that, relative to test fires, actual fires present unknown and unanticipated conditions; therefore, control of actual fires may take longer than the control of test fires. He recommended that a reasonable application rate to be used at air fields should be 0.13, 0.18, and 0.20 gpm/ft^2 for AFFF, fluoroprotein, and protein foam, respectively. The recommended rates were adopted by ICAO RFFP I and II and by NFPA 403. This concept has not only survived to the present, but it has, with occasional minor revisions to update changes in the operating aircraft fleet, been adopted worldwide by both consensus standards-making organizations and national regulatory authorities.

The adequacy of the NFPA/ICAO application rates assumes that AFFF is qualified against the U.S. military specification (MIL SPEC), MIL-F-24385F [21], and that the other foams are listed by Underwriters Laboratory, Inc. (UL) Standard 162 [22], or equivalent.

Meeting the military specification or the UL Standard ensures a discreet minimum level of performance and a reasonable factor of safety. A factor of safety is important because the assumed application rates may be compromised by training deficiencies, delivery equipment malfunction, inaccessibility of shielded fires, initial overuse of foam, three-dimensional fire scenarios, difficulties in deployment and control, or adverse winds.

Research reports clearly show that the margin of safety inherent in the assumed NFPA/ICAO application rates is greater with AFFF than with other foams, as shown in figure 4. Even at application rates as low as 0.05 gpm/ft^2, AFFF achieved fire control in an average time of under 30 seconds.

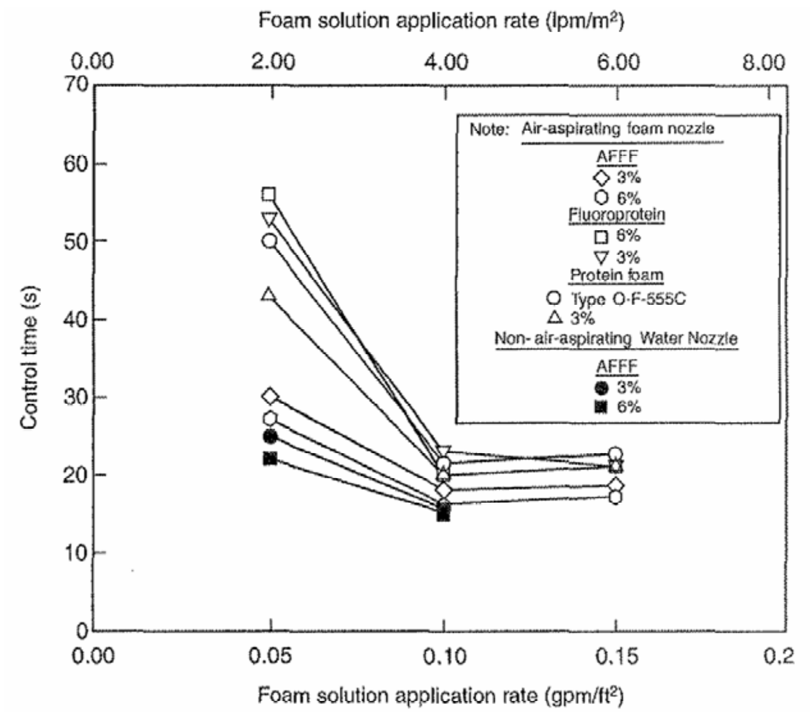

Figure 4. Fire Control Time as a Function of Solution Application Rate for AFFF, Fluoroprotein, and Protein Foams for Jet A Pool Fires [23]

An analysis by Scheffey [19] showed that a scaling relationship exists between small-scale tests, especially the MIL SPEC qualification tests, and actual large-scale ARFF scenarios. The time needed to control a unit of burning area, sec/ft^2, designated in the literature as "specific control time," decreases as a function of burning area for increasing application rates of AFFF. The MIL SPEC tests are more challenging than the larger tests in terms of time to achieve control, but the MIL SPEC test produces an agent that can meet NFPA requirements at less than the design application rate of 0.13 gpm/ft^2.

This research clearly indicates that the NFPA-assumed rates are adequate for the PCA and provide a reasonable factor of safety. The literature also implies that the margin of safety is greater with AFFF, especially the MIL SPEC AFFF, than with the other two primary agents or with AFFF agents that are tested to lower standards. Recognizing this, AC 150/5210-6D [5] states that AFFF must meet the requirements of MIL-F-24385F, which is consistent with the position established in NFPA 403. It is widely accepted that essentially all airports in the U.S. use MIL SPEC AFFF.

3.3.3 Agent Required for Extinguishment and Crash Area Security.

The ICAO RFFP I did not develop a specific definition of Q_2 but recognized the need to distinguish between fire control and extinguishment. ICAO RFFP II defined Q_2 as "the quantity required for continued control of the fire after the first minute and/or complete extinguishment of the fire." ICAO RFFP II was unable to identify a recommended time period for the extinguishment time. This was due to the numerous variables involved for each aircraft accident, such as the size of the aircraft, area of fire, and three-dimensional fires.

The current ICAO Airport Services Manual defines Q_2 as "the water required after control has been established and is needed for such factors as the maintenance of control and/or extinguishment of the remaining fire" [4].

NFPA 403 defines Q_2 as "the quantity of water for foam production to continue control or fully extinguish the pool fire" [1].

Appendix B of NFPA 403 (Section B.4.2) attempts to distinguish between fire control and fire extinguishment.

> "The quantity required for continued control of the fire after the first minute or for complete extinguishment of the fire or for both."

Section B.5 of NFPA 403 extends the definition by stating:

> "Q_2 relates to the need to have sufficient fire suppression agents available to maintain conditions that do not pose a threat to life in the PCA until such time as rescue operations are completed. The secondary role of Q_2 is to extinguish all fires in and peripheral to the PCA."

In essence, all the definitions appear to draw the same conclusion; while Q_1 is the quantity to achieve control in the PCA within 1 minute, Q_2 is the quantity to maintain control within the PCA and to ultimately achieve total extinguishment.

Each Q_2 definition makes a distinction between control and extinguishment. As presented by the RFFP, and as repeated in appendix B of NFPA 403, "Control time is the time required from the arrival of the first firefighting vehicle to the time the initial intensity of the fire is reduced by 90 percent." In contrast, the RFFP [10 and 11] and NFPA 403 [1] define extinguishment time as "the time required from the arrival of the first firefighting vehicle to the time the fire is completely extinguished."

The definitions of Q_2 also imply a particular sequence of application. Q_1 is applied initially by the first responding ARFF vehicles to ensure fuselage integrity and to facilitate passenger escape. After the delivery of Q_1, discharge continues as Q_2 to maintain control and achieve total extinguishment.

The amount of agent needed to maintain control and achieve total extinguishment, Q_2, was difficult to quantify because of the many factors involved. The ICAO RFFP II report states in

Section 3.5.2 that quantification of extinguishment time was not possible "in view of the numerous variables involved at each aircraft accident such as size of the aircraft, area of fire and three dimensional fires." The report further states in Section 3.9.3 that "there was no objective method on which to base the calculation of this quantity." However, in ICAO RFFP II Recommendation #3/2, the panel members stated that while "Q_2 cannot be calculated exactly," there are factors that may be used to develop estimated quantities. The factors considered of primary importance are:

- Maximum gross weight
- Maximum passenger capacity
- Maximum fuel load

Following the above statement, the ICAO RFFP II offered recommended quantities of Q_2 calculated "as a percentage of Q_1." The actual table of recommended Q_2 quantities contained in the ICAO RFFP II report is shown in table 1.

Table 1. The ICAO RFFP II Q_2 as Percentage of Q_1 [11]

Aerodrome CAT	Q_2 = Percentage of Q_1
1	3
2	22
3	37
4	66
5	100
6	129
7	152
8	170

The rationale or method used in deriving the specific quantities shown in table 1 were not explained in the ICAO RFFP II report. There is only mention that the various factors bearing on Q_2 where "plotted on a graph" and the resultant graphs yielded the tabulated quantities. Hewes, in an historical review of ARFF agent requirements, says that Q_2 graphs were drawn for different aircraft sizes, passengers, gross weight, and expert experience. He shows an exponential graph with no units [24]. Undoubtedly the quantities reflected the collective judgment of the ARFF specialists who comprised the ICAO RFFP II. Analysis in section 5.1.1 of this report indicates that these factors may relate to the original PCA, which was two-thirds the TCA (see Table 15 of ICAO RFFP II [11]).

All versions of NFPA 403 since the mid-1970s have adopted the ICAO RFFP I and II Q_2 concept. In fact, the current NFPA 403 quotes directly from the ICAO RFFP II report when describing Q_2. The current values of Q_2 in NFPA 403 are only slightly different from those developed by RFFP II, reflecting changes in aircraft sizes and the overlap between NFPA "airport categories" and ICAO "aerodrome categories."

3.3.4 Water for Interior Firefighting—Q_3.

Q_3 was added to NFPA 403 [1] in the 1998 edition. Appendix A-2-3-1 of the 1998 edition explained the rationale for agent requirements in addition to quantities for exterior fuel fire control (Q_1 and Q_2) as follows:

- Information from actual incidents in recent years has shown that with increased aircraft crash worthiness, water for interior firefighting operations is also necessary. This quantity of water, called Q_3, is based on the need for hand lines to be used for interior firefighting.

- Hence, the total quantity of water (Q) is now defined as follows: $Q = Q_1 + Q_2 + Q_3$. The values of Q_3 are based on accepted water flow requirements for the type of firefighting operations to be experienced when combating an interior aircraft fire.

Along with the stated requirement for interior firefighting, the 1998 edition also added a sentence to the definition of aircraft rescue:

> "Additionally, rescue and firefighting personnel will, by whatever means necessary, and to the extent possible, enter the aircraft and provide all possible assistance in the evacuation of the occupants."

Q_3 was quantified in the appendix of the 1998 edition, as shown in the table 2.

Table 2. The Q_3 Requirements per NFPA 403, 1998 Edition [1]

Airport CAT	Q_3 Equals
1	0
2	0
3	60 gpm x 5 min = 300 gal
4	60 gpm x 10 min = 600 gal
5	125 gpm x 10 min = 1250 gal
6	125 gpm x 10 min = 1250 gal
7	125 gpm x 10 min = 1250 gal
8	250 gpm x 10 min = 2500 gal
9	250 gpm x 10 min = 2500 gal
10	250 gpm x 10 min = 2500 gal

While not explicitly stated in the NFPA 403 Annex A, the rationale for these flow rates are based on standard firefighting hose lines of 227 to 473 liters per minute (60 and 125 gpm). For CATs 8 to 10, the judgment of the committee was that two hand lines might be needed. The 10-minute duration required for most categories was also based on judgment.

3.4 CURRENT CATEGORIZATION OF AIRPORTS.

Airport categories are useful to translate aircraft critical areas and associated primary agent application rates into total quantities of agent needed and eliminate the need to individually calculate the TCA/PCA of each aircraft. NFPA, FAA, and ICAO all use airport categories or FAA indices. Throughout this report, the term category is generally used for analysis relating to airport size. When a discussion is related to CFR requirements, this section should be referenced for the detailed differences between NFPA categories and FAA indices.

From 1950 to 1960, aircraft were originally categorized by gross weight. Later, NFPA changed the categorization to the length of the aircraft plus the passenger capacity; this became obsolete with the introduction of wide-body aircraft. In 1968, ICAO and NFPA changed to the length-only concept, dividing the aircraft into eight indices according to the type of operation.

1. Light, single-engine aircraft
2. Light, twin-engine aircraft
3. Large, twin-engine general aviation aircraft
4. Small feeder line turbo props
5. Local service two-engine jets, DC-9, B-737
6. Transcontinental four-engine and three-engine jets, DC-8, B-727
7. Medium intercontinental wide body, DC-10, L-1011
8. Large intercontinental B-747 wide body

The last five categories (indices) are used for FAA certification purposes, and essentially remain the same as of this writing. Revisions have been made to the ICAO and NFPA categories. Section 3.5 discusses the current categories from NFPA 403-2009 and the associated TCA and PCA. Index E (CAT 9) is currently the highest FAA index. Part 139 does not explicitly designate maximum aircraft widths; however, AC 150/5210-6D [5] references NFPA 403 [1] TCA/PCA criteria.

Representative aircraft associated with airport categories are also discussed in section 3.5, as provided in NFPA 403 Annex A. A more complete list of aircraft characteristics for CATs 5-10 aircraft is provided in appendix A of this report.

Table 3 shows the number of airports in the U.S. listed by NFPA 403 category and FAA index.

Table 3. Number of Airports by NFPA 403 Categories and FAA Indices

Airport ARFF Index (Index/Category)	Number of Airports
A (1-5)	134
B (6)	96
C (7)	82
D (8)	30
E (9-10)	24

3.5 CURRENT QUANTITY OF FIREFIGHTING AGENTS.

Tables 5.3.1(a) and (b) of NFPA 403-2009, reproduced in tables 4 and 5, provide the current requirements for primary and secondary agents. The U.S. customary units are shown in table 6.

Table 4. Airport Category by Overall Length and Width of Aircraft [1]

Airport CAT U.S.			Overall Length of Aircraft up to but Not Including		Maximum Exterior Width up to but not Including		TCA	PCA
NFPA	FAA	ICAO	m	ft	m	ft	ft^2	ft^2
1	A*	1	9	30	2	6.6	1,356	904
2	A*	2	12	39	2	6.6	1,765	1,177
3	A*	3	18	59	3	9.8	3,275	2,183
4	A	4	24	78	4	13.0	5,360	3,573
5	A	5	28	90	4	13.0	9,959	6,639
6	B	6	39	126	5	16.4	14,379	9,586
7	C	7	49	160	5	16.4	18,265	12,177
8	D	8	61	200	7	23.0	24,156	16,104
9	E	9	76	250	7	23.0	30,201	20,134
10		10	90	295	8	25.0	36,231	24,154

Notes:

(1) Airport categories are used in the calculations to eliminate the need for calculating specific quantities of firefighting agents for each type of aircraft.

(2) Although only water is normally necessary for interior hand line attack, logistically and tactically it should be discharged as foam and is therefore included in the quantities of water necessary for foam production.

(3) TCA calculated based on NFPA 403 “up to and including” length minus 0.2 ft and width minus 0.1 ft.

* It is FAA Category A if the airport has scheduled service with aircraft that have more than nine passenger seats.

Table 5. Representative Aircraft by Airport Categories [1]

Airport CAT	Aircraft Type	Overall Fuselage Length		External Fuselage Width	
		m	ft	m	ft
1	Beech Bonanza 35	8.01	26.33	1.07	3.05
	Cessna 206	8.20	26.90	1.22	4.00
	Mooney M-20	7.60	24.90	1.13	3.70
2	Cessna 414	11.06	36.30	1.43	4.70
	Piper Aerostar	10.60	34.80	1.19	3.90
	Piper Cheyenne 2	10.60	34.70	1.31	4.30
3	Beech 1900	17.65	57.90	1.40	4.60
	Beech Kingaire 200	13.35	43.80	1.77	5.80
	Lear 55	16.80	55.20	1.58	5.20
4	D.H. Dash 8	22.25	73.00	2.69	8.83
	Fokker F-27 2000	23.56	77.30	2.70	8.86
	Short 360	21.60	70.90	1.95	6.40
5	ATR 72	27.16	89.10	2.87	9.40
	D.H. Dash 7	24.60	80.70	2.59	8.50
	Gulfstream 3	25.30	83.10	2.71	7.40
6	BAE 146-200	28.55	93.67	3.56	11.68
	Airbus A-320 300	37.57	123.27	3.95	12.96
	Boeing 737-300	33.40	109.60	3.76	12.34
7	Boeing 727-200	46.68	156.16	3.76	12.34
	Boeing 757	47.34	155.30	3.96	13.00
	M.D. 88	45.10	147.90	3.34	10.96
8	Airbus A-300	53.61	175.90	5.64	18.50
	Boeing 767-300	54.96	180.30	5.03	16.50
	D.C. 10-40	55.54	182.23	6.02	19.75
	Lockheed L-1011	54.44	178.62	5.97	19.59
9	Airbus A-340 300	63.67	208.90	5.64	18.50
	Boeing 747-200	70.40	230.99	6.50	21.40
	Concorde	62.10	203.75	2.87	9.42
	M.D. 11	61.24	200.90	6.07	19.90
10	Airbus Industrie A380/800	73	239.5	7.14	23.4
	Airbus Industrie A380/900	79.4	260.5	7.14	23.4
	Antonov AN-225	84.10	275.70	6.40	20.90

Table 6. Firefighting Agents, Discharge, and Response Capabilities in U.S. Customary Units [1]

Airport CAT	Resp. Phases	Resp. Capability (sec)	AFFF		Fluoroprotein or FFFP		Protein Foam		Comp. Agents[a]	
			Req. Water (U.S.)	Disch. Capab. (gpm)	Req. Water (U.S.)	Disch. Capab. (gpm)	Req. Water (U.S.)	Disch. Capab. (gpm)	Quant. (lb)	Disch. (lb/sec)
	Q_1[b]	120	120	120	160	160	180	180	100	5
1	Q_2[c]		0		0		0			
	Q_3[d]		0		0		0			
TOTAL			120		160		180			
	Q_1[b]	120	157	157	213	213	236	236	200	5
2	Q_2[c]	180	43		57		64			
	Q_3[d]		0		0		0			
TOTAL			200		270		300			
	Q_1[b]	120	285	285	392	392	438	438	300	5
3	Q_2[c]	180	85		118		132			
	Q_3[d]	240	300	60	300	60	300	60		
TOTAL			670		810		870			
	Q_1[b]	120	468	468	646	646	715	715	300	5
4	Q_2[c]	180	272		374		415			
	Q_3[d]	240	600	60	600	60	600	60		
TOTAL			1,340		1,620		1,730			
	Q_1[b]	120	863	863	1,194	1,194	1,331	1,331	450	5
5	Q_2[c]	180	647		896		999			
	Q_3[d]	240	1,250	125	1,250	125	1,250	125		
TOTAL			2,760		3,340		3,580			
	Q_1[b]	120	1,245	1,245	1,725	1,725	1,920	1,920	450	5
6	Q_2[c]	180	1,245		1,725		1,920			
	Q_3[d]	240	1,250	125	1,250	125	1,250	125		
TOTAL			3,740		4,700		5,090			
	Q_1[b]	120	1,585	1,585	2,192	2,192	2,437	2,437	450	5
7	Q_2[c]	180	2,045		2,828		3,143			
	Q_3[d]	240	1,250	125	1,250	125	1,250	125		
TOTAL			4,880		6,270		6,830			
	Q_1[b]	120	2,095	2,095	2,901	2,901	3,222	3,222	900	10
8	Q_2[c]	180	3,185		4,409		4,898			
	Q_3[d]	240	2,500	250	2,500	250	2,500	250		
TOTAL			7,780		9,810		10,620			

Table 6. Firefighting Agents, Discharge and Response Capabilities in U.S. Customary Units [1] (Continued)

Airport CAT	Resp. Phases	Resp. Capability (sec)	AFFF		Fluoroprotein or FFFP		Protein Foam		Comp. Agents[a]	
			Req. Water (U.S.)	Disch. Capab. (gpm)	Req. Water (U.S.)	Disch. Capab. (gpm)	Req. Water (U.S.)	Disch. Capab. (gpm)	Quant. (lb)	Disch. (lb/sec)
	Q_1[b]	120	2,619	2,619	3,626	3,626	4,030	4,030	900	10
9	Q_2[c]	180	4,451		6,164		6,850			
	Q_3[d]	240	2,500	250	2,500	250	2,500	250		
TOTAL			9,570		12,290		13,380			
	Q_1[b]	120	3,195	3,195	4,424	4,424	4,915	4,915	900	10
10	Q_2[c]	180	6,069		8,405		9,338			
	Q_3[d]	240	5,000	500	5,000	500	5,000	500		
TOTAL			14,260		17,830		19,250			

[a]The minimum quantity is based on ISO-qualified potassium bicarbonate. Powder can be substituted by a listed agent exceeding the performance of potassium bicarbonate.
[b]Quantity of water for foam production for initial control of the pool fire.
[c]Quantity of water for foam production to continue control or fully extinguish the pool fire.
[d]Water available for interior firefighting.
ISO = International Standards Organization

Table 7, derived from the current edition of NFPA 403 [1], shows required water quantities for AFFF for each airport category, based on equation 2.

Table 7. The NFPA 403 Constituents of Q for AFFF

Airport CAT	Q_1 (gal)	Q_2 (gal)	Q_3 (gal)	Q (gal)
1	120	0	0	120
2	157	43	0	200
3	285	85	300	670
4	468	272	600	1,340
5	863	647	1250	2,760
6	1245	1245	1250	3,740
7	1585	2045	1250	4,880
8	2095	3185	2500	7,780
9	2619	4451	2500	9,570
10	3195	6069	5000	14,260

It should be noted that both NFPA and ICAO express Q as "water for foam production," which essentially equals gallons of unexpended foam solution.

Table 9-2 of ICAO Annex 14-2004 contains similar requirements and is reproduced here as table 8.

Table 8. The ICAO Minimum Usable Amounts of Firefighting Agents [3]

Aerodrome CAT (1)	Foam Meeting Performance Level A		Foam Meeting Performance Level B		Complementary Agents Dry[2] Chem. Powders (kg) (6)
	Water[1] (L) (2)	Discharge Rate Foam sol/min. (L) (3)	Water[1] (L) (4)	Discharge Rate Foam sol/min. (L) (5)	
1	350	350	230	230	45
2	1,000	800	670	550	90
3	1,800	1,300	1,200	900	135
4	3,600	2,600	2,400	1,800	135
5	8,100	4,500	5,400	3,000	180
6	11,800	6,000	7,900	4,000	225
7	18,200	7,900	12,100	5,300	225
8	27,300	10,800	18,200	7,200	450
9	36,400	13,500	24,300	9,000	450
10	48,200	16,600	32,300	11,200	450

Note 1. The quantities of water shown in columns 2 and 4 are based on the average overall length of aeroplanes in a given category. Where operations of an aeroplane larger than the average size are expected, the quantities of water would need to be recalculated. See the Airport Services Manual, Part 1, for additional guidance.

Note 2. Any other complementary agent having equivalent firefighting capability may be used.

Part 139 does not have a summary table but describes the requirements in its text language (see section 3.5.3 of this report for this summary). AC 150/5210-6D, which can be used to comply with Part 139, states that numerical quantities can be found in NFPA 403.

3.5.1 Quantification of Q_1 and Q_2.

The current NFPA 403 Q_2 requirements, assuming AFFF as the primary agent as a percentage of Q_1, are shown in table 9.

Q_2, as a percentage of overall Q, varies from 0% to 46%. Similarly, Q_2, as a percentage of Q_1, varies from 0% to 190%. For airport categories below CAT 5, Q_2 is less than Q_1 (table 6). Q_2 is equal to Q_1 for CAT 6 (table 6). For categories greater than 6, which would encompass airports supporting aircraft larger than B-737s or A320s, Q_2 exceeds Q_1.

The ICAO Airport Services Manual does not show a breakdown of the specific components comprising total Q. However, "Q_2 as a percentage of Q_1" is stated to be identical to that used by the NFPA. Section 2.4.10 of the ICAO Airport Services Manual provides the percentages of Q_1 used to derive Q_2, which compare to the NFPA Q_2 volumes.

Table 9. The NFPA 403 Q_2 Quantities as a Function of Q_1

Airport CAT	Q_2 (gal)	Q_2 as a Percentage of Q_1
1	0	0
2	43	27
3	85	30
4	272	58
5	647	75
6	1245	100
7	2045	129
8	3185	152
9	4451	170
10	6069	190

Current regulations were also reviewed relative to requirements for Q_2 (see section 3.5.3, table 9). Part 139 establishes mandatory legal requirements for FAA-certificated airports in the U.S. Relative to foam agent quantities, Part 139 requirements have always been lower than those in NFPA 403 and ICAO Annex 14. No explicit rationale for this substantial difference has been identified. An analysis in section 6.2.1.1 indicates that the Part 139 minimums may be directly related to the aircraft footprint, which is the fuselage length times the wingspan. The concept that Part 139 quantities equal Q_1 is substantiated in an historical review of agent quantities [24].

For many years, an acceptable methodology for complying with Part 139 has been available through AC 150/5210-6C. Prior to 2004, agent guidelines in the AC were less than those in NFPA 403. The 2004 version, AC 150/5210-6D [5], allows firefighting agents, quantities, and discharge and response capabilities for each index referenced in NFPA 403, Chapter 5, Table 5.1.3(b), to be used to comply with 14 CFR 139.315. NFPA Q_1 and Q_2 (and also Q_3) quantities can be used to comply with Part 139.

There are indications that many U.S. airports exceed the Part 139 requirements. Section 4.10 provides details on this.

3.5.2 Quantification of Q_3.

Section 5.3.1 of NFPA 403 defines Q_3 as the water for interior firefighting. The Q_3 quantities and discharge rates are shown in table 6. Discharge at the interior must be available in the prescribed time.

The following changes pertaining to Q_3 were made in the 2003 edition of NFPA 403.

- The prescribed time (240 seconds) for beginning the application of Q_3 was added.

- The Q_3 flow rate was increased to 500 gpm for a CAT 10 airport. Retaining the same 10-minute duration of flow resulted in an increase of Q_3 for a CAT 10 airport from 2500 to 5000 gallons. This increase in Q_3 caused a corresponding increase in overall Q, bringing the total required quantities to their current level (table 7).

- Staffing requirements were added, with the provision (Section 8.1.2.2 of NFPA 403) that a task and resource analysis shall be performed to determine additional staffing levels. Additionally, the following statement appearing in Section 8.1.3 of NFPA 403.

  > "Responding units shall include personnel trained and equipped for cabin interior firefighting and shall demonstrate the ability to apply agent to the interior of the aircraft within 4 minutes of the alarm."

- A new Annex D to NFPA 403 describes the procedures to be followed while performing a Task and Resource Analysis, including an assessment of the ability to "extinguish an internal fire and rescue trapped personnel," which relates to entry with hose lines. As part of the analysis, the new Annex D requires that worst-case scenarios be postulated and specific timelines and procedures be developed for those postulated scenarios to identify and quantify the manpower needed to handle such incidents should they actually occur. Section D.13 presents a scenario that can be used to determine the capability for interior firefighting and the delivery of Q_3.

Part 139 and ICAO do not include Q_3. AC 150/5210-6D recognizes the Q_3 quantities by referencing NFPA 403 Table 5.3.1(b) as an acceptable means to comply with 14 CFR 139.315.

3.5.3 Comparisons of Total *Q* Requirements.

Table 10 shows a comparison between total *Q* requirements for airport categories, as specified in current NFPA, ICAO, and FAA documents.

Certain issues are worthy of further discussion: the differences between NFPA and ICAO requirements, the differences between Part 139 and FAA AC requirements, and remission factors inherent in Part 139 requirements and ICAO.

Table 10. Comparison of NFPA, ICAO, and FAA Minimum Water Requirements for Total AFFF Solution Quantities

NFPA/ICAO CAT	FAA Index	NFPA *Q* (gal)	ICAO *Q*	FAA/FAR *Q*	FAA/AC *Q*	NFPA GPM	ICAO GPM	FAA/FAR GPM	FAA/AC GPM
1	A*	120	60	Note (1)	120	120	60	NR**	120
2	A*	200	180	Note (1)	200	160	140	NR**	160
3	A*	670	320	Note (1)	670	280	240	NR**	280
4	A	1,340	630	Note (1)	1,340	470	470	NR**	470
5	A	2,760	1430	Note (1)	2,760	860	790	NR**	860
6	B	3,740	2070	1500 (2)	3,740	1250	1060	500	1250
7	C	4,880	3200	3000 (3)	4,880	1590	1400	1000	1590
8	D	7,780	4810	4000 (4)	7,780	2100	1900	1200	2100
9	E	9,570	6420	6000 (5)	9,570	2620	2380	1200	2620
10	E	14,260	8530	6000 (5)	14,260	3200	2960	1200	3200

NFPA: Requirements of 2009 edition of NFPA 403
ICAO: Requirements of ICAO Annex 14, "Aerodromes," Volume 1, Fourth Edition, July 2004, performance level B foam
FAA/CFR: Minimum legal requirements for FAA-certificated airports per Part 139
FAA/AC: FAA recommended levels per AC 150/5210-6D of July 28, 2004 (6D adopted NFPA 403)

Notes:
(1) 500 lb of powder/halon or twin agent unit (TAU) with 450-lb potassium bicarbonate (PKP) and 100-gal AFFF solution
(2) One vehicle with 1500 gal of water and 500 lb of powder/halon, or two vehicles (one meeting note (1) and one with 1500 gal water)
(3) Two vehicles (one with 1500 gal of water and one with 1500 gal of water and 500 lb of powder/halon), or three vehicles (one per note (1) and two totaling 3000 gal of water)
(4) Three vehicles (one per note (1) and two totaling 4000 gal of water)
(5) Three vehicles (one per note (1) and two totaling 6000 gal of water)

*FAA Index A if scheduled aircraft has nine or more passengers.
**Under FAA/CFR, foam turrets are not mandatory for airports smaller than Index B.

<u>3.5.3.1 Comparison of NFPA and ICAO</u>.

The difference between the NFPA and ICAO is attributable to three factors:

1. ICAO does not have a requirement for Q_3, foam/water for interior firefighting.

2. The Q_1 calculations are based on different assumed fuselage lengths within each category. NFPA Q_1 calculations are based on the maximum length within each category, while ICAO Q_1 calculations are based on the average fuselage length within each category.

3. With Q_1 being higher in NFPA, Q_2 is also higher since Q_2 is a fixed percentage of Q_1 within each category.

Table 11 shows the difference between current NFPA and ICAO requirements.

Table 11. The NFPA vs ICAO *Q* Quantities

NFPA/ICAO CAT	NFPA *Q* (gal)	ICAO *Q* (gal)
4	1,340	630
5	2,760	1430
6	3,740	2070
7	4,880	3200
8	7,780	4810
9	9,570	6420
10	14,260	8530

The following example for airport CAT 8 describes the difference between NFPA and ICAO. Under the airport categorization common to both NFPA and ICAO, CAT 8 covers aircraft whose fuselage length varies from "160 feet up to, but not including, 200 feet," ICAO would base their Q_1 calculation on an assumed fuselage length of 180 feet, the midpoint of the range; the ICAO Q_1, based on L = 180, would yield Q_1 = 1910 gal; and since Q_2, under both ICAO and NFPA methods, is equal to 1.52 times Q_1, the ICAO Q_2 becomes 2900 gal. Since ICAO does not have a requirement for Q_3, the overall Q for ICAO is based on $Q = Q_1 + Q_2$, which for CAT 8 becomes $Q = 1910 + 2900 = 4810$ gal, the same amount as shown in table 10.

In contrast, NFPA would base their Q_1 calculation on the maximum length within the range. A review of all NFPA Q_1 amounts revealed that in actuality, the NFPA uses a length of 0.2 feet less than the "up to, but not including," number, which for CAT 8 would be 199.8 feet. Using the NFPA-assumed length yields a Q_1 of 2094 gallons. Q_2, which is 1.52 x Q_1, becomes 3182 gallons. For CAT 8, NFPA requires a Q_3 of 2500 gallons. Thus, the NFPA Q for CAT 8 becomes

$$Q = Q_1 + Q_2 + Q_3 = 2094 + 3182 + 2500 = 7776 \text{ gallons} \qquad (6)$$

This total is rounded off to the 7780 gallons in table 11.

The above example also shows that there is a factor of safety built into the NFPA Q, since, in almost all cases, the aircraft used to determine any category has an actual fuselage length shorter than the top end of the range (see appendix A and section 5.1). Consider the example of a CAT 8 airport where the largest serviced aircraft is an Airbus A-300, which has an actual length of 175.9 feet and an actual width of 18.5 feet. If the Q_1 calculation was based on the actual dimensions, instead of the assumed top end of the category range, the resultant Q would be 6980 gallons, about 10% less than the 7780 gallons requirement in table 11. (It should be noted that the NFPA also bases their Q_1 calculation on an assumed maximum width, actually the "up to, but not including width" minus 0.1 feet).

Correspondingly, a margin of safety exists in the ICAO requirement only if the largest aircraft in any category is less than the midpoint of the category range. ICAO recommends that an airport that serves aircraft larger than the average category size have increased agent quantities for that aircraft size.

3.5.3.2 Comparison of Part 139 and AC 150/5210-6D.

As shown in table 10, there is a substantial difference between the requirements of Part 139 and the latest AC 150/5210-6D on firefighting agents. Part 139 establishes the minimum legal requirement for FAA-certificated airports in the U.S. The AC alternatively provides an acceptable methodology for complying with Part 139. For agent quantities, Table 5.3.1(b) in reference 1 can be used to comply with 14 CFR 139.315. While no explicit technical rationale for the current Part 139 requirements were identified in the analysis literature search, it is likely based on the agent quantity needed to control a fire covering an aircraft footprint (fuselage length times the wingspan), see section 6.2.1.2.

The disparity between the Part 139-required and FAA-recommended *Q* amounts is especially significant when "remission" of category is permitted.

3.5.3.3 Remission Factor.

Remission is an allowable reduction in airport category where the frequency of aircraft movements at an airport falls below an established frequency threshold. Both Part 139 and ICAO permit remission, NFPA does not.

ICAO Annex 14, Section 9.2.3, states

> "where the number of movements of the airplanes in the highest category normally using the aerodrome is less than 700 in the busiest consecutive three months, the level of protection provided shall be not less than one category below the determined category" [3].

Note that either a takeoff or a landing constitutes a "movement."

14 CFR 139.315 states

> "When there are fewer than five average daily departures of the largest air carrier aircraft serving the airport, the index required for the airport will be the next lower index group than the index group prescribed for the longest aircraft" [2].

Even though ICAO uses "movements" and Part 139 uses "departures," these factors are very similar if one considers that an aircraft "departure" requires a previous "landing," meaning that the Part 139 threshold of "five average daily departures" can be considered as ten aircraft "movements" per day. The ICAO threshold for remission is 700 movements within 3 months, which equates to an average of almost eight "movements" per day and is very close to the Part 139 threshold.

Remission under Part 139 can be very significant, especially if remission allows an index reduction from Index B to Index A (which, in NFPA and ICAO terminology, would be a reduction from CAT 6 to CAT 5). Consider, for example, an FAA Index B (CAT 6) airport where the category is based on an Airbus A-320 aircraft. If, on a daily basis, that aircraft had only four "departures" (which in reality probably means four landings and four takeoffs), then remission would be permitted back to Index A (CAT 5). As noted in table 10, for Index A, Part 139 only requires either "500 lb of powder/halon or a TAU with 450 lb PKP and 100 of AFFF." This would be for an aircraft that carries 7000 gallons of fuel, is 124 feet long, and has 164 passengers onboard.

3.6 NUMBER OF VEHICLES AND RESPONSE TIME.

3.6.1 Number of Vehicles.

NFPA 403 has the most stringent requirements related to the number of ARFF vehicles required to provide the primary agent (table 12). ICAO has one less vehicle required for CATs 5, 9, and 10. Part 139 requirements are slightly different than NFPA requirements (minimum of three vehicles for Index E).

Table 12. Minimum Number of ARFF Vehicles

Airport CAT/Index	Number of Vehicles		
	NFPA	ICAO	FAA
1/A	1	1	1
2/A	1	1	1
3/A	1	1	1
4/A	1	1	1
5/A	2	1	1
6/B	2	2	2
7/C	3	2	3
8/D	3	3	3
9/E	4	3	3
10/E	4	3	3

3.6.2 Response Times.

A summary of response times is shown in table 13. Response time is the total period of time from receipt of alarm until the first ARFF vehicle arrives at the location and is ready to discharge agent. NFPA 403, Sections 9.1.3 and 9.1.4, requires that the demonstrated response time of the first-responding vehicle to reach any point on the operational runway shall be 2 minutes or less, and to any point remaining within the on-airport portion of the rapid-response area to be no more than 2 1/2 minutes, in optimum visibility and surface conditions. NFPA 403 Section 3.3.11.3 defines the rapid-response area as a rectangle that includes the runway and the surrounding area extending to a width of 500 ft (150 m) outward from each side of the runway centerline. It extends to a length of 1650 ft (500 m) beyond each runway end, but not beyond the airport property line. Other ARFF vehicles necessary to achieve the agent discharge rate listed in table 6 must arrive at intervals not exceeding 30 seconds.

Table 13. The ARFF Response Times for Runway Accidents

Standard/Regulation	Response Time (minutes)	Response Point
NFPA 403	2	Any point on operational runway
Part 139	3	Midpoint of farthest runway
ICAO Requirement	3	Any point on operational runway
ICAO Recommendation	2	Any point on operational runway

ICAO and Part 139 allow a 3-minute response time to any point on the runway and to the midpoint of the farthest runway, respectively.

These requirements apply to "unannounced emergencies," which are cases where the accident occurs without prior declaration of an in-flight emergency. There would be no warning and no strategic prepositioning of ARFF vehicles.

For Part 139, the ARAC report [8] recommended changing the response point to the "farthest end of the farthest runway." This is equivalent to the NFPA "any point on the operational runway."

3.7 SUMMARY OF CURRENT METHODOLOGY.

The development of the current methodology and basis of current agent requirements is documented. The performance goals of NFPA 403 are embodied in the scope, definitions, and annex material. This has resulted in requirements based on the TCA/PCA concept. This concept evolved from fire test data, hazard analysis, and actual crash data. There appears to be a sound technical basis for this methodology. Maintaining the fuselage integrity of an aircraft involved in an accident appears to be the primary basis of the Q_1 agent quantity that must be immediately applied to a fire. The idea of cutting a rescue path does not appear to relate to the Q_1 agent quantity. Rather, Q_2 quantity provides final fire extinguishment so occupants can move away from the accident area. The agent quantities for NFPA 403 are more than those required by ICAO, and substantially more than those required by Part 139. The FAA, through AC 150/5210-6D, provides a method to allow NFPA 403 agent quantities to be used to comply with the legally mandated 14 CFR 139.315 agent requirements. Response times for ICAO and Part 139 are also greater than NFPA 403.

4. AIRPORT ACCIDENT REVIEW.

4.1 OVERVIEW.

A review of airport incidents was performed to establish trends, qualitative probabilities of accident characteristics, potential crash fire threat characteristics, effectiveness of ARFF response, and potential limitations of ARFF equipment and capabilities. The intent was to judge the fire area of representative incidents involving exterior fuel fires and to assess the amount of firefighting agent used. As expected, both characteristics were difficult to quantify, but some useful data was identified. Finally, a number of major incidents were reviewed to identify attributes of fire size, time for occupant evacuation/survival, and the time and effectiveness of ARFF response.

The exact definition of a "survivable" incident has varied over time. Sarkos, in developing the rationale for a full-scale, wide-body fire test article, described survivable accidents as those in which one or more occupants survive the impact [15]. The National Transportation Safety Board (NTSB) has provided a more detailed definition of a survivable accident as follows:

> "An accident in which the forces transmitted to the occupant(s) through the seat and restraint system do not exceed the limits of human tolerance to abrupt accelerations and in which the structure in the occupants' immediate environment remains substantially intact to the extent that a livable volume is provided for the occupants through the crash sequence" [25].

This definition was cited in the NTSB's 1981 study on cabin safety in large transport aircraft [25]. According to the study, the definition was (1) developed using aviation crash injury research by Cornell University and aviation safety engineering and research by the Flight Safety Foundation and (2) used in the Aircraft Crash Survival Design Guide, which was prepared by the U.S. Army Research and Technology Laboratories along with other federal agencies. The definition has been used by the NTSB since that time and was used to determine the survivability of accidents involving 14 CFR Part 121 U.S. air carrier operations from 1983 to 2000 [26].

As evidenced in the loss review, the effectiveness of ARFF response is dependent on whether the structural integrity of an aircraft fuselage is compromised. If there is structural damage from the crash or penetration from an exterior fire exposure, the cabin interior "livable volume" may be rapidly compromised.

As an introduction to the current accident review, the accident evaluation included in the Gage report [6] was reviewed. They analyzed old, detailed surveys of aircraft accidents up to 1963. This data indicated that the conventional rescue concept (i.e., guide and remove occupants from the aircraft) was applicable to crew-only aircraft. In passenger transports, the occupants either escaped themselves, or, unless the fire was extinguished, they perished. They noted this escape, however, may have been aided or made possible by fire suppression activities.

The Gage report's updated survey of accidents up to 1971 did not indicate any significant variation from the previous conclusion. The updated survey of aircraft fire accidents focused on those with low-impact forces that occurred on or adjacent to the airport, i.e., potentially survivable. A total of 49 incidents in the time period from 1960 to 1970 were evaluated; this did not cover all fire incidents in that period, only those for which a reasonable amount of information was available. In these accidents, the occupants escaped without aid in 9 incidents, the fire service may have enabled or aided the escape in 13 incidents, there was no escape in 16 incidents, and the escape situation was indeterminate in 10 incidents. A conventional rescue was identified in only one of these accidents. These incidents are provided in the Gage report and in appendix B of this report.

The Gage report identified the primary function of ARFF services as the preservation of life, with the preservation of property a secondary, but important, function. They considered the use of the term rescue for these functions as unfortunate since the common connotation of rescue implies the physical guidance or removal of an individual from a position of danger. However, if the function of life preservation is considered, or rescue is defined as removing either the endangered or the danger, the crash fire function is clarified. This life preservation function may include, but is not limited to, the following.

- Guide, remove, or transport occupants from an endangered aircraft
- Reduce the fire intensity to permit the occupants to escape
- Extinguish the fire to remove the danger
- Establish a path through the fire for escape

The Gage report considered the conventional rescue concept as probably the most infrequent of these functions in actual incidents.

4.2 AIRCRAFT ACCIDENT SURVIVABILITY.

The NTSB collects incident data and investigates major accidents. In 2001, the NTSB published a review related to the survivability of accidents over the time period from 1983 to 2000 [26]. The NTSB annually publishes a review of aircraft accident data for U.S. Air Carrier Operations, which summarizes the degree of occupant injury by aircraft damage. The annual publications had not, in the past, analyzed the issue of survivability in detail. The purpose of the survivability report [26] was to examine aircraft occupant survivability for air carrier operations in the U.S. This was because the majority of the NTSB's survival factor investigations are conducted in connection with accidents involving air carriers. More survivability data are available for air carrier operations than are available for commuter and general aviation operations. An accident is defined as an occurrence associated with the operation of an aircraft in which a person suffers death or serious injury, or in which the aircraft receives substantial damage. The report also examined cause-of-death information for the most serious of the air carrier accidents.

It was found that, in all accidents involving air carrier operations from 1983 through 2000, 51,207 occupants (95.7%) survived and 2,280 died. In 528 (93%) of the 568 accidents, more than 80% of the occupants survived. Because in the majority of air carrier accidents the occupants' survival was never threatened, the NTSB focused on the survivability of serious accidents. They defined a serious accident as one that involved a fire (pre- or postcrash), had at least one serious injury or fatality, and had either substantial aircraft damage or complete destruction. In 26 serious accidents, 55.6% (1524 out of 2739) of the occupants survived. In 12 of those incidents, more than 80% of the occupants survived. Of the nonsurvivors, 716 died from impact, 340 died from unknown causes, 131 died from fire/smoke, and 28 died from other causes. There was nearly five times more impact than fire fatalities.

An important distinction between impact deaths and fire deaths is that impact deaths typically occur as a result of aircraft impact forces, whereas fire deaths typically occur after impact. The high proportion of impact-to-fire fatalities is the result of the inclusion of a number of nonsurvivable accidents in the subset. For an accident to be deemed survivable, the forces transmitted to occupants through their seat and restraint system cannot exceed the limits of human tolerance to abrupt accelerations, and the structure in the occupants' immediate environment must remain substantially intact to the extent that a livable volume is provided for the occupants throughout the crash. Using this definition of a survivable accident, the NTSB examined accident reports and determined that 7 of the 26 serious accidents were not survivable because of the impact forces.

In examining 19 of the 26 serious accidents that were at least partially survivable, 1523 (76.6%) of the 1988 occupants in these accidents survived. It was determined that 306 of the occupants died from impact, 131 (6.5%) died from fire, and 28 (1.4%) died from other causes. In the survivable serious accidents, over twice as many occupants died as a result of impact forces than as a result of fire. As with all 14 CFR Part 121 accidents, the most likely outcome for the serious survivable accidents is that most occupants survive. In 12 of the 19 serious survivable accidents (63.2%), more than 80% of the occupants survived. In 2 of the 19 serious survivable accidents (10.5%), fewer than 20% of the occupants survived.

These data indicate a high degree of survivability for even the most serious accidents. It also indicates that, while impact is the most likely cause of death, fire is a factor. No attempt was made to analyze the attributes of fire-induced deaths (e.g., thermal burns or smoke inhalation) for the 1983-2000 NTSB data sets, which included in-flight accidents and accidents involving crashes remote from airports. Fire-related threats are evident in an analysis of accidents at or near airports, as described in section 4.4.

4.3 LOCATION OF ACCIDENTS.

For a crash scenario assessment and ARFF effectiveness analysis, the accidents described in section 4.2 must be located at or near an airport. A brief review of accidents was performed to qualitatively establish the likelihood of an accident or incident occurring where ARFF could be a factor. Two sources of information were referenced (1) data from the FAA [27], as summarized by the ARAC ARFFRWG Committee and (2) data provided for this project by the Air Lines Pilots Association, International (ALPA) [28].

The ARAC committee provided a review and summary of the FAA data, which is provided here. Accidents and incidents were categorized as follows:

- Undershoot: During landing, the aircraft touches down within 2000 feet of the runway end.
- Landing Off: During landing, any part of the aircraft's landing gear touches down off the runway after passing the runway threshold.
- Veer-Off: During either landing rollout or takeoff roll, the aircraft runs off the side of the runway.

- Overrun: During landing rollout or takeoff roll, the aircraft runs off the end of the runway, or runs off the side of the runway but comes to rest beyond the departure end.

- Other: During landing, the aircraft impacts the ground more than 2000 feet from the runway threshold. During takeoff, the aircraft becomes airborne, but then impacts the ground prior to making airborne power reduction, or reaching VFR pattern altitude.

For each event, the aircraft location was recorded in terms of the distance along the runway centerline or extended centerline (X distance) and the perpendicular distance from the centerline or extended centerline (Y distance).

While there were over 500 accidents and incidents recorded, only 246 were "identified as relevant." (It was assumed for the purpose of this discussion, the accidents and incidents, where the "X" and "Y" distances were unknown, were not included in the relevant 246 accidents.) For those accidents and incidents that were relevant, this analysis divided the runway into quarters (e.g., 0% to 25% being the first quarter from the runway end, 25% to 49% being the second quarter, etc.). The first and fourth quarters of the runway were categorized as the "runway end." With that premise, the following figures were found:

- Undershoots: 18

- Landings Off: 7

- Veer-Off: 23

- Overruns: 33

  Of the 33 overruns that came to rest within 1600 ft of the runway end, 30 stopped within 1000 feet of the end.

- Other: 87

Of the 246 relevant accidents and incidents recorded in this study, 52 did not have an "X" factor (unknown), which meant the ARFFRWG could not determine where the aircraft came to rest in relationship to the runway's length. This left 194 accidents and incidents that could be used for this analysis; i.e., attempting to determine where accidents/incidents occurred in relation to the runway.

Of the 194, 150 or 77.7% qualified as being at, or before/beyond, the end of the runway.

Based on the information summarized above, the ARFFRWG concluded that this report provided sufficient support to warrant moving the notional endpoint for response-planning purposes to the farthest end of the farthest runway, as opposed to the runway's midpoint.

Information provided by ALPA graphically shows incident and accident history (the time period is not identified). This data is provided in appendix C. It is not clear how ALPA normalized the data for different runway lengths. The data show that most veer-offs occurred within 500 feet of either side of the runway[3]. Many incidents and accidents occurred near the end of the runway, within 1000 feet of the end, and beyond the end of the runway (up to 2 miles before the landing edge and 1 mile beyond the takeoff edge). While specific data and number of accidents are not provided, a substantial percentage of accidents occurred in the approach and takeoff areas. This suggests that ARFF may respond well beyond the area identified by the FAA (runway safe area) or NFPA 403 (rapid-response area).

4.4 THE ARFF RESPONSE TO AIRPORT ACCIDENTS.

Survivability and impact data clearly show that ARFF can be expected to respond to survivable crashes that potentially involve fire at or near the airport. A more detailed review of NTSB data and information in the public domain related to ARFF response was performed. A survey of aircraft fire incidents from March 1992 to the time of this writing was conducted using the NTSB online database of accident reports (http://www.ntsb.gov/ntsb/query.asp). Information on individual events was supplemented by accident reports, media reports, video, and photographs. The criteria for the search included incidents or accidents that

- were at or within about 1 mile of the airport
- were fire occurrences

While the emphasis was on Part 121 Carriers, Part 139, Part 91 (general aviation), and foreign carriers were included because ARFF responded to some of these incidents (i.e., at large airports), and the data were considered valuable for analysis. Other situations, mostly outside the U.S. where there was no NTSB formal investigation, were also included when data were available.

The data were evaluated in terms of the aircraft type, number of occupants, survivors, aircraft damage, location of impact with respect to the airport, and ARFF response. Only accidents or incidents that involved fire and occurred at or within approximately 1 mile of the airport were included. In-flight fires were only included if the aircraft landed and ARFF responded.

Since only accidents in which ARFF responded were included in the distilled data, there were some anomalies. For example, the Quincy, Illinois, runway collision (November 19, 1996) was not included because there were no ARFF personnel at the airport to respond.

A total of 1230 accidents and incidents were reviewed. Of those incidents, 73 were identified in which ARFF responded to an actual fire. These occurrences are listed separately in appendix D.

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[3] ALPA shows the runway safe area as 500 ft on either side of the runway. FAA recommends 500 ft total, 250 ft on either side of the runway. The 1000-ft length at either end of the runway correlates with FAA recommendations.

These 73 incidents were further categorized in terms of ARFF effectiveness and whether occupants self-evacuated or required assistance. Tables D-1 through D-3 provide these data for the following situations:

- Table D-1—those occurrences (11) in which the accident was nonsurvivable or there was a problem with the ARFF response.
- Table D-2—those occurrences (33) in which all or most of the occupants evacuated the aircraft before ARFF arrived or without ARFF assistance ("unassisted").
- Table D-3—those occurrences (29) in which ARFF assisted in the evacuation of the aircraft ("assisted"). When it was undetermined if ARFF assisted, these occurrences were included in the ARFF-assisted category in table D-3.

Table D-1 shows that in all 11 nonsurvivable incidents, the aircraft was totally destroyed. Two incidents would more accurately be designated as partially survivable, i.e., not all occupants suffered life-threatening, blunt-trauma injuries. On March 7, 2007, in Indonesia, a B-737 aircraft crashed just outside the airport perimeter on landing. The official investigation report stated "ineffective firefighting operation may have resulted in increasing the number of fatalities and injuries." The ARFF equipment reportedly did not meet ICAO agent requirements and could not easily access the crash site just outside the airport fence.

On August 27, 2006, an accident involving a CRG 100 aircraft in Lexington, Kentucky, occurred and ARFF response was delayed. A number of passengers survived the impact but succumbed to smoke inhalation and burns. Police arrived at the scene in about 5.5 minutes, and it took them another 3.5 minutes to access the crash location due to tall vegetation. The fire department responded within 1 minute of the crash and arrived at the scene in about 11 minutes.

Table D-2 shows the 33 occurrences where occupants self-evacuated. Generally, most or all the occupants survived the accident. Of these 33, 8 involved minor engine or landing gear fires. Of the remaining 25 occurrences, 6 involved general aviation, or 14 CFR Part 135 aircraft, in which ARFF responded to the scene. Of the remaining 19 occurrences, 8 occurred outside of the U.S. and 5 involved evacuation of the crew only. Two accidents occurred in which there was substantial loss of life: (1) the June 10, 2008, A310 crash in the Sudan, in which there was a delayed ARFF response and (2) the March 22, 1992, Fokker 28 accident in New York, in which the ARFF response was unprepared for an in-water scenario.

Twenty-nine occurrences were identified in which ARFF assisted with evacuation (table D-3). Nine of these occurrences involved minor engine or landing gear fires. Of the 20 major occurrences (substantial damage or aircraft destruction), 3 involved 14 CFR Part 135 or general aviation aircraft. Of the remaining 17 occurrences, 10 were outside the U.S., 7 involved major loss of life, and 5 involved complete evacuation of a large number of occupants.

In 2 of the 29 accidents involving successful evacuation of a large number of occupants, the scenario involved an engine fire where damage was substantial. In another 2 of the 29 accidents, the assistance of ARFF was unclear. In the accident on August 2, 2005, Toronto, Canada, ARFF apparently had an impact on postcrash survivability.

A review of the assisted versus unassisted evacuations for major accidents involving a large number of occupants revealed that both are relatively uncommon occurrences. A total of 26 of these accidents were identified (12 assisted and 14 unassisted). In five major, nonfatal situations and seven fatal crashes, ARFF likely assisted in the evacuation and helped rescue survivors. In 12 major, nonfatal accidents, all occupants essentially evacuated unassisted; while in 2 fatal crashes, all surviving occupants self-evacuated. While the data is hardly overwhelming, it does support the contention that

- when occupants are ambulatory (i.e., nonfatal fires where there is no traumatic injuries), they tend to self-evacuate without assistance.
- when the crash involves traumatic injuries (i.e., fatal crashes), ARFF may assist in evacuating some occupants.

A review of several specific incidents for each situation is provided in section 4.5.

The ignition of a fuel spill fire is a rare occurrence. As noted by the Flight Safety Foundation, no UK airport contacted by researchers in 2001 had experienced a fuel spill fire [29]. However, when they occur, fuel spill fires resulting from fueling operations potentially expose the occupants to a fire threat, particularly the crew. Table D-2 includes the September 5, 2001, refueling fire in Denver, Colorado, where a fuel spill and ignition caused the death of a ground handler. Onboard occupants were able to deplane unassisted. ARFF responded within 3 minutes and quickly extinguished the fire. Another fueling incident occurred in Miami, Florida, (December 1, 1998) where the crew escaped and ARFF extinguished the fire.

4.5 AIRCRAFT ACCIDENT SCENARIOS.

Aircraft accident scenarios are presented in this section to illustrate the effectiveness of ARFF response for major incidents (e,g., high occupant load and significant fire damage). Several representative accidents occurred prior to 1998 (not in appendix D), but are included since they have valuable lessons. The analysis is provided for four accident groups where

- the ARFF was a definite contributing factor to evacuation success.
- most or all passengers evacuated before ARFF could affect firefighting.
- even with a timely response, significant occupant fatalities occurred because of the rapid progression of fire.
- ARFF delay or other factors reduced ARFF effectiveness.

4.5.1 The ARFF-Assisted Accident.

4.5.1.1 Delta Flight 1141, Dallas, TX, August 31, 1998.

On August 31, 1998, Delta Flight 1141, with 108 occupants, suffered an aborted takeoff at Dallas/Fort Worth International Airport. The B-727-200 clipped its wing on the runway as it was taking off. Takeoff was aborted and the semi-intact aircraft came to rest approximately 3200 feet from the end of the runway, just within the fenced perimeter of the aircraft operations area. The fuselage had broken in three sections. Fire was sparked on the initial liftoff sequence and when it came to rest, it was burning furiously, particularly in the rear area. The jet was holding 4776 gallons of Jet A fuel.

Within 30 seconds of alert, ARFF was enroute. The first two units arrived within approximately 4 minutes, 20 seconds after alert. Three trucks were on the scene within 5 minutes, three more within 6 minutes, and five more within 11 minutes. Most survivors had evacuated, but the last ambulatory survivors were sprayed with AFFF. Knockdown was declared within 6 minutes of ARFF arrival, although a 60-acre grass fire caused by the fuel spill had to be contained by later-arriving mutual aid units (40 minutes). Sixty fire fighters used a total of 15,800 gallons of water and 650 gallons of AFFF to totally control, suppress, and extinguish the fire.

ARFF and police affected rescues during the active exterior and subsequent interior firefighting attack. Personnel in the cockpit were rescued. The majority of occupants evacuated on their own via forward exits or breaches in the fuselage. There were 13 fatalities, with most occurring as a result of smoke inhalation. One exit, where occupants attempted to escape, was inoperable due to the crash. Fire and smoke in this area, compounded by openings in the fuselage, caused fatalities. The NTSB report is somewhat contradictory regarding the timing of fire and smoke penetration and development in the aft area. The report notes that evidence showed the fire entered the aft cargo area before the aircraft came to rest. After the airplane stopped, the fire burned through the cargo compartment and cabin floor. The fire also entered the cabin through the break in the aft fuselage and other fuselage openings. This fire trapped passengers in the aft end of the cabin. The report states that burnthrough of the cabin floor caused these smoke inhalation fatalities, but seems to ignore the potential smoke from the exterior fire entering through fuselage openings. The NTSB concluded that, even though the fuselage had separated, the occupiable volume of the cabin was not substantially compromised. Seat fire-blocking material installed in this aircraft was determined to have contributed to occupant survival, particularly in the forward part of the aircraft. In seats without fire-blocking material, estimated survival time is 2 minutes 50 seconds. Survival time in this incident was estimated to be 4 minutes 20 seconds, the same as the first-arriving ARFF units. The open fuselage may have acted as a chimney, allowing cool, clean air to enter the cabin. This may have contributed to occupant survival.

4.5.2 The ARFF-Unassisted Accidents.

4.5.2.1 China Air Flight 120, August 20, 2007.

China Airlines Flight 120 at Naha Airport in Okinawa, Japan, on August 20, 2007, is a classic case of a fire-induced aircraft evacuation prior to ARFF arrival. The official report was not available at the time of this writing, and this accident was not included in table D-2. Media reports indicate that, while taxiing to the gate, the B-737-800 right-wing area became involved in a fuel fire. This apparently was the result of a loose bolt puncturing the right-wing fuel tank, creating a 2- to 3-cm hole. The airplane had 110 passengers and 8 crew members onboard.

In this fire, passengers and crew completely evacuated well before (more than 2 minutes) ARFF arrival. The interior of the aircraft was clearly threatened, as evidenced by the collapse of the aft end of the fuselage (and probable loss of cabin integrity), just before ARFF vehicles arrived.

4.5.2.2 American Airlines Flight 1420, Little Rock, AR, June 1, 1999.

On June 1, 1999, American Airlines Flight 1420 overran the runway at Little Rock, Arkansas (Index C). A McDonnell Douglas (MD)-82, with 145 occupants, crashed into structural light supports and came to rest about 800 ft (244 m) from the end of the runway, about 15 ft (4.6 m) below the runway surface on an environmental slope leading to the Arkansas River. A fire ensued. The captain and ten passengers were killed, all but one from traumatic injuries.

The ARFF response was immediate, but slow (10-20 mph) due to the unknown location of the aircraft and low visibility (estimated to be 100 ft). The ARFF equipment did not arrive on the crash scene until 16 minutes after notification. By that time, all but one occupant (the flight officer) had self-evacuated; the ARFF personnel reported seeing occupants jumping from the aircraft as they approached the scene. The fire was controlled in 60 seconds by the Index C response involving three trucks and four fire fighters. Complete extinguishment occurred in another 30 seconds. The fire fighters extracted the injured crew member. One passenger died of smoke inhalation after remaining in the aircraft to assist evacuation of other passengers. The fire was in the left-wing area and, reportedly, did not enter the aft fuselage area until the passengers had evacuated. Smoke did enter the cabin immediately after the fire had begun.

Although this accident was classified in section 4.4 as ARFF-assisted, all but one occupant had evacuated prior to their arrival.

4.5.2.3 Air France Flight 358, Toronto, Canada, August 2, 2005.

The August 2, 2005, Airbus A340-313 accident at Toronto Pearson Airport is a good example of a successful evacuation and a rapid ARFF response. In the section 4.4 analysis, it is designated as an accident where ARFF assisted in evacuation. The timing of the evacuation event shows the small margin of time available for actual assistance in a survivable postcrash fire.

Air France Flight 358 overshot the runway during landing in bad weather. The aircraft came to rest in a ravine roughly 984 ft (300 m) from the end of the runway. A fuel tank ruptured as the aircraft left the runway. There was little fire, but a fire in the left-wing area ensued and grew after the aircraft came to rest. Smoke was observed in the passenger cabin by some occupants before the aircraft came to rest. During evacuation, black smoke, but no fire, was observed in the cabin. The total evacuation of 297 passengers and 12 crew members was estimated to have occurred in a little more than 2 minutes. Twelve passengers were injured. There were no fatalities.

ARFF responded within 26 seconds of the accident occurrence and were on the scene within 1 minute. Although designated as a CAT 9 airport, the ARFF equipment and personnel response was much greater. A total of 15 ARFF personnel initially responded (11 was the minimum) since the accident occurred during a shift change. The initial ARFF AFFF discharge was estimated to be 63% more than required for CAT 9. The ARFF personnel entered the aircraft and searched the flight deck and first six rows, but were ordered to evacuate because of dangerous conditions and explosions. Two high-reach extendable turrets (HRET) were available, but the terrain prevented their use. The aircraft sustained substantial fire damage over most of the fuselage. Dilution of foam by rain was cited as a factor in reducing firefighting effectiveness. The timing of this accident shows that, although ARFF arrived very quickly, many passengers had undoubtedly evacuated the aircraft prior to their arrival. The fire was reported to have originated in the left-wing area and spread to the fuselage. While the fire was apparent to those in the immediate area, it did not create untenable conditions until after occupants evacuated.

4.5.2.4 Continental Flight 603, Los Angeles, CA, March 1, 1978.

On March 1, 1978, Continental Airlines Flight 603 aborted a takeoff at Los Angeles International Airport due to collapsed landing gear. The DC-10, with 200 passengers and 14 crew members, skidded to a stop past the end of the runway. The left wing fuel tank (holding an estimated 10,000 gallons of jet fuel) ruptured and a spill fire occurred. It initially involved the left wing and fuselage and spread to the right-wing area.

The incident was heard and observed by fire station personnel, who responded immediately with a 3000-gallon crash truck having a 750-gpm monitor. They were on the scene within 90 seconds. The ARFF vehicle was positioned at the aft, right tail area to provide a safe rescue path for occupants evacuating from the right side of the aircraft. Most occupants had exited on arrival of the ARFF vehicle, which affected fire control within 1 minute. Other vehicles arrived in the 3- to 4-minute time frame, and the fire was totally extinguished within 2 minutes. Several escape slides failed to operate properly or were melted by the fire.

Two passengers were killed when they ignored flight attendant instructions and exited via the left wing. They jumped into the fire area and were asphyxiated. Thirty-one other passengers were injured; several were burned. In addition to the rapid response by ARFF personnel, disaster planning and training were credited with the positive results from this incident. The commander noted that there was very little radio traffic during the initial stages of the incident.

From photographs, the size of the fire was estimated to be approximately 12,000 ft^2 (1,115 m^2).

4.5.3 Accidents Involving Fatalities due to Rapid Fire Progression.

4.5.3.1 British AirTours, Manchester, UK, August 22, 1985.

Even under optimum ARFF response conditions, occupants may be threatened and killed by an exposing fuel fire; i.e., Manchester, England, British AirTours fire on August 22, 1985 [30 and 31]. The B-737-236, with 137 occupants, incurred a catastrophic engine failure during takeoff. Takeoff was aborted, and the left engine trailed flames as the pilot was braking. As the aircraft was coming to a stop, a pool fire developed under and around the left engine. Passengers immediately began to evacuate under direction from the crew, but flame penetration into the aircraft was very rapid. It was estimated that flames penetrated the fuselage within 20 seconds, windows within 40-50 seconds, and the cabin wall within 1 minute. The first rapid intervention vehicle was on the scene within 25 seconds, about the time of flame penetration. Additional vehicles arrived quickly, and the pool fire was quickly extinguished. There was a persistent, running fuel fire from the involved engine, which was extinguished with halon secondary agents. Despite the rapid ARFF arrival, flames penetrated the fuselage. The static fire area was not considered large, given the full-fuel load; it involved a partial area under the left engine. A total of about 650 gallons was spilled, much of it while the aircraft was decelerating. However, the wind pushed the remaining static flames against, and under, the fuselage, which contributed to rapid fuselage penetration and rapidly deteriorating internal conditions; toxic fumes rapidly developed, even in the absence of flashover conditions. Fifty-five occupants perished, mostly in the aft area adjacent to impinging pool fire area.

This fire was rapidly extinguished by the ARFF response (no exact time was estimated), which had a CAT 8 capability even though a B-737 only requires a CAT 6 capability. Passenger evacuation was assisted by ARFF discharge of AFFF during the evacuation process. Investigators determined that early penetration appeared to conflict markedly with the expected survival of 1-3 minutes for an intact fuselage exposed to a pool fire.

It was concluded that the ARFF pool fire extinguishment tactics and procedures were as effective as conventional techniques would allow, but that the notion that prompt, mass application of foam is all that is needed is a fallacy. Recommendations for improving internal firefighting were made.

As a result of the fire, the FAA conducted tests in an attempt to replicate the fuselage burnthrough [32]. In the test, the external fire penetrated the cabin in approximately 1 minute after pool fire ignition. The mode of fire penetration into the cabin was direct melting of the fuselage skin and burning of the insulation and interior panels.

4.5.3.2 The U.S. Air Flight 1493, Los Angeles, CA, February 1, 1991.

On February 1, 1991, U.S. Air Flight 1493, a B-737 with 83 occupants, collided on landing with a Fairchild Metroliner III with 12 occupants at Los Angeles International Airport. The B-737 crushed the smaller aircraft beneath it and ultimately collided with a building. A large ground fire ensued, with survivors evacuating through the fire area. The ARFF personnel and equipment arrived in less than 1 minute after notification and controlled the ground fire within 1 minute. The initial crash caused penetration of the forward cabin of the B-737, resulting in an interior cabin fire. The ARFF personnel mounted an interior attack against the intense and very difficult interior cabin fire. It was extinguished in 30 minutes.

All occupants of the Metroliner were killed. Twenty-four of the eighty-three occupants of the B-737 were killed; twenty by asphyxiation, three by thermal burns, and one (the captain) by trauma. Occupants had difficulty evacuating over the right-wing exit, which became a choke point where about ten victims were found. It was unclear whether the interior firefighting efforts were initiated prior to the victims succumbing to smoke; perhaps some of them might have been saved with a more effective interior fire attack. Two remote fire attacks with (presumably) 1.5-inch hand lines were made. Halon, a secondary agent, was also discharged into the cabin. It was ineffective, partly because the cabin had self-vented.

Reported, 20,000 gallons of water and 1,046 gallons of AFFF were reported to be used.

4.5.3.3 Air Canada Flight 797, Cincinnati, OH, June 2, 1983.

On June 2, 1983, Air Canada Flight 797 suffered an in-flight fire in the aft lavatory. The DC-9 made an emergency landing at the Greater Cincinnati International Airport. ARFF personnel and equipment were in position where the aircraft landed. They applied a protective coating of foam on and under the fuselage (in case of an exterior fire, which did not occur) as occupants escaped through the exits. No flames were visible but the exterior paint just forward of the engine was blistering and beginning to glow red. All survivors escaped in about 30 seconds; 23 of the 46 occupants survived.

An initial 1.5-inch hand line attack at the center-wing exit was made, just as flashover was occurring as a result of air introduced by opening the exits. AFFF was applied to the interior, but the fire was too intense for the fire fighters to enter. No flames were observed. A rear-entry attack was subsequently made; again, fire fighters were driven back by intense heat and smoke. Initial water supplies were depleted in about 10 minutes, when the cabin fire had been knocked down. The fire then intensified and ultimately extinguished in about 30 minutes after the water supply had been re-established. Most victims had toxic carbon monoxide blood saturation. It is unclear how many victims perished after the initiation of firefighting efforts. While the airport was an FAA Index C, it reportedly had Index E ARFF equipment capacity.

4.5.4 The ARFF Effectiveness Impacted by Delayed Response.

4.5.4.1 Northwest Flight 1482, Detroit, MI, December 3, 1990.

On December 3, 1990, a Northwest B-727 (Flight 299) collided during takeoff with a Northwest DC-9 (Flight 1482) at Detroit Metropolitan Airport. The B-727, with 150 occupants, came to a stop before the end of the takeoff runway. The DC-9 (44 occupants) was clipped by the B-727 wing and lost its right engine and suffered a fuel spill fire as a result of the engine loss.

Visibility was poor due to fog (possibly as low as 50-100 feet). The Index E ARFF response was within 1 minute and responded initially to the B-727. An ARFF vehicle discharged a foam blanket over an unignited fuel spill. The aircraft was subsequently evacuated using nonemergency procedures.

The DC-9 became immediately involved in a fuel spill fire, and the survivors noted that a "blowtorch-like" flame entered the cabin almost immediately at the right rear of the plane. Survivors evacuated the aircraft before ARFF arrived. The ARFF equipment was redirected from the B-727 to the DC-9. The first responding mini-pumper arrived approximately 6 minutes after the incident occurred (originally estimated to be 3 minutes). The engine and pool fires were extinguished within 3 minutes of ARFF arrival. The ARFF mounted an interior attack at two locations on the left side of the aircraft, but were driven back by heat and smoke. This interior attack was attempted with hand lines (via ground access, ladders, and a bumper turret). The interior fire vented, and an exterior attack suppressed the fire about 3 minutes after ARFF arrival. The total amount of MIL SPEC AFFF solution used for the exterior and interior attack was 8500 gallons.

Eight occupants of the DC-9 perished, and twenty-four were injured. Three occupants died of blunt-force trauma, three of asphyxiation, and one of thermal burns (the cause of death for one victim was not identified). The arriving fire officer in charge believed that the cabin environment appeared to be nonsurvivable since the cabin was entirely engulfed in fire.

4.5.4.2 COMAIR Flight 5191, Lexington, KY, August 27, 2006.

On August 27, 2006, COMAIR Flight 5191 took off from the wrong runway in Lexington, Kentucky. The Bombardier CL600 with 50 occupants overshot the runway and crashed about 1800 ft (550 m) from the end of the runway. Public safety personnel arrived at the scene about 5 minutes after the crash and located the burning wreckage, working through tall vegetation in another three minutes. They extricated the first officer from the cockpit. ARFF arrived approximately 11 minutes after the first alert, traveling approximately 2.5 miles via public roads, a dirt road, and on off-road terrain. They extinguished the fire, which included a split fuselage fully engulfed with fire, in about 3 minutes. An extendable turret was available, but the infrared (IR) camera on it was not used.

The accident was judged to be partially survivable. Only one occupant survived. About half the victims had nonsurvivable trauma. The others succumbed to smoke (9) and thermal burns (11) as a result of fire entering the open fuselage. The response was deemed “timely and well coordinated,” and it was concluded that the interior cabin quality deteriorated as a result of the postimpact fire entering through the open fuselage.

4.5.5 Summary.

A review of the loss incidents shows that major accidents involving ARFF response are infrequent but nonetheless occur. The majority of accidents can be roughly divided into two groups: (1) those in which occupants are ambulatory and most evacuate before the arrival of ARFF and (2) survivable accidents in which the fire threat is nearly immediate and chances of survival are a function of the proximity of occupants to the fire threat, the growth rate of the fire, and the timeliness of the ARFF response. There is crossover between these two rough categorizations. A fire may be growing and posing an increasing threat, but there is sufficient time to evacuate the aircraft (example, China Air accident). Alternately, the fire growth may be so imminent and threatening that even an essentially zero response time by the ARFF results in numerous fire victims (examples, Manchester and Detroit accidents). When exterior pool fire blocks all exits and occupants must wait onboard the aircraft, ARFF responders must control the fire before the occupants can subsequently evacuate. More likely, many occupants evacuated through exits that were not blocked by an exterior fire, and the ARFF arrived to control the exterior fire while the last remaining ambulatory occupants evacuated. The challenge then became attempting to save or rescue nonambulatory occupants threatened by the exterior fire, which ignited an interior fire or filled the interior with smoke. This is a function of fuselage integrity; a split fuselage allows immediate entrance of smoke and fire. An intact fuselage provides a delay; this delay is a function of the external threat and integrity of the fuselage element. This delay can be very short, measured in seconds or minutes.

This will be discussed in detail in section 5.2. Because of the sensitivity to time, ARFF response time became a factor in the effectiveness of rescuing the nonambulatory occupants. In some cases, occupants may be ambulatory, but succumb while attempting to evacuate. Structural integrity of the nearest evacuation route (i.e., operability of the exit) is a factor.

In a review for the ARAC ARFFRWG, Omans provided a review of major accidents, some of which are included here [33]. He concluded that:

> "1. Most survivors are escaping on their own or with the assistance of the cabin crew or other passengers. They are not being rescued by the fire department in most situations. They are also not escaping into a safe area created by the fire department. There are not many cases of the fire department rescuing someone from the interior of a large frame aircraft accident.
>
> 2. People are not being killed by exterior fuel spill fires in aviation accidents. They are dying from smoke inhalation, on the inside of the aircraft, often near an exit."

This review supports conclusions 1 and 2, with some caveats. Exterior fires can, and do, lead to (potentially rapidly) degrading interior conditions, which then may result in fire deaths of nontraumatically injured occupants. The number of these types of incidents in the U.S., particularly in recent years, is very low. Cherry [34] noted that there has been an improvement (up to a 30% reduction since 1980) in the accident rate being experienced by the worldwide fleet. Cabin fire protection improvements, such as seat fire-blocking materials, should also provide benefits.

4.6 SIZE OF EXTERIOR FUEL FIRE.

The 1971 Gage report estimated the probable maximum dimensions of a crash fire as a function of aircraft dimensions. The report identified 27 incidents in which there was sufficient photographic coverage so the size of the fire relative to the aircraft dimensions could be estimated. The maximum fire dimension in these accidents was 75% of the product of the fuselage length and the wingspan. In all but two accidents, the fire area was less than 60% of the fuselage-span product. Fires that involved only one side of the aircraft were significantly smaller, probably because, in most cases, the crash forces were substantially less.

The Gage report concluded that a reasonable maximum expected dimension of an aircraft crash fire is an area equal to two-thirds the product of the fuselage length and the wingspan. Fires involving only one side of the aircraft could be safely estimated to be a maximum of one-third the fuselage-span product. It was concluded that these areas encompass all but the most extreme aircraft crash fires; these areas were used in the proposed regulations for setting the maximum anticipated fire area for purposes of establishing crash truck extinguishing capability.

A survey similar to the Gage report was performed for this analysis, as shown in table 14. A total of 33 accidents were reviewed. The results were very similar to the Gage report. In 26 of the 33 incidents, the fraction of the fuselage-span product represented by the fire area was less than 53%. In the remaining five accidents, three involved nonsurvivable crashes into buildings (Brazil, July 17, 2007; Taipei, February 16, 1998; and Miami, August 7, 1997); two involved fatal general aviation/commuter crashes; and one involved a ground fire during fueling (Bangkok, March 3, 2001). ICAO now recommends that an airport serving aircraft larger than the average size of the category have agent quantities sized for the increased aircraft size.

The EASAMS report reviewed the size of aircraft spill fires of 318 incidents in which 55% (175) involved fire. Of the 22 fires in which the fire area was reported, 4 had fire areas greater than 10,764 ft^2.

The U.S. Air Force analyzed actual crash data trends to substantiate the observation that the actual fire area is less than the TCA [35]. This was expected to be true, since actual crashes or ground-initiated incidents occur on sloped pavements or ground surfaces. Released fuel will spread and flow to the low points of the surrounding terrain according to the horizontal gradients of the surface and/or the slope and permeability of surrounding soil. They cited data from three U.S. Air Force ground-initiated aircraft fires: Barksdale DC-10, Kelly B-52, and Pease KC-135, which had actual fire areas of 42%, 58%, and 43%, respectively, of the TCA for each aircraft.

For the time period 1967-2000, Cherry reviewed western-built, turbojet aircraft accidents involving fatalities or aircraft destruction [36]. Of the 147 accidents identified, 101 were deemed survivable, and of the 101 accidents, 70 involved fire. Of the 70 fire-related accidents, 43 (62%) involved, or likely involved, ground pool fires. Of the 43 ground pool fires, 4 are included in table 14, and 3 others are included in section 4.5.

Defining the location of the fire was performed in the EASAMS report. In a review of 22 fires, 8 were found to involve one side of the aircraft, and 14 involved both sides of the aircraft. For 39 spill incidents (no fire), 22 were found to involve one side of the aircraft and 17 involved both sides of the aircraft. No attempt was made in the this analysis to establish any trend on which particular area of the aircraft was involved. Qualitatively, fires appear to occur on one or both sides of an aircraft. The cockpit, logically, usually sustains the least amount of damage. Otherwise, no particular trend in fire area was established.

Cherry found that fire damage to aircraft is less severe when landing gear collapses and the fuselage is resting on the ground [36]. This seems logical, because

- a fuel spill is less likely to spread under the aircraft.
- burning of the underbelly is prevented.
- weak points of the fuselage, e.g., ventilation openings, are less likely to be exposed.

Table 14. Estimated Accident Fire Size

Type of Aircraft	Date	Location	Relative Dimensions of the Fire		Relative Fire Area	Comment	Fuel Load/ Fire Area[1] (gal/ft^2, L/sq m)	Fire Area/ TCA
			Fraction of the Fuselage Length (estimated)	Fraction of the Total Wingspan (estimated)	Percentage of the Fuselage-Span Product			
Canadair CRJ-100ER	2/14/2008	Yerevan, Armenia	2/3	4/5	0.533	Crashed on takeoff. Destroyed by postimpact fire. ARFF responded and assisted in evacuation.	0.35 gal/sq ft 14.23 L/sq m	0.32
Fokker 100	1/2/2008	Tehran, Iran	1/2	1/3	0.167	Ran off runway during takeoff. ARFF responded.	0.33 gal/sq ft 13.37 L/sq m	0.12
Learjet 35A	11/4/2007	San Paulo, Brazil	1.00	1.00	1.000	This airplane crashed into buildings that also caught fire.	0.49 gal/sq ft 19.77 L/sq m	0.49
Hawker 800XP	10/29/2007	Orange County, FL	1/5	1/5	0.040	Fire was contained by the landing gear.	0.54 gal/sq ft 21.87 L/sq m	0.03
DC-9-82	9/28/2007	St. Louis, MO	1/6	1/15	0.011	ARFF was waiting as the airplane landed.	0.27 gal/sq ft 10.92 L/sq m	0.01
Boeing MD-82	9/16/2007	Thailand	1/2	1/4	0.125	Fuselage broke into pieces and caught fire after crashing on second go-around.	0.37 gal/sq ft 14.97 L/sq m	0.11
Boeing 737-800	8/20/2007	Japan	4/5	5/8	0.500	An engine caught fire after landing, and it progressed to the fuselage.	0.45 gal/sq ft 18.42 L/sq m	0.52
Airbus A320-233	7/17/2007	Brazil	1	1	1.000	The fire was larger than what would be expected due to the involvement of a building.	0.57 gal/sq ft 23.36 L/sq m	0.95

Table 14. Estimated Accident Fire Size (Continued)

			Relative Dimensions of the Fire		Relative Fire Area			
Type of Aircraft	Date	Location	Fraction of the Fuselage Length (estimated)	Fraction of the Total Wingspan (estimated)	Percentage of the Fuselage-Span Product	Comment	Fuel Load/ Fire Area[1] (gal/ft^2, L/sq m)	Fire Area/ TCA
Tupolev TU-134A-3	3/17/2007	Samara, Russia	5/8	1/5	0.125	The wing separated. Landed upside down and caught fire.	0.3 gal/sq ft 12.27 L/sq m	0.10
Boeing 737-400	3/7/2007	Indonesia	7/8	1/3	0.290	From video evidence, it appears as though this fire was predominantly on one side of the airplane.	0.56 gal/sq ft 22.67 L/sq m	0.23
Bae-146-200A	10/10/2006	Norway	3/4	2/3	0.500	There was a postcrash fire after the airplane overran the runway.	0.38 gal/sq ft 15.63 L/sq m	0.28
Tupolev TU 154M	9/1/2006	Mashad, Iran	1/3	0.06	0.020	Burned portside of fuselage (where the wing broke off).	0.68 gal/sq ft 27.54 L/sq m	0.02
Bombardier CRJ-100	8/27/2006	Lexington, KY	7/8	2.69/21.21	0.111	The official report indicates that passenger's seats were destroyed by the fire. The wings detached from the airplane during the crash.	0.35 gal/sq ft 14.23 L/sq m	0.07
Airbus A310-300	7/8/2006	Russia (Irkutsk)	3/4	2/5	0.300	This airplane crashed into buildings and caught fire at the end of the runway.	0.9 gal/sq ft 36.86 L/sq m	0.36
Airbus A340	8/2/2005	Toronto, Canada	1	1/2	0.500	The report indicates the fire was predominantly located at the left- and right-wing root main landing gears and in the fuselage, from cockpit door to rear pressure bulkhead.	1.42 gal/sq ft 57.89 L/sq m	0.68

Table 14. Estimated Accident Fire Size (Continued)

Type of Aircraft	Date	Location	Relative Dimensions of the Fire		Relative Fire Area	Comment	Fuel Load/ Fire Area[1] (gal/ft^2, L/sq m)	Fire Area/ TCA
			Fraction of the Fuselage Length (estimated)	Fraction of the Total Wingspan (estimated)	Percentage of the Fuselage-Span Product			
Antonov AN-24V	6/2/2005	Khartoum, Sudan	2/3	1/4	0.167	The fire was on the left side, where the engine scraped the ground during a crash landing.	0.16 gal/sq ft 6.35 L/sq m	0.14
Canadair CL-600-2A12	11/28/2004	Montrose, CO	1	1	1.000	Pictures show fully burned airplane.	3.79 gal/sq ft 154.27 L/sq m	0.44
Jetstream 32	10/19/2004	St. Louis, MO	7/8	2/5	0.350	The airplane was destroyed by impact and postimpact fire.	0.2 gal/sq ft 8.05 L/sq m	0.22
Boeing 747-244BC	10/14/2004	Canada	1	1/3	0.330	The airplane lost a wing when crashing. This was a cargo airplane.	1.19 gal/sq ft 48.49 L/sq m	0.49
Boeing MD-10-10F	12/18/2003	Memphis, TN	5/6	1/2	0.420	The landing gear failed and it skidded to a stop. A fire occurred. Damage is shown in a video and photographs.	1.46 gal/sq ft 59.41 L/sq m	0.46
Boeing 727-232	7/26/2002	Tallahassee, FL	7/8	1/2	0.438	Postimpact fire. Fire damage shown in photographs.	0.64 gal/sq ft 26.07 L/sq m	0.39
Boeing 737-400	3/3/2001	Bankgkok Thailand	4/5	1	0.800	Photographs and video show event occurrence. Wing explosion/fire.	0.56 gal/sq ft 22.67 L/sq m	0.63
Boeing 747-400	10/31/2000	Taipei, Taiwan	1/2	1/4	0.125	Crashed into construction equipment. Center section and forward consumed by fireballs initially from wing tanks.	1.1 gal/sq ft 44.88 L/sq m	0.20

Table 14. Estimated Accident Fire Size (Continued)

Type of Aircraft	Date	Location	Relative Dimensions of the Fire		Relative Fire Area	Comment	Fuel Load/ Fire Area[1] (gal/ft^2, L/sq m)	Fire Area/ TCA
			Fraction of the Fuselage Length (estimated)	Fraction of the Total Wingspan (estimated)	Percentage of the Fuselage-Span Product			
Douglas MD-82	6/1/1999	Little Rock, AR	1/3	1/5	0.067	Postimpact fire. Damage to fuselage (mostly) in the aft 1/3 (from photographs).	0.37 gal/sq ft 14.97 L/sq m	0.06
Boeing 747-259B	12/1/1998	Miami, FL	1/6	1/5	0.033	Fire during refueling (under right side wing).	1.16 gal/sq ft 47.08 L/sq m	0.05
Airbus A300	2/16/1998	Taipei, Taiwan	1	1	1.000	Crashed into houses while landing/approach. Caught fire to houses in addition to airplane. Fully burned airplane.	0.63 gal/sq ft 25.59 L/sq m	1.08
Douglas DC-8-61	8/7/1997	Miami, FL	1	1	1.000	Crashed shortly after takeoff. Destroyed by postimpact fire. Fire controlled in 15 minutes, extinguished in 30 minutes.	0.84 gal/sq ft 34.28 L/sq m	1.15
Douglas MD-11	7/31/1997	Newark, NJ	0.875	0.116	0.102	Destroyed by postimpact fire and impact forces. The fuselage width (plus small part of wing root) and most of the length (except for part of nose and tail) burned.	1.18 gal/sq ft 48.24 L/sq m	0.11
Douglas DC-10-10CF	9/5/1996	Newburgh, NY	0.50	0.20	0.100	Smoke in cockpit. Crew evacuated. Fire broke out 1 hour after landing and destroyed the airplane. ARFF was unsure about hazardous contents, which contributed to the fire severity.	0.82 gal/sq ft 33.48 L/sq m	0.11

Table 14. Estimated Accident Fire Size (Continued)

Type of Aircraft	Date	Location	Relative Dimensions of the Fire: Fraction of the Fuselage Length (estimated)	Relative Dimensions of the Fire: Fraction of the Total Wingspan (estimated)	Relative Fire Area: Percentage of the Fuselage-Span Product	Comment	Fuel Load/ Fire Area[1] (gal/ft^2, L/sq m)	Fire Area/ TCA
Douglas DC-9-31	7/2/1994	Charlotte, NC	0.83	0.20	0.167	Broke into pieces during crash. Tail crashed into house.	0.33 gal/sq ft 13.45 L/sq m	0.13
Douglas DC-8-61	8/18/1993	Guantanamo Bay, Cuba	1	1	1	Destroyed by postimpact fire. ARFF responded, extinguished fire, extricated crew. Used 275 gal of AFFF, 907 lb of Halon, and 37,500 gal of water. Thirty acres of brush also caught fire.	0.84 gal/sq ft 34.28 L/sq m	1.15
Douglas DC-10-30F	12/21/1992	Faro, Portugal	0.75	0.25	0.188	Crashed on runway. Right wing separated. Fire started.	1.3 gal/sq ft 52.98 L/sq m	0.23
LOCKHEED L-1011	7/30/1992	Flushing, NY	0.50	0.30	0.150	Crashed after aborted takeoff. Fuel tanks caught fire after crash.	0.86 gal/sq ft 35.16 L/sq m	0.17

[1]Assumes tanks are full.

The review was extended to a comparison of the estimated fire area as a fraction of the TCA for the involved aircraft. The data show that in all but four accidents, the fire area was less than or equal to 68% of the TCA. Three of the four accidents exceeding 68% of the TCA involved nonsurvivable crashes into buildings, as noted above. The fourth (Guantanamo Bay, August 18, 1993), involved a large brush fire (30 acres). Twenty-seven accidents (82%) had a fire area ≤50% of the TCA, and nineteen (60%) had a fire area ≤25%. Of the TCA, these data confirm that, except for catastrophic nonsurvivable or limited survivable situations, the PCA estimate of 67% of the TCA is reasonable.

4.7 THE ARFF RESPONSE TIMES.

Cherry reviewed the response time of 54 major accidents from 1962 to 2000 [36]. The response time was defined as the time the aircraft stopped to the time fire fighters arrived, which varied from 30 to 1200 seconds. The data suggested that, in 50% of the accidents, ARFF arrived within 4 minutes. Many of the longer response times involved off-site accidents. Data for "zero" response time was included, which indicated ARFF was given prior notification and was already at the accident site (prepositioned). Two accidents were noted as zero response time; others likely included prenotification (e.g., Sioux City, 1989, 30-second response time due to prenotification).

The ARAC considered situations in which ARFF had prenotification of an accident. In these situations, ARFF could be prepositioned. The ARAC stated that "numerous surveys over time indicate that the vast majority of aircraft-related responses commence with advance warning of an emergency in progress and prepositioning ("staging") of equipment" [8]. They recommended additional response time criteria for ARFF prepositioning when emergencies are known.

No detailed analysis of this attribute was performed for this report. The EASAMS report stated that, of 500 accidents reviewed, 55% involved some degree of fire, and 13% involved prewarning. The majority of serious fire accidents, listed in appendix D, appear to have occurred without warning. Even with prewarning or nearly instantaneous response, occupants succumbed to the resulting fire.

4.8 THE ARFF FIRE CONTROL TIME.

Cherry [36] evaluated accident data from 1962 to 2000 to determine fire fighter control time for accidents involving ground pool fires. Control time was measured as the time of arrival to the time that ARFF established control of the fire (no additional details are provided).

Of the 43 ground pool fire accidents identified, 12 had sufficient information to establish time of control. The times ranged from 60 seconds to 4200 seconds. The data suggested that, in 50% of these accidents, control was established in within 10 minutes. Many accidents took much longer to control.

Of the 12 accidents cited above, 4 are included in appendix D. Control time ranged from 60 to 720 seconds. This shows that the data must be carefully reviewed in the context of ARFF agent requirements. For example, one fire involved an overshot into water where all survivors escaped before ARFF could assist in rescue, and another fire was a major crash (half fatalities and the survivors essentially self-evacuated) with the fuselage split open and the forward end fully engulfed with fire.

4.9 AIRCRAFT EVACUATION TIME.

Cherry [36] estimated the time to initiate evacuation. Of the 147 major incidents reviewed, 7 were identified as featuring an intense fire threat, in which the initiation of evacuation time could be estimated. This time ranged from 8 to 40 seconds. Time to complete evacuation was also assessed for 24 accidents involving fire. Times ranged from 55 to 360 seconds, partially a function of occupant load. The data suggested that 50% of evacuations were completed within 130 seconds and 90% within 325 seconds.

4.10 AGENT QUANTITIES FOR EXTERIOR SPILL FIRE CONTROL.

Just as an analysis of pool fire size based on historical data is challenging, so is the analysis of agent used at major accidents. Since before the early 1990s, ALPA has tracked the amount of water used for foam production at reported accidents [37]. It has been updated through 2007 and provided by ALPA (appendix E). When data was available (infrequently), it was included in the appendix D effectiveness review.

An earlier version of the ALPA data was submitted to the NFPA 403 technical committee during the 1993 edition review cycle in an effort to increase required Q_1 and Q_2 quantities. The technical committee felt there was insufficient technical information to support the increase in Q_1 and Q_2. During this code change process, the concept of Q_3 was developed; i.e., there was recognition that there should be a dedicated amount of firefighting agent for potential hand line operations. These hand line operations are for extinguishing persistent fires around a wreckage, and for potential interior attack.

There is no doubt that large quantities of agent are used at major accidents. The issue is how and when these agents are applied, and for what use. In theory, if airports only have the minimum agent quantities required, then some of the agent quantities cited in appendix E could never be achieved. Airports may have more capacity than minimum requirements. Agent could be supplemented by mutual aid or airport structural firefighting vehicles. Resupply typically occurs for major accidents, where water is resupplied from hydrants, and additional foam stock is used.

A more careful review of accidents and fire control times indicates that the amount of agent used for initial control and extinguishment for survivable major accidents is a fraction of the gross amount of overall agent used. For example:

- Los Angeles, 1991—the ground fire was extinguished in 1 minute. Assuming a CAT 9 response with a 2400-gpm application rate (a very conservative estimate, since the first arriving vehicle likely had half or less this application rate), 2400 gallons would have been applied for initial control/extinguishment. This is less than the 17,000 gallons total agent used.

- Detroit, 1990—the fire was reportedly controlled in 3 minutes. They reportedly had Index E capability. Assuming 2400 gpm for the full 3 minutes (conservative, particularly since a mini-pumper was first on the scene), 7200 gallons of agent would have been applied. Total agent used was 10,000 gallons.

- Manchester, 1985—exterior pool fire control was deemed "rapid." The agent used for initial control and extinguishment was less than the 10,000 gallons total agent.

- Cincinnati, 1983—there was no exterior pool fire, but 7400 gallons of agent were used.

- Los Angeles, 1978—the pool fire was controlled in 1 minute by a vehicle using a 750-gpm monitor. It was totally extinguished within 2 minutes. Total agent used was 7800 gallons.

Another example of substantial use of foam agent is the crash landing of a B-777 at Heathrow Airport, UK (January 17, 2008). The aircraft, carrying 136 passengers and 16 crew members, experienced engine problems on approach and landed short of the runway, sliding 656 feet as the nose and main landing gear collapsed. A fuel tank was ruptured, causing a significant leak that continued for 1.5 hours after the accident. The leak did not ignite, and passengers evacuated successfully, with ten injuries. ARFF responded and foamed the pool around the aircraft using hand lines as occupants completed their evacuation. A view of the leakage area around the aircraft showed a foamed footprint of about 27,000 ft^2. At an application rate of 0.17 gpm/ft^2 for film-forming fluoroprotein foam, this would be about 4600 gallons. In all, 79,000 gallons of water for 6% foam production were used [38].

The EASAMS analysis also included an historical review of agent used [7]. In 15% of the incidents, more foam was used than that required by the RFFP (March 1970). Protein foam was used in these accidents. The authors noted that this data should be interpreted with care. For smaller aircraft, more than sufficient agent may have been available. At major accidents, supporting services may have augmented airport supplies. They note that "there will always be some risk of the rescue and firefighting service being unable to deal with the exceptional accident with their mobile water supplies."

The need for substantially more agent for an initial attack of a pool fire appears to be unsubstantiated by the loss data. This was essentially the conclusion by the NFPA 403 technical committee during the 1993 review cycle. As with all loss data, there are exceptions. The October 31, 2000, Taiwan fire involving a B-747 required 10-15 minutes to control. ALPA reports that up to 40,000 gallons of agent may have been used. While this accident was noted as involving ARFF assistance in evacuation, most occupants likely evacuated before or just as ARFF arrived and began firefighting. It certainly was a major fire, involving a split fuselage. The Phuket, Thailand accident (September 16, 2007) could not be assessed in terms of control and extinguishment time. Of the 42 survivors, 10 were reportedly assisted by ARFF. The effectiveness of foam during firefighting was reportedly reduced by heavy rain; subsequently, a reflash of the fire occurred.

The data appears to support the conclusion by Omans [33] that required agent quantities are sufficient for exterior spill control.

As a practical matter, it appears that many U.S. airports exceed Part 139 minimum agent requirements by a great deal [39]. A survey of 50 random airports (10 from each Index B through E) conducted in 1991 by ALPA yielded the results shown in table 15.

Table 15. The ARFF Agent Capabilities of Representative U.S. Airports [39]

FAA Autopilot Index, AFFF RQT, and USAF Aircraft***	Selected Airports	Initial Attack Capability (Water and AFFF Agent) (gallons)
B	Missoula Intl, MO	4,500
2000	Medford–Jackson, OR	2,885
	New Hanover County, NC	3,180
	Duluth Intl, MN*	5,940
	Jackson Hole, WY	5,000
	Rapid City Regional, SD	4,000
	Meadows Field, CA	3,580
	Durango–LaPlata, CO*	2,805
	Kalamazoo County, MI	1,700
	Average	3,732
C	Washington National, DC	11,018
3000	Burbank–Glendale, CA	4,295
	Long Beach/Daughtery, CA	12,460
B-52	Palm Springs, CA	4,120
C-141	Savannah Intl, GA	6,489
KC-135	Monterey Peninsula, CA	4,170
E-3A	Chicago–Midway, IL	4,635
XC-135	Colorado Springs Muni, CO	6,695
	Memphis Intl, TN	17,613
	Salt Lake City Intl, UT	9,370
	Average	8,087
D	Anchorage Intl, AK**	15,553
4000	Jacksonville Intl, FL	7,928
	Tampa Intl, FL	7,560
KC-10	Stapleton Intl, CO	9,583
	Port Columbus Intl, OH	6,280
	La Guardia, NY	12,875
	McCarran Intl, NV**	7,426
	Greater Pittsburgh Intl, PA	9,576
	San Diego/Lindbergh, CA	10,300
	SW Florida Regional, FL	7,210
	Average	9,429
E	Atlanta–Hartsfield, AL	23,690
5000	Los Angeles Intl, CA	12,875
	Newark Intl, NJ	8,266
C-5	Honolulu Intl, HI	6,180
E-4	JFK Intl, NY	13,375
	Miami Intl, FL	12,885
	Chicago–O'Hare, IL	20,600
	Phoenix–Sky Harbor, AZ	9,270
	Seattle–Tacoma Intl, WA	7,725
	San Francisco Intl, CA	19,055
	DFW Intl, TX	24,102
	Average	14,366
	Average – Cs, Ds, and Es	10,748

*Tanker capability included.
**Additional equipment "Poor" or "Reserve" not included.
***Military aircraft specified may exceed FAA index.

NFPA, in a review of U.S. airport ARFF capabilities in 1999, found similar results [40]. The percent of airports exceeding CFR water capacity requirements and meeting NFPA 403 requirements were

- CAT 4: 62.9%
- CAT 5: 20.5%
- CAT 6: 32.4%
- CAT 7: 56.3%
- CAT 8: 48.3%
- CAT 9: 77.3%

This data indicates that, particularly for larger airports, many airports exceed CFR requirements.

4.11 AGENT QUANTITIES FOR INTERIOR FIRE CONTROL.

The loss history does not provide quantitative data on the amount of agent needed for an interior attack. In major accidents, large quantities of agent are used after the ground fire is extinguished, as shown in section 4.10.

Omans [33] contends that current CFR agent quantities are not adequate for most confined spills[4] and interior fires. He notes that many aircraft interior fire situations are not near a firefighting water supply; he recommends that tankers for resupply be part of the airport or mutual aid response. Certainly, there are accidents in the loss history where ARFF response to potential trapped or nonambulatory survivors is less than optimum in terms of availability of equipment, including hand lines. This was recognized by the NFPA 403 committee in the 1993 revision cycle, where Q_3 was added. It is also recognized in the allowance for airports to specify HRET equipment for ARFF vehicles.

4.12 EMERGENCY RESPONSE PLANNING.

In reviewing the loss history, a recurring theme was evident: the importance of emergency response planning. This relates to both tactical and strategic responses. Tactical, as used here, relates to the ability to transition from the initial ground fire to the need to potentially assist or rescue nonambulatory occupants. Omans correctly points out that, in many situations, the ARFF tactical response has been insufficient to address the potential for trapped survivors [33]. Tactical response to trapped survivors includes means of access near or into the aircraft, potential need to make an aggressive interior attack (including sufficient agent), and the need to resupply agent.

This tactical response should be an element of an overall strategic response for a major accident. The emergency response plan (FAA Airport Emergency Plan) documents the strategic response. The loss history shows the importance of these plans in effective response to a major accident. At major accidents at Sioux City (1987), Toronto (2005), and Heathrow (2008), emergency response managers/officers noted the value of having practiced the response embodied in

[4] It is not clear what Omans meant by confined spill, since he believes there is sufficient agent for exterior spill fire control.

emergency response plans. While some weaknesses are nearly always observed, the value of the plans and associated training are reflected in successful operations. For example, in the Heathrow B-777 crash with associated unignited fuel spill, an ARFF full-scale simulation was conducted 10 months earlier. Using this experience, plus tabletop exercises, the incident commander implemented a tactical response using foam hand lines instead of turrets. This reduced the potential impact to evacuating occupants. Resupply of foam was found to be an issue, which required revision to the strategic plan [38].

Limitations in emergency response planning have been identified in major accidents in Thailand (2007) and Denver (1987). In both cases, radio communications was an issue (e.g., different frequencies used by responders). Medical triage and impact of weather were also factors. The ARFF equipment training, aircraft familiarization, and emergency exit requirements were identified as emergency response issues in a cargo aircraft interior fire in Philadelphia (1996).

4.13 SUMMARY OF AIRPORT ACCIDENT REVIEW.

Data from the accident review in this report confirms trends identified in earlier studies.

Accident data indicates there is a high degree of survivability for even the most serious accidents. Most accidents occur at or near the ends of the runway. In many cases, passengers are ambulatory and evacuate the aircraft before the arrival of ARFF. A small fraction of occupants (6.5%) involved in major accidents succumb to effects of a postcrash fire. The effectiveness of ARFF assistance at major incidents varies. It was concluded that, when occupants are ambulatory (no traumatic injuries), they tend to self-evacuate. When accidents involve traumatic injuries (i.e., fatal crashes), ARFF may assist in evacuating some occupants. There were only 27 major accidents identified involving large occupant load where ARFF provided potential assistance, indicating the low probability of such an accident. Even under the most favorable response scenarios, ARFF response may have limited effectiveness because of potential rapid breach of the fuselage (by fire or by impact) and resulting rapidly deteriorating cabin conditions.

The trends identified in earlier studies relating to the size of airport accident fires and associated agent use were observed in the accident review. The fire size in most accidents is less than the product of the fuselage length times wingspan, and is usually 50% or less of this area. In exceptional cases, the fire may involve the entire airplane area. ARFF personnel may use much more agent than the CFR or NFPA 403 requires, but the amount of agent generally used for initial fire control appears to be within the required amounts. Additional agent is used in major accidents during the final extinguishment, securing, and recovering phases. Many U.S. airports exceed Part 139 minimum agent requirements. Emergency planning appears to be an important element in successful ARFF responses to major accidents.

5. HAZARD ANALYSIS.

The history of the agent calculation methodology and the accident review provide the basis for reanalyzing fire threats to aircraft. To ensure that all plausible fire threats are identified, a review of aircraft characteristics was performed. Potential new threats from aircraft being introduced into the commercial fleet were identified. Exterior and interior fire threats analyses were then performed.

5.1 AIRCRAFT CHARACTERISTICS.

5.1.1 General Characteristics of Commercial Aircraft.

A complete chart of aircraft characteristics for CATs 5-10 aircraft is provided in appendix A. These data are taken from various sources, some of which conflict with one another. The data should be considered representative and are used here as part of the fire threat assessment.

Table 16 provides representative aircraft in each current aircraft category. The aircraft selected has the longest (or nearly the longest) fuselage length in the category, a relatively wide wingspan, large occupant load, and relatively high fuel load. In each category, it was relatively easy to identify aircraft with the greatest rounded value in each of these areas.

There are anomalies that make the classification of maximums difficult. For example, smaller aircraft in Index 5 have large fuel loads with respect to capacity (Gulfstream III, 3303 gallons, capacity of 26) compared to larger aircraft (BAe146-100, 3099 gallons, capacity of 80). In Index 7, the DC 8, still used as a freighter, has a fuel capacity of 24,275 gallons. This is much greater than the 19,940 gallons of the A310-300 used in table 16 as the representative aircraft. The A330-300 qualifies as Index 9 (209 ft length), but its characteristics are similar to the A330-200, which is an Index 8 because it is just less than 200 ft long.

There is no general correlation of the fuel and passenger loads between aircraft within and across the categories. The only trend is a general increase in these loads and the length and width, as the categories increase.

Table 16. Representative Aircraft Characteristics

CAT (Index)	Aircraft	Overall Length (ft)	Width (ft)	Overall Wingspan (ft)	Length x Wingspan (ft^2)	Maximum Passenger Load	Maximum Fuel Load (gal)	Category TCA/PCA (ft^2)	Two-Thirds Length x Wingspan (ft^2)	Two-Thirds (Length x Wingspan)/ PCA	NFPA 403 Q_2/Q_1
4 (A)	Bombardier Dash 8	73	7	85	6,205	50	835	5,360/ 3,573	4,137	1.15	0.58
5 (A)	ATR-72-500	89	9	89	7,920	74 (+2 crew)	1,574	9,959/ 6,639	5,280	0.80	0.75
6 (B)	A320	123	13	111	13,650	164	25,337	14,379/ 9,586	9,100	0.94	1.0
7 (C)	A310-300	153	19	144	22,030	240	19,940	18,265/ 12,177	14,687	1.2	1.29
8 (D)	A330-200 B-787-800	193 197	16.5 19	198 197	38,210 38,810	293 440	25,700 33,528	24,156/ 16,104	25,873	1.6	1.52
9 (E)	B-747	231	20	196	45,280	480	54,000	30,201/ 20,134	30,187	1.5	1.7
10 (E)	A380-800	240	23	262	62,880	840	81,890	36,231/ 24,154	41,920	1.7	1.9

Since the original development of the TCA/PCA concept, aircraft have become increasingly larger. This is evident by the data in appendix A, as models of aircraft are "stretched" to accommodate greater passenger loads. Stretching the fuselage to accommodate larger passenger capacities can cause the same "family" of aircraft models to exist within multiple ARFF indices or categories. For example, the B-737 aircraft transitions from CAT 6 (148 passengers for a B-737-700) to 184-189 passengers for the B-737-800/900, for the same fuel load. The A340 has variants in both CAT 7 (A340-200) and CAT 9 (A340-300/500/600). The 251-ft B-747-800 is CAT 10, increasing the passenger load by 49 over the CAT 9 B-747-400 (416 passengers, at 231 ft).

An analysis was performed to test the concept that the NFPA Q_2 and ICAO agent amounts may have been derived from the original TCA concepts. This was the fuselage length times the wingspan, hereafter referred to as the aircraft footprint. Tables 4 and 16 provide the maximum TCA and PCA areas for each category. Two-thirds of this TCA was then calculated and divided by the PCA. This ratio was then compared against the Q_2/Q_1 ratios currently in NFPA 403, as shown in table 9. These ratios are almost the same, indicating a relationship between Q_2 and the size of the original TCA. It appears that the Q_2 adjustment factor directly relates to the area of the original PCA, which was two-thirds the fuselage length times wingspan. Whether intentional or not, this ensures that Q_2 is nearly enough to suppress the entire aircraft footprint area and, when combined with Q_1, is more than enough to suppress the aircraft footprint area (see section 6.2.1).

The indexing concept addresses most aircraft in current service. The question is whether it adequately addresses large-frame aircraft, which are being introduced into the commercial fleet. For example, to accommodate the large passenger load, the A380 has two full passenger decks. The B-747 is currently the only other aircraft with a double deck, extending over roughly one-third of the lower passenger compartment. The A380 has been described as an A340 main deck with an A300 upper deck [41]. Access to the A380 will be significantly different than most aircraft. The height from the ground to the bottom of the highest passenger door is 26 ft (7.9 m), roughly twice the height of other large aircraft (13-18 ft). The only comparable condition is the upper deck of the B-747, which also has ingress and egress doors from the upper deck with associated emergency slides.

There is concern that the evacuation slides extend a significant distance from the aircraft. A photograph of the slides is shown in figure 5. Upper-deck slides extend to roughly the outer edge of the inboard engines, preventing close approach of fire apparatus to the aircraft. This could severely limit or prohibit the use of the HRET for skin penetration. Additionally, the number of evacuation slides obstructs application of agent onto any fire or fuel spill directly beneath the aircraft.

Figure 5. The A380 Evacuation Slides

5.1.2 Attributes of Composite Materials.

Like the B-787, the A380 uses advanced composite materials on a large scale. Many major structural elements of both aircraft are made of composites. Two large sections of the A380 upper-fuselage skin are GLAss REinforced fiber metal laminate (GLARE). Carbon fiber laminates are widely used and are found in the upper-deck floor beams and empennage skin. Unlike the B-787, which will feature an all-composite fuselage, the A380 fuselage is still more than 50% aluminum (non-GLARE).

Composites have advantages and disadvantages in terms of exposure to fire. From a structural standpoint, they are more thermally fire-resistant than aluminum. However, because they are partially constructed of combustible materials, they burn. For this analysis, the exterior pool fire is the primary threat of interest.

Composites are engineered materials made from two or more constituent materials. Composites are generally reinforced fiber-based materials that are impregnated with an organic polymer (resin). Structural marine and infrastructure applications generally use glass reinforcement polyester, vinyl ester, or epoxy resins. Aerospace applications use both carbon- and glass-reinforced composites using specialized resin systems. The type and amount of composite materials used on aircraft vary depending on the manufacturer and application on the aircraft. Some of the composite data is considered proprietary. Generally, aviation composites use a thermosetting resin, which remains hard even when exposed to heat. They do not melt and drip like thermoplastic materials. Composites burn when exposed to flame, emitting smoke. Surface burning is generally readily extinguished using water. Many composites self-extinguish when the flaming exposure is removed. Depending on the duration of the exposure, underlying layers may continue to smolder after surface flame extinguishment.

The potential health hazard from burning or residually burned composites in a postcrash fire is well established [42], and treated in ARFF firefighting doctrine and tactics guidance [43-45]. The focus of this discussion is on the fire characteristics of composites; the health issues are not evaluated here.

The composites used on the A380 are discussed in detail by Pora [46]. Key structural elements are shown in figure 6. Many of these structures and associated manufacturing techniques evolved from composite use on the A310, A320, and A340. For example, 13% of the A340 wing structure is carbon fiber-reinforced plastic (CFRP). The 56-ft- (17-m)-long keel beam will be composite for the A340-600. The A310 has a composite fin box, and the A320 has an all-composite tail.

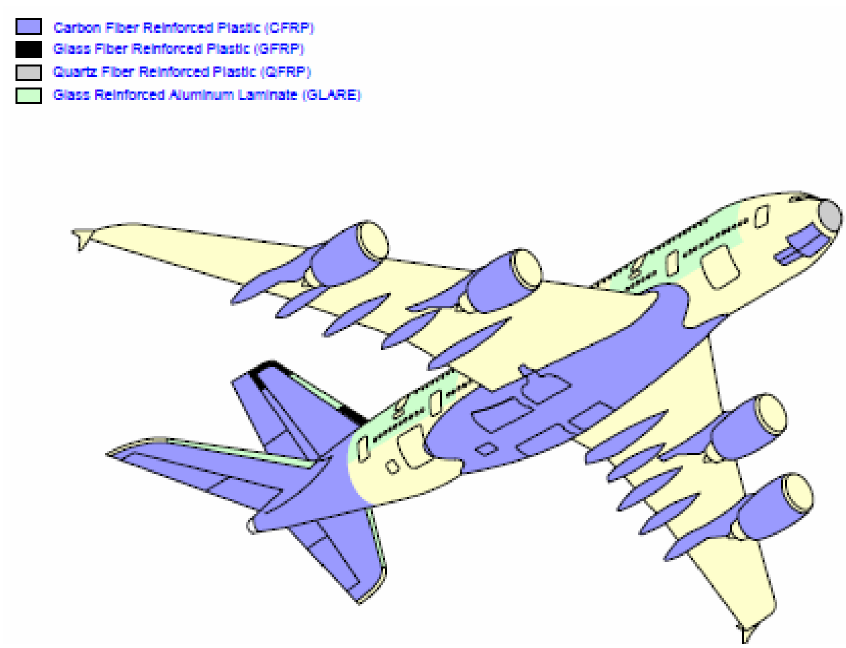

Figure 6. Composites' Use on the A380

A new structural technology is being used on the A380 fuselage. GLARE is used on the upper fuselage, as shown in figure 7 [47]. GLARE is constructed by alternating layers of aluminum and unidirectional glass fiber plies impregnated with an adhesive resin. Approximately 5285 ft^2 (500 m^2) of the fuselage is GLARE; the remaining pressurized fuselage skin is aluminum. This area is on the upper half of the fuselage, as shown in figure 7. GLARE has been in use on German A310 military aircraft since October 1999. The A380 is the first use of GLARE on commercial aircraft fuselage skin.

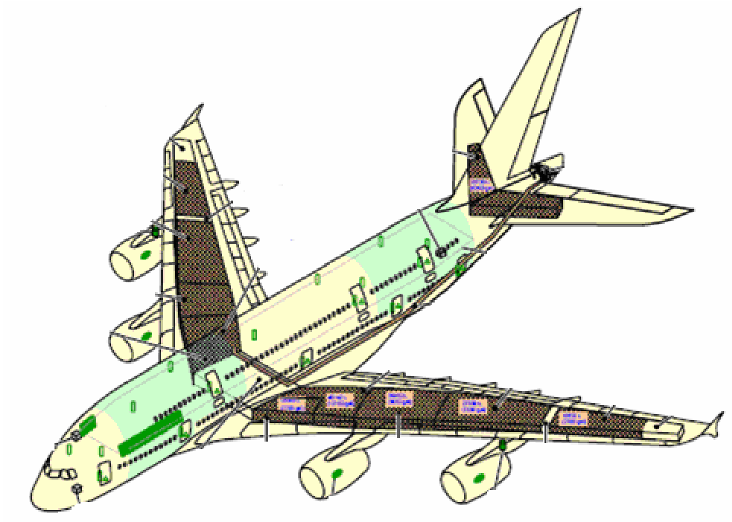

Figure 7. Installation of GLARE on A380 Fuselage (GLARE is in green)

The Boeing airplane rescue and firefighting information site (www.boeing.com/commercial /airports/rescue_fire.htm) provides a graphic of proposed composite use on the B-787 (figure 8). No further technical details have been made publicly available. Reportedly, the fuselage skin carbon laminate is similar to a 16-ply material made available to the FAA for testing.

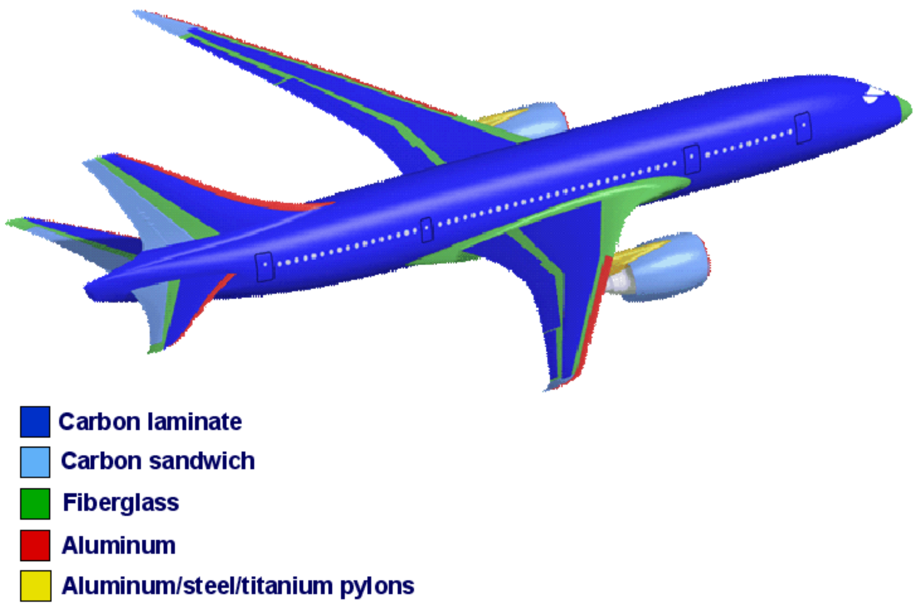

Figure 8. The B-787 Composite Material Locations

Similar to Airbus aircraft, Boeing uses structural composites on current aircraft designs. The B-777, -767, and -757 are all portrayed in the Boeing firefighting website as having composites used for engine nacelles, wing leading edges, aileron panels, tail rudder, elevators and vertical stabilizer components, wing-to-body fairing, main and nose landing gear doors, and empennage skin panels.

5.2 EXTERIOR LIQUID FUEL FIRE THREAT AND SUPPRESSION.

5.2.1 Stages of Liquid Fuel Fire.

A good description of the mechanics of fuel fire hazard was provided in the Gage report.

It was noted that a crash fire creates an immediate hazard to the aircraft and its occupants when the aircraft fuel is spilled from a rupture of the fuel tanks or lines. These ruptures could occur as a result of

- contact of the lines or tanks with a fixed obstacle.
- contact of the lines or tanks with a detached or displaced aircraft component.
- relative motion between aircraft components caused by impact loads.
- dynamic acceleration forces that generate internal loadings.

In addition, once a fire has started, whether it involves the fuel or another combustible, the lines or tanks could be ruptured as a result of fire exposure.

The Gage report asserted that most occurrences that produce fuel spillage take place when the aircraft is in motion. Pressure and viscosity forces of the air tend to disperse spilled liquid fuel into droplets or a fine mist. As the aircraft slows, the droplets increase in size, becoming a solid stream as the aircraft stops.

The droplets, mist, and liquid fuel wet the ground along the wake of the source; this wetting deepens and broadens to the position where the aircraft comes to rest. The Gage report contended that the fuel that wets the ground in the wake of the aircraft is normally a very thin layer. If ignited, it burns away rapidly; if not ignited, it may evaporate or soak into the ground quickly. If the fuel mist is ignited, a large, rapidly enveloping fire results, which often leads observers to believe that the aircraft exploded. However, this mist fire rises away from the aircraft and burns out in 15 to 20 seconds. The mist fire generally does not present a direct hazard to the aircraft or the occupants inside. However, this mist fire can ignite liquid fuel spilled on the ground, spilling from tanks, or on wetted surfaces. This mist fire was the subject of research to create an anti-misting aviation fuel. Tests of this concept were unsuccessful, and the effort was abandoned.

If the mist fire does not occur, the spilled liquid fuel can be ignited by numerous other ignition sources present in an aircraft crash. If the spilled fuel is above its flashpoint, the fire then propagates through the vapor-air mixture over the surface of the fuel at a rate of 700 to 800 ft/min for low-flashpoint liquids (aviation gasoline (AvGas)). Both AvGas and JP-4 have flashpoints well below zero, and in almost all accidents the fire may spread in this manner. However, kerosene (Jet A) and JP-5 fuels, with flashpoints of 110° and 140ºF, respectively, are frequently below their flashpoints when spilled. The ignition source must then heat the liquid sufficiently to evaporate some liquid and then ignite the resultant vapor-air mixture. Once ignited, the flame heats adjacent layers of the liquid fuel and increases its evaporation rate to produce a combustible fuel-air mixture above the surface of the fuel. In this manner, the flame propagates slowly over the fuel surface at a rate of only 30 to 40 ft/min.

Once the fire is ignited, radiant heat from the fire plume warms and evaporates the liquid fuel in the pool. The vaporized fuel and air diffuse into the combustion zone above the surface of the liquid pool, where the burning reaction occurs. Gasoline almost immediately attains a combustion rate of 0.15 in. of liquid depth per minute; kerosene fuels will burn more slowly at first but reach a combustion rate of 0.13 in./min in a period of 2 to 3 minutes. The temperature of the plume ranges from about 1100°F at the edge to l500° to 2000°F in the center; intermittent peak temperatures as high as 2200°F may occur. The height of the plume is on the order of 1.5 to 2.0 times the diameter of the fire.

The Gage report identified the basic stages of a crash fire as consisting of

- an enveloping mist fire that persists for 15 to 20 sec.
- a residual fire involving spilled or/and spilling fuel that gradually increases in intensity. This developing fire may ignite other combustibles, such as magnesium components, tires, oil, hydraulic fluid, and cargo.
- a developing fire that reaches a level of maximum intensity in about 2 to 5 minutes.
- a gradual decrease of the maximum-intensity fire when the spilling and spilled fuel is exhausted. This may not occur for a considerable time and may be quite slow.

The development of the fire may be accelerated or its maximum intensity may be increased by vapor-air explosions in confined spaces or by the sudden overpressure failure of the tankage under fire exposure. There is no ready method to estimate when fuel tanks or lines may rupture, but it may be relatively rapid. In the China Air incident (Okinawa, 2007), a starboard wing tank ruptured in about 1 minute (see section 4.5.2.1). Interior aircraft fires may be increased in intensity by the relieving of oxygen cylinders.

An aircraft crash fire is primarily a two-dimensional spill fire. However, spilling fuel, fuel on aircraft structures, and burning of other combustibles will add a third dimension to a portion of the fire. In addition, when fire is present inside compartments, such as the fuselage, nacelles, and wheel wells, three-dimensional fires may also exist. The dimensions of a crash fire are defined by the area in which significant quantities of liquid fuel have spilled or are spilling. The fuel that spills in the wake of the aircraft or that flows some distance from the spill source generally burns away quickly and does not create an exposure hazard or extinguishing problem. The area in which the fuel is spilled depends on the sources of spillage and on the terrain at the crash site. If a crash occurs on an upslope, the fuel will flow down, enveloping the aft fuselage in the fire; if it occurs on a downslope, the forward fuselage will be enveloped in fire.

The dynamics of liquid fuel fires have not changed since the Gage report. The occurrence of misting fuel fires seems to have lessened, at least in incidents within the U.S. Passengers still report dramatic fires, e.g., blowtorches, which should not be discounted. These fires may lead to more rapid weakening and penetration of the fuselage. The Gage report contention that a developing fire reaches a maximum intensity in 2 to 5 minutes needs qualification. Sarkos [15] notes that accidents occurring with relatively small amounts of fuel spillage (or none at all) and, with the fuselage primarily intact, can result in a cabin fire leading to fire fatalities. While the

Gage report statement may be generally true (e.g., the China Air, 2007 incident), it does not yield the most conservative result from a fire threat standpoint.

The near-universal replacement of AvGas and JP-4 with Jet-A and JP5/8 for large aircraft has improved fire safety, both in terms of ignition resistance and low flame spread rates over fuels, as noted in the Gage report.

There is concern that fuel stored outside the wing areas in the new A380 may lead to a more persistent, shielded pool fire within a damaged fuselage. The A380 carries over 6000 gallons of fuel outside the wings in a tail section fuel tank called the trim tank. Other aircraft carry fuel outside the wings, including the B-777-300, B-747, and A300-600. This has not been explicitly identified as an issue in the loss history. Fuel stored only in the wings would not necessarily prevent a shielded fuel fire within a damaged fuselage structure.

5.2.2 Estimating Fuel Spill Sizes in Aircraft Accidents.

In the analysis for this report, it was difficult to directly relate aircraft fuel quantity to the potential fire area in an aircraft accident. Geyer made several attempts to use aircraft fuel loading for estimating ARFF requirements. In his 1972 analysis, he noted that, within any given length category, certain aircraft present a greater intrinsic fire hazard than others, based on the fuel capacity [13]. Geyer's fire tests revealed the fundamental parameters in any aircraft accident involving ground wind effects on free-burning pool fires. The resulting flame-trailing phenomenon (i.e., the aircraft downwind of the spill fire) was the key threat. Geyer asserted that the maximum quantity of fuel carried onboard an aircraft that could be spewed over the critical fire area was also important. The potential hazard associated with a given aircraft could realistically be expressed in terms of the fuel spill density within the critical fire area and its total free-burning time. Representative fuel spill densities and burning times were calculated for several aircraft using the critical fire area and the total fuel capacity of each aircraft (see appendix F). The fuel burning times were based on a fuel burning rate of 0.089 gpm/ft^2 for JP-4, 0.082 gpm/ft^2 for Jet A, and 0.102 gpm/ft^2 for AvGas for large pool fires. Geyer believed the fuel spill density might also serve as a means for estimating the magnitude of the potential hazard that could result from ruptured or exploding fuel tanks. With this knowledge of potential fuel spill densities, the potential hazard associated with each individual aircraft in a particular length category can be estimated.

The usefulness of fuel loading as a direct measure for ARFF response capabilities, as postulated by Geyer, has not been realized. Geyer recognized this limitation in later work while studying military aircraft [14]. Geyer calculated the theoretical and practical critical fire areas for selected military aircraft along with their maximum fuel load, fuel density, and burning time within the PCA and the number of occupants on each aircraft. These hazards were portrayed graphically, in which the number of aircraft occupants was plotted as a function of the fuel spill density within the PCA, along with the fuel burning time (see appendix F). These data assumed the instantaneous release of the total fuel load over the PCA, which could only occur during takeoff. Geyer concluded that there was no meaningful relationship between the fuselage length of military and commercial aircraft and the fuel spill density and burning time. Since the melting time of aluminum aircraft skin is approximately 1 minute, all aircraft would be subject to destruction by fire without the rapid intervention of ARFF. Geyer's recommendation was that

ARFF vehicle requirements should be based on the largest PCA, assuming a minimum burn time of 3 minutes. This essentially equates to an assumption (which remains to the time of this writing) that there is potentially unlimited burn time.

Providing a direct correlation between aircraft fuel load and probable fire area seems like an appropriate approach in calculating ARFF agent requirements. Sarkos correctly points out that the jet fuel load fire hazard represents the greatest danger in aircraft crash accidents [15]. In accidents where large quantities of fuel are released and ignited and the fuselage is damaged or susceptible to direct fuel fire impingement, the dominance of the fuel fire is clear. Using current data and knowledge, this approach was again revisited.

The first attempt was to use a simple correlation method to calculate the maximum unobstructed fuel spill area for a given fuel load. A guideline used in previous studies is a spill area of 12 ft^2 per gallon of fuel [14]. This equates to a 0.13-inch (3.3-mm) fuel thickness, which is in reasonable agreement with handbook values of 4 mm for minimum fuel spill thicknesses [48]. For a B-747 with a fuel load of approximately 52,000 gallons, there is a potential maximum fire area of about 624,000 ft^2 or over 14 acres of fire. This area is unreasonably large and is not supported by any of the loss history; the biggest areas involve secondary grass/brush fires associated with a crash. Maximum areas identified in the literature search are 1 to 2 orders of magnitude (10-100 times) less than this area.

Using this minimum fuel depth and a fuel regression (burning) rate of 0.125 in/min, the minimum fuel depth area described above would burn for about 1 minute. If the minimum fuel depth was tripled to create a fuel burn time of not less than 3 minutes (as established by Geyer), the result would be a fire area of roughly 210,000 ft^2 for the B-747 example. This is an unreasonably large potential fuel spill area compared to actual crash fires.

A revised estimating technique was attempted using the loss history data described in table 14. Only the ten accidents involving takeoff were used in the analysis, because it was reasonable to assume a full fuel load. This fuel load was divided by the assessed fire area to determine the number of gallons of fuel per area of fire involvement. The resulting fuel load factor varied from 0.33 to 3.79 gal/ft^2. A lower factor represents a greater hazard, i.e., less fuel is required to create 1 square foot of burning area. For example, if a fuel factor of 1.0 gallon of fuel per square foot of fire area was found to be representative of actual incidents, a fire area for a full release of fuel from a B-747 (52,000 gallons of fuel) could be expected to be 52,000 gal ÷ 1.0 gal/ft^2 equals 52,000 ft^2 of fire area.

Again, the data proved unsatisfactory for using the fuel load to assess potential fire size. When the fuel factor was low (e.g., 0.2 to 0.4 gal/ft^2), the accident was either catastrophic (all or most passengers were killed, usually involving a crash into other structures) or the airplane was small (e.g., CAT 3). However, this did not hold true in all cases. Also, there was no general correlation between this factor and the fire area/TCA ratio previously estimated. Finally, the number of takeoff accidents used (ten) was too small to draw generalized conclusions.

Fuel spill rates might be used to estimate fire sizes. Mansfield [49] provided a guideline estimate of fuel spill size, ±20%, based on the fuel leak rate

$$D = 3.5\ \sqrt{Q} \tag{7}$$

where D = diameter of the spill (feet)
Q = spill leak rate (gpm)

Using the example of the B-747 with a 52,000-gallon fuel load, a maximum 3-minute duration spill size can be estimated to be about 170,000 ft^2, somewhat less than the 210,000 ft^2 estimated with the minimum fuel depth calculation. Except for truly catastrophic situations (e.g., September 11, 2001 terrorist attack on the World Trade Center), crash fires do not involve the discharge of the entire aircraft fuel load contents in 3 minutes. There is no reasonable method to quantify a representative fuel spill rate.

In summary, previous findings that demonstrated the challenges of directly correlating aircraft fuel load with potential crash fire area were identified as "unrewarding." There was no quantitative method to predict how much fuel will spill, when it will ignite, at what rate it may spill, or what total quantity may be involved. There is no method to predict whether a fire will be located in close proximity to the aircraft, whether the fire will occur on just one side, or whether the aircraft fuselage will be immersed in fire.

This finding suggests that the threat analysis approach described in section 3.2.2, and which forms the basis of the current Q_1 calculation, is a more reasonable approach than estimating the potential maximum fire size. In other words, the fire size should be assumed to be of unlimited or infinite size, and the agent required based on protecting occupants.

Note that the loss history includes only aircraft having fuel loads up to approximately 52,000 gallons (e.g., current version of the B-747). The fuel load of the new A380 is approximately 82,000 gallons. While increases in fuel load have been made in the past, and adjustments have been made to the index/category Q_1, the A380 represents a 50% increase over the next biggest fuel load currently in the commercial fleet. While nothing in the history shows that this would necessarily cause a substantially bigger pool fire area, a cautious approach for protection is in order.

5.2.3 Estimating Suppression for Pool Fires.

5.2.3.1 Introduction to Analysis Method.

In section 5.2.2, it is established that quantifying the size of a liquid pool fire threat is extremely difficult. To analyze the recommended agent required, the pool size variable was eliminated by assuming an unlimited fuel supply and fire size. If there are sufficient resources to ensure occupant safety for this unlimited fire size, most reasonable crash scenarios should be addressed. Given an unlimited fire size, the approach was to calculate the radiant heat from the fire and the resulting impact on an intact aircraft fuselage. Provided that occupants survived this threat, they may then exit and move to safety away from the aircraft. Two conditions were established: (1) the prevention of heat penetration into the aircraft and (2) the subsequent interior ignition and prevention of a thermal threat to individuals who have exited the aircraft.

Three representative aircraft lengths were used: (1) 240 ft (e.g., A380, representing the upper end of CAT 9); (2) 159 ft, representing the upper end of CAT 6; and (3) 89 ft, representing the upper end of CAT 4. Aircraft have different fuselage aluminum thicknesses based on the size of the aircraft and the location on the fuselage. A worst-case (very thin) fuselage thickness was assumed (0.02 in.). To check the sensitivity of the analysis to this parameter, a 0.10-inch thickness was also investigated. Additionally, a fuselage meeting the new FAA 4-minute burnthrough criteria (e.g., composite or well-insulated fuselage, see section 5.3.1) was also investigated for the high-challenge scenario.

Two other parameters were varied. Since wind affects fire characteristics, 0- and 20-mph wind conditions were assessed. Heat-transfer characteristics are time-dependent, so the arrival time of ARFF was varied to determine the impact of delayed agent application.

The scenarios evaluated and associated variables are shown in table 17.

Table 17. Scenarios Evaluated for Agent Requirements

Scenario	Aircraft Length (m (ft))	Aircraft Skin Thickness (mm (in.))	Aircraft Skin Material	Wind
1	73 (240)	0.5 (0.02)	Aluminum	No
2	48 (159)	0.5 (0.02)	Aluminum	No
3	27 (89)	0.5 (0.02)	Aluminum	No
4	73 (240)	2.5 (0.1)	Aluminum	No
5	73 (240)	0.5 (0.02)	Aluminum	Yes, toward aircraft
6	73 (240)	2.5 (0.1)	Aluminum	Yes, toward aircraft
7	73 (240)	0.5 (0.02)	Aluminum	Yes, away from aircraft
8	73 (240)	Unspecified	Composite	No

Having established the fire threat and fuselage characteristics, the agent required to meet threshold performance criteria (i.e., prevention of interior ignition and injury to evacuated occupants) was calculated using the conservative value of 0.13 gpm/ft^2 for AFFF fire control and extinguishment. A companion report [9] provides the details and derivation of the models used to estimate the volume of suppression agent needed to prevent interior aircraft ignition for a range of ARFF arrival times and fuel spill offset distances. The following sections summarize the results of the analysis.

5.2.3.2 Fire Threat Model.

In the fire threat model, the aircraft was assumed to be intact, and the spill fires were not assumed to immerse any portion of the aircraft. An analysis of spill fire scenarios indicated that immersed portions of the aircraft could result in interior ignition in as little as 40 seconds, which is shorter than the assumed ARFF arrival time. The following provides an overview of the analysis method.

Ignition of the aircraft interior was established as a performance threshold because flashover conditions can develop within 60 seconds after interior ignition. This is consistent with observations from aircraft incidents and fuselage tests as well as with data obtained from interior fire spreading in passenger rail cars. Not all interior ignition scenarios result in rapid development of flashover conditions; this depends on the location of ignition and the type and arrangement of collocated combustible material. Nevertheless, the analysis is based on the ignition time as a conservative performance threshold.

The model used to determine the ignition of the aircraft interior was derived using a minimum of two independent sets of criteria. The first criterion was based on the time required to melt any portion of the aircraft skin and is applicable only to high heat flux boundary conditions given a melting temperature of about 649°C for aluminum (the assumed skin material). Interior ignition, in this case, was assumed to be 10 seconds after the skin melted, consistent with previous analysis approaches. The second criterion was based on the time required for the 204°C isotherm (material area having uniform temperature) to penetrate 1.1 cm into the insulation. This is a heuristic-performance threshold that was deduced from full-scale aircraft tests and the melting temperature of a DuPont™ Tedlar®, a typical moisture barrier for aircraft insulations. This criterion typically applies to low heat flux boundary conditions (i.e., large offset distances or large-diameter spill fires). To determine the melting times and isotherm penetration distances for scenario- and parameter-specific transient exterior boundary fluxes, the heat transfer model HEATING was used. The aircraft skin and insulation were treated as a one-dimensional heat transfer system in this model.

The model used to determine safe egress was based on determining the distance at which the heat flux to a person would be equal to the pain threshold tenability limit, 2.5 kW/m^2. This is a steady-state tenability limit; transient exposures and dose equivalents were not considered. Higher heat fluxes could result in second-degree burns or blistering in less than 60 seconds.

The heat flux at a target location (aircraft skin or person) was determined by computing the flame shape and view factor under a given wind condition. The fire was assumed to be equal to the airplane length and to extend indefinitely perpendicular to the airplane fuselage. Targets were assumed to be rotated and elevated so the view factor was maximized. The maximum elevation for an airplane target location was 6.1 m (20 ft). For a person, it was 1.8 m (6 ft). A person was also assumed to travel to safety in a direction parallel to and within 1 m of the fuselage.

The heat flux is a direct function of the distance between the fire and the target for a given spill fire scenario. The quantity of agent necessary to produce a favorable outcome (i.e., prevent ignition or allow safe egress) was determined assuming that 0.13 gallon of agent was necessary to extinguish 1 ft^2 of burning fuel. In practice, the agent volume to suppress fire may be as low as 0.07 gal/ft^2 of burning fuel. The agent was assumed to consist of two volumes: an initial volume associated with the earliest arriving ARFF vehicle (i.e., Q_1), and an additional volume that arrives later and is tied to the total required capacity of the airport crash fire rescue equipment (i.e., Q_2 or Q_T). The initial agent volume was assumed to be used to prevent interior aircraft ignition and was delivered over a 60-second period, as required by NFPA 403. The additional agent volume was assumed to be used to suppress the fire to allow for safe egress. Because egress is based on a steady-state threshold value, it was not necessary to assume an agent arrival or delivery time for the additional agent volume.

It was found that a heat flux of 9.59 kW/m^2 was the threshold value for causing the aircraft interior to ignite. This is called the isoflux in this analysis. The isoflux distance is the maximum distance from an aircraft where a fire could cause interior ignition due to thermal radiation. The distance from the edge of the fire at which this flux occurs varies with the scenario, but ranges from about 3 m for an aircraft located downwind of a fire to 33 m for an aircraft located upwind of a fire.

It was found that over the parameter range considered, there are basically five ARFF response time fuel spill offset regions. These regions are as follows:

- Time Region I: ARFF needs to extinguish the fire to the 9.59-kW/m^2 isoflux distance to prevent aircraft ignition.
- Time Region II: ARFF needs to extinguish the fire beyond the maximum distance that the fire could produce an incident heat flux of 9.59 kW/m^2 (the isoflux) at the aircraft outer surface to prevent interior aircraft ignition. This occurs in situations where the fuselage is heated to such an extent that an incident heat flux less than 9.59 kW/m^2 may still result in interior ignition.
- Time Region III: ARFF arrives before the aircraft ignites, but suppressing some or all of the spill fire does not prevent ignition. In other words, ARFF has arrived too late or the fire is too close to the aircraft to prevent interior ignition.
- Time Region IV: ARFF arrives after the aircraft interior has ignited.
- Time Region V: the maximum incident heat flux at the aircraft is less than 9.59 kW/m^2, thus, ignition is not predicted regardless of the ARFF suppression actions.

Figure 9 shows example Scenario 1 wherein the time regions for a 240-ft-long aircraft with a 0.02-in.-thick aluminum skin is exposed to a spill fire without wind.

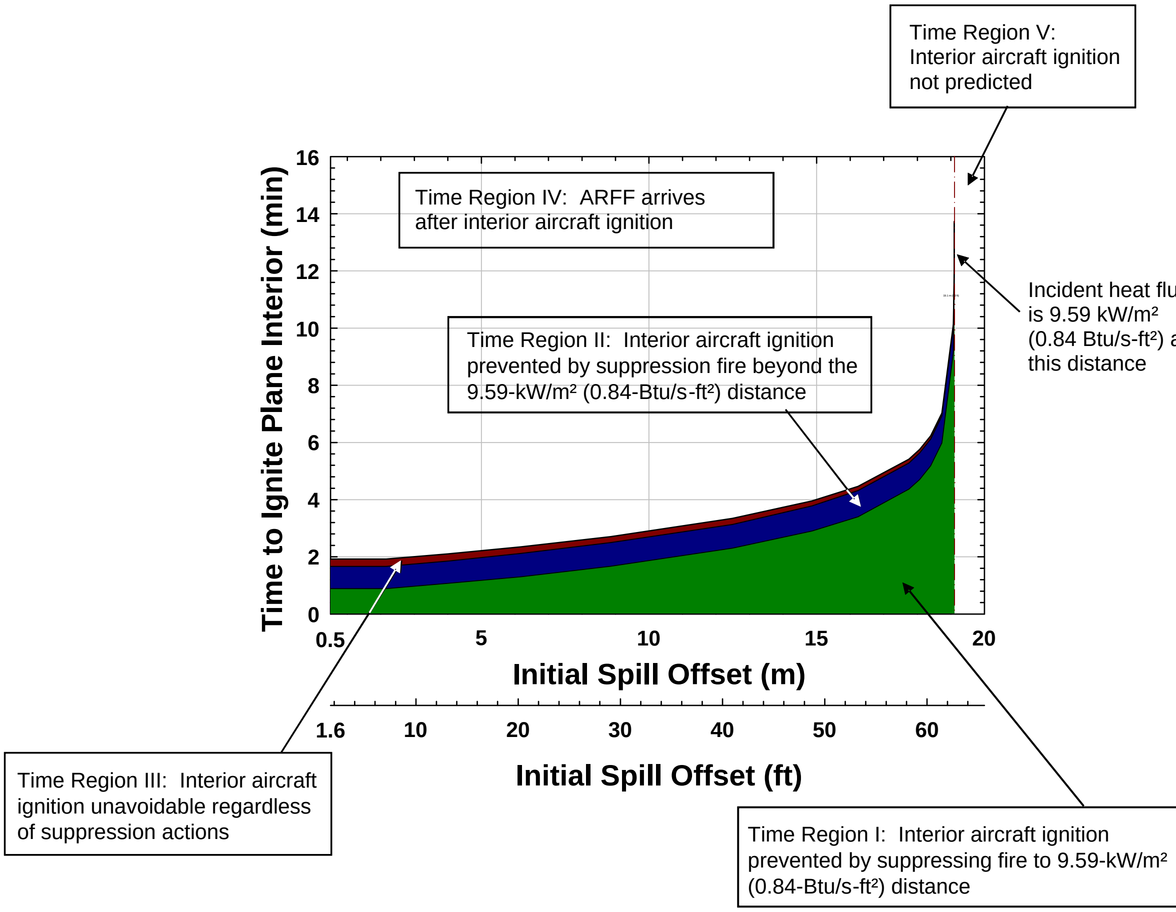

Figure 9. Example Response Time Regions, Scenario 1

Two estimated agent tables are associated with each group of scenarios considered in the companion report [9]. The initial table summarizes the volume of agent required to prevent ignition for different initial spill fire offset distances and ARFF arrival times. This corresponds to the initial agent volume brought by the first arriving ARFF (Q_1). The range of offset distances considered is between about 0.5 m and the distance at which ignition is not predicted, which varies among the scenarios. The assumed ARFF response times ranged from 1 to 4 minutes. A maximum first arriving capacity of 5000 gallons of agent was also assumed; initial agent volumes greater than 5000 gallons were not determined since 5000 gallons was assumed to be a reasonable maximum initial capability. The table entries are color coded by time region. Scenario 1 is applicable to a 240-ft-long aircraft having a 0.02-in.-thick aluminum skin exposed to a spill fire without wind. An example of the initial table for Scenario 1 is shown in table 18.

Table 18. Suppression Agent Volumes Required to Prevent Ignition, Scenario 1

Initial Spill Offset (m (ft))	ARFF Arrival Time (min)						
	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0.5 (1.6)	7,450 L (1,970 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P
1 (3.3)	7,250 L (1,920 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P
2 (6.6)	6,680 L (1,770 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P
3 (9.8)	6,290 L (1,660 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P
5 (16.4)	5,440 L (1,440 gal)	9,090 L (2,400 gal)	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P
6 (19.7)	5,070 L (1,340 gal)	6,380 L (1,690 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P	I.C.N.P	I.C.N.P
8 (26.2)	4, 300 (L) (1,140 gal)	4, 300 (L) (1,140 gal)	13,250 L (3,500 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P	I.C.N.P
10 (33)	3,520 L (930 gal)	3,520 L (930 gal)	4,260 L (1,130 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P	I.C.N.P
12 (39)	2,750 L (730 gal)	2,750 L (730 gal)	2,750 L (730 gal)	4,930 L (1,300 gal)	18,900+ L (5,000+ gal)	I.C.N.P	I.C.N.P
14 (46)	1,980 L (520 gal)	1,980 L (520 gal)	1,980 L (520 gal)	1,980 L (520 gal)	4,160 L (1,100 gal)	18,900+ L (5,000+ gal)	I.C.N.P
16 (52)	1,180 L (310 gal)	1,180 L (310 gal)	1,180 L (310 gal)	1,180 L (310 gal)	1,180 L (310 gal)	1,640 L (440 gal)	18,900+ L (5,000+ gal)
18 (59)	430 L (110)	430 L (110)	430 L (110)	430 L (110)	430 L (110)	430 L (110)	430 L (110)
19.1 (63)	none	none	none	none	none	none	none

Key: I.C.N.P: Internal aircraft ignition cannot be prevented under the assumed conditions.
Green: Time Region I
Blue: Time Region II
Red: Time Region III or IV
Black: Time Region V
+over 5000-gal condition

A secondary table is used to summarize the volume of additional agent required to allow for safe egress for different offset distances and ARFF arrival times (table 19). The amount of agent necessary to prevent ignition is assumed to have been used initially, if applicable. In cases where interior ignition is predicted, flame impingement is possible (wind conditions), or over 5000 gallons of agent are required to prevent ignition, the agent volumes shown are the total amounts required to allow for safe egress. This may lead to some initially counterintuitive results: the agent volumes decrease, then increase, then decrease with an increasing offset distance. This is merely an artifact of the presentation; in all cases, the total volume of agent required to allow for safe egress decreases with increasing offset distance. The table entries are coded by time region for easy comparison with the corresponding initial agent table. Table 19 shows an example of the secondary table for Scenario 1.

Table 19. Additional Suppression Agent Volumes Required to Allow for Occupants to Egress the Aircraft on the Fire Side†, Scenario 1

Initial Spill Offset (m (ft))	ARFF Arrival Time (min)						
	1.0	1.5	2.0	2.5	3.0	3.5	4.0
0.5 (1.6)	26,200 L (6,930 gal)	33,700 L (8,900 gal)‡	33,700 L (8,900 gal)	33,700 L (8,900 gal)	33,700 L (8,900 gal)	33,700 L (8,900 gal)	33,700 L (8,900 gal)
1 (3.3)	26,200 L (6,930 gal)	33,500 L (8,850 gal)‡	33,500 L (8,850 gal)	33,500 L (8,850 gal)	33,500 L (8,850 gal)	33,500 L (8,850 gal)	33,500 L (8,850 gal)
2 (6.6)	26,400 L (6,980 gal)	33,100 L (8,750 gal)‡	33,100 L (8,750 gal)	33,100 L (8,750 gal)	33,100 L (8,750 gal)	33,100 L (8,750 gal)	33,100 L (8,750 gal)
3 (9.8)	26,400 L (6,980 gal)	32,700 L (8,650 gal)‡	32,700 L (8,650 gal)	32,700 L (8,650 gal)	32,700 L (8,650 gal)	32,700 L (8,650 gal)	32,700 L (8,650 gal)
5 (16.4)	26,500 L (7,000 gal)	22,800 L (6,040 gal)	31,910 L (8,440 gal)	31,910 L (8,440 gal)	31,910 L (8,440 gal)	31,910 L (8,440 gal)	31,910 L (8,440 gal)
6 (19.7)	26,500 L (7,000 gal)	25,100 L (6,650 gal)	31,500 L (8,340 gal)‡	31,500 L (8,340 gal)	31,500 L (8,340 gal)	31,500 L (8,340 gal)	31,500 L (8,340 gal)
8 (26.2)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	17,500 L (4,630 gal)	30,750 L (8,140 gal)‡	30,800 L (8,140 gal)	30,800 L (8,140 gal)	30,800 L (8,140 gal)
10 (33)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	25,700 L (6,810 gal)	30,000 L (7,930 gal)‡	29,900 L (7,930 gal)	29,900 L (7,930 gal)	29,900 L (7,930 gal)
12 (39)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	24,300 L (6,420 gal)	29,200 L (7,730 gal)‡	29,200 L (7,730 gal)	29,200 L (7,730 gal)
14 (46)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	24,300 L (6,420 gal)	28,400 L (7,520 gal)‡	28,400 L (7,520 gal)
16 (52)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	25,800 L (6,880 gal)	27,700 L (7,320 gal)‡
18 (59)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)
19.1 (63)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)	26,500 L (7,000 gal)
20 (66)	26,100 L (6,910 gal)						
25 (82)	24,180 L (6,400 gal)						
30 (98)	22,240 L (5,880 gal)						
35 (115)	20,310 L (5,370 gal)						
40 (131)	18,370 L (4,860 gal)						
50 (164)	14,510 L (3,838 gal)						
60 (197)	10,640 L (2,810 gal)						
70 (230)	6,770 L (1,791 gal)						
80 (262)	2,900 L (770 gal)						
85 (279)	970 L (260 gal)						
87.5 (287)	none						

†No initial agent assumed for table 18 I.C.N.P and 18,900+-L (5,000+-gal) cases.
‡ Table 18 18,900+-L (5,000+-gal) case.

Key: I.C.N.P: Internal aircraft ignition cannot be prevented under the assumed conditions.
Green: Time Region I
Blue: Time Region II
Red: Time Region III or IV
Black: Time Region V
+over 5000-gal condition

The agent volumes needed to prevent interior aircraft ignition, as shown in table 18 and the corresponding tables in the companion report, have a counterintuitive trend. In many instances, the maximum volume of agent reported for a particular ARFF arrival time decreases as the ARFF arrival time increases. Table 20 provides an example, which is a subset of the cases shown in table 18. One interpretation of the information in table 20 is that the required suppression agent volumes decrease with increasing response time (see shaded cells). This is not an entirely correct interpretation of the results since the volumes reported correspond to specific offset distances for which a solution was determined. For a fixed ARFF response time, the agent volume varies continuously with offset distance up to the point where no solution is possible or the volume of agent is greater than 5000 gallons. This means that the maximum volumes reported in the tables for a fixed ARFF response time are not required amounts, but rather, volumes necessary to prevent ignition for the particular fire offset distance per se. In simple terms, faster arriving ARFF have a greater opportunity to prevent interior ignition. An exposing fire could be closer to the aircraft, requiring a greater amount of agent. Consider the 3-minute ARFF response shown in table 20 where 1100 gallons of suppression agent is required to prevent ignition, given an initial offset distance of 14 m. If the offset distance decreases to 12 m (39 ft), the agent volume becomes greater than 5000 gallons. Between 12 and 14 m, an intermediate offset distance and corresponding volume of suppression agent between 1100 and 5000 gallons could be determined. This example also shows the sensitivity of the exposing fire location to the ability of ARFF to affect the outcome.

Table 20. Suppression Agent Volumes Needed to Prevent Ignition for Scenario 1 (Subset of Table 18)

Initial Spill Offset (m (ft))	ARFF Arrival Time (min)				
	2.0	2.5	3.0	3.5	4.0
8 (26.2)	13,250 L (3,500 gal)	$18{,}900^+$ L ($5{,}000^+$ gal)	I.C.N.P	I.C.N.P	I.C.N.P
10 (33)	4,260 L (1,130 gal)	$18{,}900^+$ L ($5{,}000^+$ gal)	I.C.N.P	I.C.N.P	I.C.N.P
12 (39)	2,750 L (730 gal)	4,930 L (1,300 gal)	$18{,}900^+$ L ($5{,}000^+$ gal)	I.C.N.P	I.C.N.P
14 (46)	1,980 L (520 gal)	1,980 L (520 gal)	4,160 L (1,100 gal)	$18{,}900^+$ L ($5{,}000^+$ gal)	I.C.N.P
16 (52)	1,180 L (310 gal)	1,180 L (310 gal)	1,180 L (310 gal)	1,640 L (440 gal)	$18{,}900^+$ L ($5{,}000^+$ gal)
18 (59)	430 L (110 gal)	430 L (110 gal)	430 L (110 gal)	430 L (110 gal)	430 L (110 gal)

Key: I.C.N.P: Internal aircraft ignition cannot be prevented under the assumed conditions.
Green: Time Region I
Blue: Time Region II
Red: Time Region III or IV
Black: Time Region V
$^+$over 5000-gal condition

The data should be interpreted by comparing the range of offset distances for which a given volume of suppression agent can prevent ignition. This always increases with increasing ARFF response time. For example, for a 14-m initial offset distance, 1100 gallons of suppression agent is required to prevent ignition if the ARFF response time is 3 minutes, but only 520 gallons is required if the response time is 2.5 minutes. Put another way, 1100 gallons of suppression agent becomes effective for fires with smaller initial offset distances as the ARFF arrival time decreases.

5.2.3.3 Discussion of Modeling Results—Fuselage Integrity.

The analysis summarized in section 5.2.3 and detailed in the companion report [9] demonstrates the sensitivity of the agent calculations to the time of ARFF response and to the proximity of the aircraft to the edge of the exposing pool fire. Success is defined as the prevention of ignition in the aircraft. An interesting characteristic results from this analysis. For most cases, more agent is predicted to be required when ARFF arrives more quickly. This is counterintuitive, since a bigger fire area is likely to occur with a longer delay. The result of more agent for quicker response is an attribute of the modeling technique and assumptions. When ARFF arrives more quickly, more time is available to prevent interior ignition, thus the leading edge of the fire can be closer to the aircraft. This leads to a greater fire area, and correspondingly more agent. This attribute will be addressed in section 6.2.1.

A detailed review of agent quantities is performed in section 6.2.1. A cursory review of the data shows how sensitive the calculations are to the proximity of the fire to the aircraft. In the scenarios, Time Region II (blue) is considered borderline, since fire must be extinguished beyond the isoflux distance to prevent interior aircraft ignition. In simpler terms, sufficient heat has already been transferred to the fuselage so the lower flux beyond the isoflux may be sufficient to cause interior fire ignition. The agent estimated for extinguishment to the isoflux distance, which assures prevention of interior ignition (Time Region I, green), is a more likely prediction of success. Using Time Region I criteria, the initial offset distance of the fire for ignition prevention for CATs 9/10, 6, and 4 varies by only 2-5 m in no-wind conditions when response time is delayed from 2 to 3 minutes. The initial offset for the 2-minute response is on the order of 10 to 12 m. For fires occurring within 3 m or less of the fuselage, success is predicted only when response time is less than 1.5 minutes. Fortunately, most crash fires have some growth period (e.g., Okinawa, 2007). Immediate fuselage involvement does occur, however (Los Angeles, 1978); in some cases, response time on the order of 1 minute is achieved (Los Angeles, 1978; Toronto, 2005).

The impact of fuselage thickness is similar to the characteristics of the response time variable. Because the skin can resist heat transfer for a longer period, the exposing fire can be closer and more agent may be used. Table 21 shows the comparison between the 0.1- and 0.2-in.-thick aluminum skin for the 240-ft aircraft. The thicker-skinned aircraft can have the leading-edge fire within 5 m compared to 12 m for the thinner aluminum (table 21). In practical terms, for the same offset distance, the thicker skin provides more time. This is manifested in the analysis by the success with a closer "offset" distances; for a response time less than 1.5 minutes, the fire can be within 0.5 m of the aircraft (Time Region I, table 13 in reference 9), and success could occur with a 2-minute response (Time Region II, table 13 in reference 9).

Again, the difference between the 2- and 3-minute responses is approximately 4 to 5 m of the additional offset distance.

Table 21. Agent Quantity Requirements, Time Region I Response, Variable Fuselage Characteristics for CATs 9/10 Aircraft

Fuselage	2-min ARFF Response				3-min ARFF Response			
	Initial Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)	Initial Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)
0.02 in Al (Scenario 1)	12	730	7000	7730	16	310	7000	7310
0.10 in Al (Scenario 4)	5	1440	7000	8840	10	930	7000	7930

The effects of fuselage protection are dramatic in the results where the new 4-minute fuselage burnthrough requirements are involved (Scenario 8, tables 21 and 22 in reference 9). With fire impinging on the aircraft, occupants have 4 minutes of protection. About 7000 gallons of agent would be needed to assure occupant safety once outside the aircraft (i.e., extinguishment of the entire fire area from the airplane where the heat flux cannot affect exiting occupants). An additional 1900 gallons may be provided as backup, but in theory, this would not be required because the 7000 gallons extinguish the fire from the fuselage to the outer limit of the individual impact area.

The effect of wind is shown in table 22. A doubling of the offset distance is required to achieve success when the fuselage is downwind of a fire. Again, quicker response results in a greater chance of success (smaller offset distance) and more potential agent. Wind effects contributed to the instantaneous involvement of the fuselage in the 1985 Manchester incident, in which the aircraft came to rest in a downwind position with respect to the engine/wing tank fire. When the fuselage is upwind of the fire, the initiating fire can be nearly at the edge of the fuselage and ARFF can still have potential success when responding within 2-3 minutes.

Table 22. Agent Quantity Requirements, Time Region I Response, Variable Wind Conditions for CATs 9/10 Aircraft

Wind Conditions	2-min Response				3-min Response			
	Initial Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)	Initial Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)
0 (Scenario 1)	12	730	7000	7730	16	310	7000	7310
20 mph, fuselage downwind (Scenario 5)	22.5	940	8350	9290	27.5	690	8350	9040
20 mph, fuselage upwind (Scenario 7)	1.5	130	3150	3280	2.5	30	3150	3180

5.2.3.4 Discussion of Modeling Results—Safe Evacuation From Fire Area.

The agent quantity that would allow safe evacuation of occupants after they have exited the aircraft (i.e., heat flux below the threshold of pain) was calculated and designated as Q_2. At the limit, this can be simply stated as the agent required to suppress a fire area from 0.5 m from the fuselage to the distance where heat flux to this point is less than 2.5 kW/m^2. For Scenario 1, this was 87.5 – 0.5 ≈ 87 m (285 ft). The fire area and resulting agent is 240 ft x 285 ft x 0.13 gpm/ft^2 ≈ 8900 gallons. Where ARFF can reasonably be assured of success (Time Region I, green), Q_2 is derived by taking the total area suppressed, minus the Q_1 initial area suppressed, minus the area close to the airplane where success cannot be assured. For example, for the 3-minute response in Scenario 1, success is achieved at a 16-m distance from the aircraft. This can be calculated as follows.

19.1 m (isoflux distance) – 16 m	= 3.1 m x 73.2 m (240 ft length) x 0.13 gpm/ft^2
	≈ 310-gal Q_1 agent
87.5 m (2.5-kW/m^2 limit) – 18.6 m	= 68.9 m x 73.2 m x 0.13 gpm/ft^2
(isoflux limit)	≈ 7000 Q_2
Total	= 7300 gallons

Note that there are rounding differences in the tables versus hand calculations. The difference between the 7300 and 8900 gallons is the area close to the aircraft where success cannot be assured.

This agent quantity is reduced as the airplane length is reduced. A discussion of the implications of the Q_2 agent quantity is provided in section 6.2.

5.3 EXTERIOR COMPOSITE FIRE THREAT AND SUPPRESSION.

5.3.1 Composite Resistance to Burnthrough and Resulting Combustion.

The FAA has recognized the value of increasing burnthrough of the fuselage from an exterior fire threat as a means of improving occupant survivability. Numerous small- and large-scale tests were conducted in support of enhancing the flame resistance of thermal and acoustic insulation, which insulates the cabin from the fuselage. The objective of the FAA effort was to increase the time to interior flame penetration from an exterior fire source, e.g., large pool fires. Cherry analyzed the potential lifesaving effectiveness of this improvement [50]. First proposed in September of 2000 [51], a final rule was passed on July 31, 2003, requiring newly installed thermal acoustic insulation to resist flame penetration when subjected to a burner flame test (14 CFR 25.856 and Part VII of Appendix E). 14 CFR Part 121 aircraft that have a seating capacity of 20 or greater and were certified (manufactured) after July 31, 2007, must comply with this new regulation. The FAA has determined that this will potentially provide an additional 4 minutes of cabin survivability for intact fuselages exposed to an exterior fire threat. The requirement covers insulation installed only around the bottom of the fuselage. It is believed that, in most situations, this insulation will extend above the cabin deck. These criteria do not apply to insulation on aircraft that is replaced. Additional flame spread restrictions on insulation have also been adopted. It will, however, be some time before these requirements are implemented and have an effect on the commercial aircraft fleet.

Reportedly, the B-787 and A380 are meeting applicable fuselage burnthrough requirements for new aircraft. Airbus reports that GLARE burnthrough time is approximately 7 minutes [47 and 52]. Temperatures on the unexposed side were reported to be 400°C (752°F) after 4 minutes and 570°C (1058°F) after 5 minutes. CFRP also has extended burnthrough times compared to aluminum. The A380 and B-787 have met FAA certification for burnthrough.

Data for the Boeing material were not available. The FAA performed a large-scale burnthrough test of a composite panel, believed to be similar to the proposed B-787 fuselage. Although a report has not yet been published, a video taken during the test was made available for this report [53]. Apparently, the primary objective apparently was to measure interior fire gases. The full-scale FAA fuselage burnthrough apparatus was used [16]. This involved a fuel pan in contact with the lower side of a mock fuselage assembly, which exposed the side of the assembly to the fuel pan fire.

Two composite panels were inserted in openings in the steel mockup. Observations from the video are shown in table 23.

Table 23. Video Observations

Min:Sec	Observation
0:50	Smoke inside fuselage
2:22	Smoking from mounting seals holding in the composite panels
3:00	Significant smoking from the seals
3:20	Smoke from interior composite area (not from around seals)
3:47	Smoke stream observed from “hole” in panel; no flame-through
4:44	More gas “holing” in composite panel
6:18	Exterior fire not observable
6:30	Interior ignition of panel at seal/edge area of composite panel
7:05	Short duration gas flaming observed inside of fuselage

The test confirmed that composites provide delayed flame penetration into the fuselage interior. The off-gassing observed is a typical composite response.

Quintiere [54] performed small-scale tests of composite materials. This study investigated the flammability of a carbon fiber composite material designed for use in aircraft skin structures. This material specification is used for the B-777 empennage skin. The composite material was manufactured by Toray Composites (America) to a Boeing material specification. The material burned in a manner similar to a charring material, i.e., the carbon fibers comprised most of its mass. The composite burned primarily from the vaporization of the resin. When it burned, the resin vapor was forced out of the fiber pores, and pressure caused the material to swell to over twice its volume. The fibers created an insulating, char-like structure that caused a reduction in the internal heating, and consequently, the burning rate dropped in time. As the burning rate dropped, extinction naturally occurred due to insufficient heating. It was noted that an external heat flux was required to sustain burning and flame spread, which is common with charring materials. The average peak heat release rate ranged from 130 ±30 kW/m^2 for a low exposure (25 kW/m^2), to 250 ±50 kW/m^2 for a moderate exposure (50 kW/m^2), to 315 ±40 kW/m^2 for a high-heat exposure, which would be expected when a fuselage is fully immersed in a pool fire (100 kW/m^2). The duration of the heat release was on the order of less than 200 seconds, after which smoldering sometimes occurred.

For comparative purposes, fire performance data for representative composites (and Douglas fir plywood) at 50 kW/m^2 are shown in table 24 [55]. The composite tested by Quintiere would be at the high end of this range of composites and lower than the plywood.

Table 24. Fire Performance Data for Selected Composite Materials at 50 kW/m^2 [55]

Material System	Ignitability	Peak Heat Release (kW/m^2)	Average Heat Release 300 s (kW/m^2)	Extinction Area (m^2/kg; a measure of smoke production)
MIL-STD-2031 (for comparison	>150	<65	<50	-
Douglas fir plywood	22	314	98	75
Glass/VE (brominated bisphenol A epoxy vinyl-ester), 1031	81	122	82	1226
Glass/VE (nonbrominated), 1167	85	276	184	999
Glass/VE (epoxy novolac vinyl-ester), 1169	85	302	198	815
GI/VE sandwich composite (1257)	70	126	93	1063
Glass/modar (1161)	119	160	91	126
Glass/epoxy, S2/3501-6 (1089)	105	178	98	580
Glass/epoxy, F155 (1040)	18	40	2	566
Glass/epoxy, 7701/7781 (1006)	49	181	108	1753
Graphite/epoxy, AS4/3501-6 (1093)	94	171	93	-
Glass/cyanate ester (1046)	58	130	71	898
Graphite/BMI (1098)	110	74	51	228
Glass/phenolic (1101)	210	47	38	176
Glass/phenolic (1014)	214	81	40	83
PE/phenolic (1073)	129	98	83	294
Aramid/phenolic (1074)	163	51	40	156
Glass/polyimide (1105)	175	40	27	170
Glass/phthalonitrile (1273)	437	35	24	157
Glass/PPS (1084)	244	48	28	690
Graphite/PPS (1085)	173	94	70	604
Graphite/PAS (1081)	122	24	8	79
Graphite/PES (1078)	172	11	6	145
Graphite/PEEK (1086)	307	14	8	69
Graphite/PEKK (1079)	223	21	10	274
GI/vinyl-phenyl POSS (HP 112)	107	77	23	93
FAA cyanate ester (bisphenol C)	Not ignited	Not ignited	Not ignited	Not ignited
Gl/geopolymer	Not ignited	Not ignited	Not ignited	Not ignited
Gr/silicone	415	10	5	-

5.3.2 Suppression of Composites.

Composites made from resins will combust when exposed to a high-heat fire. Depending on the material, it may self-extinguish when direct flame impingement is removed. Long-duration exposure may result in continued smoldering of the material after cessation of flaming. The issue is whether this added combustible material, including wings, fuselage, and structural elements, presents a currently unmitigated hazard with respect to ARFF.

Some in the industry see exterior composite combustibility as a diversion from the advantages of greater use of aircraft composites. Aviation composite material manufacturers, in discussing potential unintended hazards of composites, note that crashworthiness standards will still be enforced, although the failure mechanisms of composites are different than traditional materials [56]. Much of the aircraft interior is constructed from composite material and is subject to toxic fume and flame spread criteria. This argument focuses on the interior fire threat only (e.g., in-flight cabin fire). The exterior fire threat scenario must also be considered, involving exterior burning, which may require suppression by the initial ARFF response. There is also potential for re-ignition of a fuel fire from smoldering fuselage composites.

A review of health, safety, firefighting, and training issues related to aircraft composites involved in fires found that limited research has been conducted on the extinguishment of composite fires. In 2000, the U.S. Air Force conducted a large-scale burn study involving IM6 carbon fiber with a five-component resin (cited in the FAA review—report not available). The tests were designed primarily to assess the exposure threat to emergency responders. It was found that, although the composite released toxic gases, they were at a relatively low concentration compared to chemicals produced by burning JP-8. Recommendations were made for ARFF protection, including self-contained breathing apparatuses.

A 2004 U.S. Air Force study was conducted on two composite wing boxes fabricated from AS4/3501-6 graphite/epoxy [57]. The test fires simulated the response that could occur following a pool fire under a static aircraft. The first scenario simulated a 1-minute delayed extinguishment of a pool fire by fire fighters located near the aircraft responding with a 150-lb halon flight line fire extinguisher. The second scenario simulated a 5-minute delayed extinguishment in which the fire department responded with AFFF. After the second test fire was initially extinguished, the composite material flared up three times, requiring additional agent to extinguish the fire. No data was provided in the test report related to the amount of agent used, duration of foam application, or foam amount required to extinguish the reflashes.

The U.S. Navy reported on combustion and firefighting tests on 3501-6/AS graphite epoxy carbon fiber used for fighter (F-8) aircraft wings [58]. As expected, the composite wing was much more resistant to burnthrough than an aluminum wing. It was found that this composite would self-sustain combustion in as little as 2.5 minutes of exposure to an external pool-type fire. For firefighting tests, four 3/8-inch-thick composite wing panels, each having 810 square inches of surface area, were assembled on a steel mock-wing/fuselage assembly. This assembly was exposed to a 48-ft-diameter (1810-sq ft) JP-5 fuel fire. In two of the four tests conducted, the wing assemblies included stored fuel. The exposure fire was allowed to burn for 3.5 to 5 minutes, long enough for the composite to burn. Fire fighters extinguished the fire using equipment from an aircraft carrier P-16 firefighting vehicle. As the P-16 came within range of the fire, the turret was used to extinguish the pool fire. The firefighting crew then used the AFFF hand line (assumed to discharge 60 gpm) or the potassium bicarbonate (PKP) hand line (4 lb/sec) to extinguish the composite wing fire.

The pool fire was easily extinguished in all tests. However, extinguishment of the composite combustion was not as easy. The surface flames were readily extinguished, but smoldering composite combustion was already established. To extinguish the smoldering composite combustion, the fire fighters applied a continuous stream of AFFF directly on the composite material. In the case of the panels on the lower wing surfaces, the fire fighters went in close with the hand line. After applying AFFF for 3 minutes or more, the smoldering composite combustion was extinguished.

The smoldering composite combustion produced a visible glow as the graphite fibers burned. It also produced faint smoke or rising heat waves as the epoxy smoldered. PKP was effective at extinguishing the surface flames on the composite panels, but it did not extinguish the smoldering composite combustion. Smoldering composite combustion was best extinguished by cooling the composite with direct application of AFFF.

The presence of JP-5 fuel in the wings seemed to affect the burning composite and helped establish the smoldering composite combustion. However, the amount of fuel had no major effect.

It was concluded that fast response by the fire fighters reduced the chance that smoldering fire will be established. Since fire fighters may have to work in close to the aircraft to control the composite fire, they must be aware of potential re-ignition of fuel under or around the aircraft.

The USAF Technical Order (TO) 00-105E-9, on Aircraft Emergency Response Information [43] is the principal repository of composite fire hazard guidance in the U.S. Included in this manual is a graphic summary of a test conducted in October 2003 at the Mojave Test Center, a part of the Mojave Air and Space Port. A large amount of carbon fiber epoxy sandwich structures (total weight unknown) plus miscellaneous solid epoxy carbon fiber and foam/rubber material were suspended on concrete blocks. They were subjected to a 5- to 10-gallon JP-8 spill fire for 5 minutes. AFFF was then applied for about 3 minutes using various penetration techniques. An IR camera was used to view hot spots. Internal resin smoldering continued to exist after AFFF application. Surface layers were extinguished; internal layers emitted white smoke when disturbed. The internal layers were above ambient temperature even after the surface layers were cooled. The conclusion was that the fire and smoldering experiences were as described in TO 00-105E-9 and that a continuous AFFF application was needed for 3 minutes to stop the smoldering. It was affirmed that a pile of composite debris in a fuel fed fire could be expected to smolder. A report for this test was not available, and no data on AFFF application rate are included in this report.

The U.S. Navy recently performed a review of naval aircraft composite fire characteristics [59], mostly carbon/graphite fibers. Along with reviewing the 1985-1986 U.S. Navy tests, data from shipboard composite tests were reviewed. Surface burning of shipboard composites is readily extinguished using standard shipboard firefighting agents, such as water or AFFF. Recent tests of a long-duration, postflashover fire in a thick shipboard composite structure indicated that fires can become deep-seated and extremely difficult to totally extinguish.

The available military fire test data provides the basis for guidance provided in TO 00-105E-9. Among other health, safety, and postincident cleanup recommendations, TO 00-105E-9 provides the following guidance.

- Burnt composite may continue to off-gas for a period of time.
- Smoldering composites are difficult to extinguish with water. If the material is not entirely cooled to ambient temperature, deep-seated smoldering may continue to exist.
- Large quantities of water are required to extinguish large piles of smoldering composites. AFFF is better suited for extinguishing all conditions of a composite fire.
- A fast response reduces the chance that smoldering composite combustion can be established.
- Continuous and direct application of foam is needed for at least 3 minutes to extinguish smoldering composite combustion with AFFF.

The USAF concluded that more firefighting agent is required to suppress a composite aircraft fire than for an aircraft crash fire involving a fuel spill fire alone. There is anecdotal information related to the crash of a USAF B-2 bomber in Guam to support this [60]. It reportedly took 6 hours and 83,000 gallons of water to extinguish.

5.3.3 Estimating Extinguishment Requirements of Aircraft Exterior Composite Fires.

Pool fire extinguishment using foam is supported by hundreds of fire tests conducted over 5 decades. Composite extinguishment criteria as described in section 5.3.2, currently use a 3-minute rule established by a number of tests and demonstrations. Additional quantification is required to make further, more accurate determinations.

Extinguishment from a theoretical standpoint is not well developed. Classic extinguishment testing/theory indicates that Class A and plastic materials have critical minimum extinguishment water application rates of approximately 0.0074 to 0.015 gpm/ft^2 (5 to 10 g/m^2-s) [61]. It is recognized that this is a minimum laboratory-scale application rate and that 10 to 20 times more water may be required for actual firefighting [62]. A minimum water flux required for manual fire extinguishment can be estimated as $0.015\ gpm/ft^2 \times 20 = 0.30\ gpm/ft^2$.

Fire extinguishment of aircraft composites was attempted on a small scale, using a cone calorimeter apparatus [63]. Water flux rates of approximately 0.56 to 0.91 gpm/ft^2 extinguished 100-mm^2 samples of graphite and Kevlar™ composites. This was postulated to be perhaps an order of magnitude greater than required, due to the inability to limit the water application rate in the small-scale apparatus.

The 1986 China Lake tests could be used to estimate extinguishment requirements. Assuming both sides of the panels were exposed and extinguished, a total of 45 ft^2 would be extinguished using an agent flow rate of 60 gpm. Using this information, for a 3-minute application time, 4 gal/ft^2 would be needed to totally extinguish the composites.

Finally, data from the composite-burning and manual-firefighting literature can be used to estimate fire extinguishment requirements. The NFPA Fire Protection Handbook provides estimates of the water amount required to extinguish fires [64]. The theoretical heat absorption of water is 2.6 MW per kg/s (2.6 L/sec). This equals roughly 16.4 MW per 100 gpm of water applied. This assumes complete efficiency in converting water to steam, but does not account for the effects of the associated steam causing localized oxygen depletion. Estimates of efficiency are approximately 25% to 50%, i.e., the water used in actual fires is 2 to 4 times more than actually needed. Several extinguishment models use an efficiency factor of 33%. Using the Quintiere data, an average peak heat release rate for the aircraft composite tested was approximately 250 kW/m^2. The average heat release rate for composites (and plywood) is generally 100 kW/m^2. Using estimated sizes of the B-787 fuselage and wing area (both top and bottom), estimates of water requirements can be made, as shown in table 25.

Table 25. Estimated Water Requirements for Composite Surface Burning

Rate of Heat Release (kW/m^2)	50% Efficiency			25% Efficiency		
	One-Quarter Fuselage	One Wing	One-Quarter Fuselage and one Wing	One-Quarter Fuselage	One Wing	One-Quarter Fuselage and one Wing
250	775	1980	2755	1550	3965	5510
100	310	795	1100	620	1585	2205

These rates would be required for extinguishment to occur in 1 minute. The heat release rates could be proportionally reduced if extinguishment over a longer time period is acceptable. The values in table 25 also provide an estimate of the gross amount of water required, i.e., the values reflect total extinguishment. This estimate also assumes that burning continues after any pool fire is extinguished; however, for the composites proposed for the A380 and B-787, it is not clear that this is a valid assumption. Heat release rates and associated water requirements, shown in table 25, would drop dramatically if the composites did not sustain combustion.

5.4 OTHER EXTERIOR FIRE THREATS.

Concern has been raised about the potential of other exterior fire threats, such as debris fields, pockets of survivability, and escape slides. Large amounts of Class A material (ordinary combustibles, including plastic) may be scattered in a crash debris field. The A380, by its sheer size, would add to combustibles. Slides necessary to evacuate the large passenger load may contribute to the fuel load and restrict ARFF access (see figure 5).

Existing aircraft have escape slides that discharge into the potential fire area. Aircraft crew are instructed and trained not to open exit doors where there is fire. Sometimes this occurs in error or is unavoidable. Evacuation slides have become involved with fire (Los Angeles, 1978).

There has been no indication that this is a significant firefighting problem, but the number of slides on the A380 covers most of the in-close area around the aircraft (figure 5).

Phillips notes that increased survivability due to increased aircraft size presents greater ARFF challenges, including pockets of survivability [41]. These are areas where passengers survive severe crashes. For example, the Sioux City, 1989, crash is representative of a transition point between initial fire knockdown and securing of the overall fire area with subsequent rescue of nonambulatory survivors and recovery of nonsurvivors. This may take substantial time to complete. It is also difficult to quantify the potential additional agent required for a suppression of a debris field. This problem exists with current large aircraft. NFPA 403 requires that ARFF vehicles have "two-shot" capability. Sufficient foam agent must be provided on each vehicle to mix with double the quantity of water that the vehicle carries. There is also a requirement to determine that a 100% water resupply capability is available (NFPA 403, section 5.3.3 [1]).

5.5 INTERIOR FIRE THREAT AND SUPPRESSION.

For the threat analysis, it is assumed that interior firefighting is an appropriate ARFF response. Section 6.3 describes the limitations of this assumption.

There are sufficient combustibles within the cabin interior to support a major, fast-growing fire, including flashover. Some descriptions of interior cabin fire growth indicate unusual fire characteristics compared to building fire compartments. Cabin fire ignition and growth are driven, in part, by ventilation conditions (air supply for the fire and exhaust path for hot gases). Classic flashover conditions, i.e., simultaneous ignition of all combustibles due to a hot upper layer, may or may not occur. For example, the 1985 Manchester fire involved unusual conditions, in which dense, toxic smoke came forward and stopped just short of a forward open door. The characteristics were subsequently replicated in FAA fire tests.

All Q_3 quantities are based on a required flow for 10 minutes. This is based on engineering judgment. For the analysis here, it is sufficient to assume that a major fire can involve the cabin area. The current Q_3 requirements were established using general firefighting guidelines and engineering judgment. For NFPA 403 CATs 3 and 4, a single, low-flow (60-gpm) hand line was deemed sufficient for any manual firefighting need. For CATs 5 through 7, a single, 125-gpm hand line, a relatively standard flow from a 1.5-inch-diameter hose at 100-psi nozzle pressure, was judged to be sufficient. For CATs 8 and 9, two hand lines (250-gpm total flow) were judged to be necessary. The NFPA 403 2003 revision cycle included an increase of Q_3 in CAT 10, specifically to address the double-deck A380. It was determined that two hand lines for each level were needed. A 4-minute (240-second) response time in which Q_3 agents are required to be at the scene was also added in the 2003 revision; the originally proposed requirement was 5 minutes from alarm or 3 minutes from arrival. It was revised during the NFPA 403 comment period to 4 minutes from alarm because "interior fire suppression should start as soon as the outside fire is under control."[5]

Agent required for interior firefighting was estimated using available calculation techniques for manual firefighting efficiency [65]

[5] From Comment 403-28 (6.1.3) to NFPA 403, May 2003 Report of Comments published by NFPA.

$$Q = \frac{v}{45} \tag{8}$$

where

Q = Required flow rate, l/s
v = Compartment volume, m^3

This methodology is based on the volume of the fire-affected space and assumes that 80% of the water is converted to steam. It also assumes that all the water is applied in 30 seconds.

Table 26 shows the calculated water discharge rate for representative aircraft in CATs 5 to 9, assuming involvement of one-half the length and the entire width of the fuselage (no subtractions for overhead and underdeck spaces).

Table 26. Estimated Interior Firefighting Agent

CAT	Representative Aircraft	Estimated Manual Firefighting Flow (gpm)	Required NFPA 403 Q_3 (gpm)
5	BAE 146	43	125
6	A320	81	125
7	B-727-200	88	125
8	B-787	258	250
9	B-747-200	416	250

Interior firefighting agent in NFPA 403 for CATs 5 to 8 aircraft is estimated to be sufficient. Additional agent may be required for CAT 9. No estimate was made for the CAT 10 double-deck situation; however, it would be similar to the CAT 9 estimate if involvement of the entire width is assumed (the overall length and maximum width of the A380 and B-747 are similar).

Caution is necessary when applying these estimates, since they have not had substantial verification for building fires and no verification for aircraft interior fires. Also, the impact of access and sustained operations are not included in this estimate.

The FAA has conducted extensive research to limit cabin ignition and fire growth. Improved burnthrough protection is described in section 5.3.1. Improved fire performance characteristics of cabin interior materials have evolved over the past 4 decades. For example, more stringent ignitability standards for seat material are credited with limiting casualties in the Dallas, 1998, accident.

5.6 HAZARD ANALYSIS SUMMARY.

There is no general correlation of the fuel and passenger loads between aircraft within and across airport categories. The only trend is a general increase in these loads as the length and width of the aircraft increase. The new commercial aircraft introduce new challenges. The A380 is a full double-deck aircraft with double the passenger load and a 50% increase in fuel capacity compared to the next largest aircraft. The B-787 fuselage will be constructed entirely of combustible composite materials. A fire hazard analysis was performed to assess these attributes with respect to current protection approaches. Previous studies demonstrated the challenges of directly correlating aircraft fuel load with potential crash fire area. There is no quantitative method to predict how much fuel will spill, when it will ignite, at what rate it might spill, or what total quantity may be involved. Therefore, an approach in which the fire size is assumed to be of unlimited size was adopted, and the agent required to protect occupants was calculated.

A radiation heat transfer model, using conservative assumptions, calculated agent quantities for the following two conditions:

- prevention of heat penetration to an intact aircraft and subsequent interior ignition, so ambulatory occupants are not exposed to untenable conditions.

- prevention of a thermal threat to individuals who have exited the aircraft.

Three representative aircraft lengths (CATs 9, 6, and 4) were assessed. Variables included aircraft fuselage thickness/material, ARFF response time, and wind conditions. Foam effectiveness was based on a conservative estimate of 0.13 gpm/ft^2 required for suppression using AFFF. Interior aircraft ignition may not be preventable if the aircraft is totally immersed in fire, even with a rapid (less than 2 minutes) ARFF response. Prevention of interior ignition is sensitive to the proximity of the fire to the aircraft, ARFF response, and aircraft fuselage characteristics. Agent quantities were estimated for these variables. The potential effectiveness of the new FAA 4-minute burnthrough criteria dramatically reduces the chances of interior ignition for the intact crash scenario. Agent quantities were also estimated for the large fire area associated with the potential thermal threat to occupants once they have exited the aircraft.

A lack of data hinders understanding the threat posed by the potential, large-surface area involvement of composite material. If composites self-sustain combustion when exposed to a pool fire threat, a significant amount of extra firefighting agent might be required. Even when smoldering occurs after the pool fire is extinguished, the amount of agent required to secure the fire area (prevent burnback or reflash of the pool fire) is not well known. The sparse data from the military suggests that even smoldering fires may require additional agent. Rough order of magnitude estimates of water-based suppression agent required to suppress a B-787 exterior fuselage fire were made. A low-end quantity of 300 gallons is estimated when one-quarter of the fuselage is burning. When a wing is also involved, the composite has a high heat release rate. Fire fighters may be inefficient when attacking the fire, and over 5500 gallons of agent may be required. There is insufficient data to make a clear determination of the agent requirements for advanced composite airframes being used in new aircraft. Additionally, the potential for combustible materials in a debris field from larger aircraft and new escape slide configuration to add to the agent requirement suffers due to lack of data.

Interior firefighting agent quantities were also estimated and compared with NFPA 403 requirements. Again, the parameters for estimating this are not well established. It was estimated that NFPA 403 quantities for CATs 5 to 8 are sufficient. Aircraft with multideck interiors in which a sustained, postcrash interior attack may be feasible (CATs 9 and 10) may require additional agent. Quantifying this need and the ability to sustain this type of attack lacks sufficient data to make a more precise assessment of agent quantities for this function.

6. UPDATED METHODOLOGY.

6.1 PERFORMANCE GOALS.

Before analyzing existing, revised, or totally new methods for specifying agents, clearly stated performance goals and associated requirements should be established. While the need for this is self-evident, it is important to establish these so the rationale for agent quantities is unambiguous. While saving lives is the primary ARFF objective, it is insufficient to set this as a performance requirement, because it is too vague for quantifying performance requirements and setting appropriate measurements or metrics. The following performance goals were established for assessing agent requirements in this report to define the clear, unambiguous purpose for each quantity of agent. For plausibly survivable aircraft crash scenarios involving scheduled aircraft with nine or more passengers, occurring at the middle, end, or near the end of the farthest runway, sufficient firefighting agent and capabilities should be provided to ensure the

- survivability of ambulatory occupants.
- ability of responders to rescue nonambulatory survivors and recover victims.

Based on the historical basis of requirements, the loss history, and a fire threat analysis, ARFF firefighting agents are provided to

1. protect the aircraft fuselage in order to protect ambulatory occupants within an intact fuselage who have not escaped before the arrival of ARFF.

2. control any fire in the immediate crash area that threatens occupants who have escaped the aircraft.

3. establish a safe area for continuous postcrash rescue and recovery efforts.

4. affect final extinguishment of all exterior and interior fires.

5. prevent

    - burnback of foam applied to liquid spills.
    - re-ignition of three-dimensional liquid fuel spills.
    - re-ignition of Class A/D exterior and Class A interior materials.

NFPA 403 implicitly requires agents for these requirements in the Q_1, Q_2, and Q_3 approach, and explicitly in the ICAO Annex 14 rationale. The FAA and ICAO do not explicitly recognize the Q_3 (interior firefighting) requirement.

6.2 EXTERIOR FIRE SUPPRESSION.

6.2.1 Pool Fire Extinguishment.

6.2.1.1 Fires Exposing Aircraft on one Side.

The establishment of an appropriate methodology was performed consistent with the performance requirements re-established in section 6.1.

As noted in section 5.2.3, there are two particular regions of interest in the interior ignition analysis: Time Region I response (green, as shown in figure 9), where the exposing pool fire is extinguished to the isoflux distance, beyond which interior ignition is prevented; and, Time Region II response (red, as shown in figure 9, where extinguishment beyond the isoflux distance is required because of the proximity and duration of the exposing fire. These regions were analyzed in more detail for the CATs 9, 6, and 4 zero-wind representative scenarios. These data are summarized in tables 27 and 28. The AFFF quantities noted in these tables correspond to AFFF solution, i.e., the water quantity to which AFFF concentrate must be added. It is analogous to the NFPA 403 and CFR water requirements for primary agents. The additional foam for the second performance criterion (occupant egress outside the aircraft, Q_2) was also included. A comparison with NFPA 403 and CFR agent requirements is provided. The calculated values of Q_1 and Q_2 do not include the offset distances where success may not be feasible. If there were actually fire in this area, ARFF responders would obviously attempt extinguishment. To account for this, the agent required for the total fire area, from the edge of the aircraft fuselage to the distance where fire flux would not affect evacuated occupants (Q_2 distance), is also provided in tables 27 and 28, designated as Q_{max}.

The data show that for Time Region I response, where ARFF is most likely successful, the estimated Q_1 falls within the NFPA 403 Q_1. For Time Region II response, estimated Q_1 is less than the NFPA Q_1 for four of the six situations. As expected, the estimated Q_1 is less than the CFR amount, which is Q_T (no breakdown for Q_1 and Q_2). The exception is for CAT 4, in which the estimated Q_1 is more than the CFR option of 100 gallons of AFFF or a secondary agent in all circumstances.

The lower-estimated Q_1 compared to NFPA Q_1 is attributable to the estimating techniques. The current analysis excludes the fire area very close to the aircraft where internal aircraft ignition cannot be prevented. The original Geyer method (section 3.2.2) included the area under, and immediately adjacent to, the aircraft. In light of this, it is not surprising that the estimated Q_1 is less than the NFPA Q_1.

The estimated Q_2 is greater than the NFPA 403 Q_2 for all situations except one. Again, this is not surprising. The Gage report [6] suggested, as verified in the companion report [9], that relatively large quantities are required to prevent thermal pain to evacuating passengers for an essentially unlimited fire size (see section 3.2.2). The FAA Q_T is less than the estimated Q_2.

Table 27. Estimated Agent Quantities—Time Region I Response, No-Wind Conditions (Gallons of AFFF Solution)

CAT	2-min ARFF Response—Estimated Agent Volumes				3-min ARFF Response—Estimated Agent Volumes				Estimated Q_{max} (gal)	NFPA 403					CFR
	Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)	Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)		Q_1 (gal)	Q_2 (gal)	$Q_1 + Q_2$ (gal)	Q_3 (gal)	Q_T (gal)	Q_T (gal)
9	12	730	7000	7730	16	310	7000	7310	8900	2620	4450	7070	2500	9570	6000
6	10	350	3240	3590	15	10	3240	3250	4240	1250	1250	2500	1250	3750	1500
4	10	130	1200	1330	12	50	1200	1250	1690	470	270	740	600	1340	Note 1

*500 lb of powder/halon or TAU with 450 lb of PKP and 100 gal of AFFF

Table 28. Estimated Agent Quantities—Time Region II Response, No-Wind Conditions (Gallons of AFFF Solution)

CAT	2-min ARFF Response—Estimated Agent Volumes				3-min ARFF Response—Estimated Agent Volumes				Estimated Q_{max} (gal)	NFPA 403					CFR
	Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)	Spill Offset (m)	Q_1 (gal)	Q_2 (gal)	Q_T (gal)		Q_1 (gal)	Q_2 (gal)	$Q_1 + Q_2$ (gal)	Q_3 (gal)	Q_T (gal)	Q_T (gal)
9	8	3500	4630	8130	14	1100	6420	7520	8900	2620	4450	7070	2500	9570	6000
6	7.5	1000	2760	3760	12.5	190	3240	3430	4240	1250	1250	2500	1250	3750	1500
4	8	320	1080	1400	10	2160	0	2160	1690	470	270	740	600	1340	Note 1

*500 lb of powder/halon or TAU with 450 lb of PKP and 100 gal of AFFF

A more appropriate comparison, to account for differences in the current estimating techniques and the NFPA 403 requirements, may be to combine the estimated and NFPA 403 $Q_1 + Q_2$ amounts. Data from tables 27 and 28 are combined in table 29 for comparison. A comparison of the estimated $Q_1 + Q_2$ with NFPA Q_T ($Q_1 + Q_2 + Q_3$) is also included. The estimated $Q_1 + Q_2$ agent volumes exceed the NFPA 403 $Q_1 + Q_2$ agent requirements by 240 to 1450 gal. When the estimated Q_1 and Q_2 agent quantities are compared with NFPA Q_T quantities, they are below, or nearly meet (within 64 gallons), NFPA quantities. The exception is the CAT 4, 3-minute Time Region II response in which the deficit is over 800 gallons (table 29). CFR quantities fall well short of estimated $Q_1 + Q_2$ by 1100 to 2200 gallons.

Table 29. Comparison of Estimated Q_1 and Q_2 Agent Quantities Compared to NFPA/CFR Requirements (Gallons of AFFF Solution)

Time Region I Response , 2-min Arrival Time							
CAT	Estimated $Q_1 + Q_2$	NFPA $Q_1 + Q_2$	NFPA $Q_1 + Q_2$ Minus Estimated $Q_1 + Q_2$	NFPA Q_T	NFPA Q_T Minus Estimated Q_T	CFR Q_T	CFR Q_T Minus Estimated Q_T
9	7730	7070	-660	9570	1840	6000	-1730
6	3590	2500	-1090	3750	160	1500	-2090
4	1330	740	-590	1340	10	100	-1230
Time Region I Response , 3-min Arrival Time							
CAT	Estimated $Q_1 + Q_2$	NFPA $Q_1 + Q_2$	NFPA $Q_1 + Q_2$ Minus Estimated $Q_1 + Q_2$	NFPA Q_T	NFPA Q_T Minus Estimated Q_T	CFR Q_T	CFR Q_T Minus Estimated Q_T
9	7310	7070	-240	9570	2260	6000	-1310
6	3250	2500	-750	3750	500	1500	-1750
4	1250	740	-510	1340	90	100	-1150
Time Region II Response , 2-min Arrival Time							
CAT	Estimated $Q_1 + Q_2$	NFPA $Q_1 + Q_2$	NFPA $Q_1 + Q_2$ Minus Estimated $Q_1 + Q_2$	NFPA Q_T	NFPA Q_T Minus Estimated Q_T	CFR Q_T	CFR Q_T Minus Estimated Q_T
9	8130	7070	-1060	9570	1440	6000	-2130
6	3760	2500	-1260	3750	-10	1500	-2260
4	1400	740	-660	1340	-60	100	-1300
Time Region II Response , 3-min Arrival Time							
CAT	Estimated $Q_1 + Q_2$	NFPA $Q_1 + Q_2$	NFPA $Q_1 + Q_2$ Minus Estimated $Q_1 + Q_2$	NFPA Q_T	NFPA Q_T Minus Estimated Q_T	CFR Q_T	CFR Q_T Minus Estimated Q_T
9	7520	7070	-450	9570	2050	6000	-1520
6	3430	2500	-930	3750	320	1500	-1930
4	2160	740	-1420	1340	-820	100	-2060

Under the extreme case of fire suppression, to the estimated Q_{max}, there is sufficient total agent provided by NFPA 403 for CAT 9, and a deficit of 500 and 350 gallons for CATs 6 and 4, respectively (table 27). The deficits exceed 2500 gallons when CFR minimum requirements are compared with Q_{max}.

These data indicate that current NFPA $Q_1 + Q_2$ quantities may be insufficient to address all likely scenarios. If the available agent from Q_3 is added, there is sufficient agent for most situations. Given that NFPA designated Q_3 for interior attack, if that quantity is included in the amount needed for exterior fire control, agent may then be deficient for any potential interior attack.

When an aircraft is downwind of a massive spill fire, there are conditions where success can be predicted, albeit at significant (12 to 28 m) pool offset distances to the aircraft (table 22). For the CAT 9 aircraft, total estimated agent requirements for these conditions still fall within NFPA Q_T quantities. Under the absolute worst-case condition, where the total fire area (Q_{max}) must be extinguished to ensure occupant evacuation, an estimated 11,500 gallons would be needed (table 20 in reference 9). This exceeds NFPA 403 Q_T by 2000 gallons. The Q_{max} represents a fire area of 88,800 ft^2. For the A380, this is a fire area that encompasses the full length of the fuselage and has a depth of 370 feet (two additional wing lengths away) from the wing tip.

6.2.1.2 Fires Exposing Aircraft on Both Sides.

An argument has been made that the current PCA is really one-third of the TCA, not two-thirds. Hewes [10] contends that from 1968 to 1970, ICAO was instructed to develop a system of determining agent quantities other than through the "guess and negotiate" method used by NFPA and ICAO at the time.[6] The Gage report was accepted, which advocated that the fire area should be the length of the fuselage times the wingspan. A one-third reduction was applied based on historical loss data. At the same time, Geyer used 50 feet on either side of the aircraft plus the fuselage length, and this was adopted as the TCA.[7] Hewes contends that this is equal to the Gage PCA (two-thirds the TCA), and that by reducing Geyer's area by one-third, the true Gage TCA is reduced by another one-third. The result, Hewes contends, is a reduction of the originally intended TCA by two-thirds.[8]

This argument relates to the total fire area required to be extinguished in the event that fuel is burning on both sides of the aircraft. The Geyer analysis took into consideration the negative consequences of an aircraft being downwind of the pool fire area. He did not explicitly address how this correlated with fire on both sides of the fuselage. The analysis in section 5.2.3 and the companion report shows the effects of wind. The TCA/PCA concept depicted graphically for years (figure 2) shows the TCA/PCA on one side of the aircraft only. The lack of detailed documentation for the scenario of when the aircraft is totally engulfed in fire probably relates to actual fire incidents and resulting fire areas. Fire is most likely to occur on one side of an aircraft. It may ultimately spread to both sides (e.g., Los Angeles, 1978 and Okinawa, 2007), but

[6] Comment 403-5 to NFPA 403, submitted by Vic Hewes, documented in the NFPA Report of the Committee on Aircraft Rescue and Fire Fighting, May 2003 Report on Comments, published by NFPA, Quincy, MA.
[7] Not entirely correct as documented in the Geyer 1969 report, which is described in detail in sections 3.2.2, in which wind was considered a key factor.
[8] Not entirely correct: reducing an area sequentially by 1/3 results in a 44% reduction of the original area, not 67% (2/3).

it takes time for this to occur. The upwind fire scenario (and associated fire area) depicted in figure 2 indirectly addresses the "engulfed" fuselage scenario. The engulfed fuselage scenario is likely to involve a smaller area than the upwind fire area in which fire is blown onto the fuselage.

An additional analysis was performed to determine capabilities for fully engulfed fire scenarios. Two situations were considered: (1) suppression of a pool fire involving both sides of an aircraft out to the critical isoflux distance and (2) suppression of the entire footprint of an aircraft (fuselage length x wingspan). The first situation, which is considered a Q_1 condition (prevent interior ignition), was analyzed for an aircraft involved for both its entire length and half its length. Representative aircraft from table 15 were used.

The results of this analysis are shown in table 30. There is sufficient Q_1 agent provided in NFPA 403 to suppress this threat for half the aircraft length. If the aircraft is involved for its total length, double the amount of NFPA Q_1 agent would be required in CATs 9 and 6. There is nearly sufficient agent for the CAT 4 scenario. Recall that in both of these situations, the performance criteria (interior ignition) are likely to be exceeded before ARFF arrives if it is assumed that engulfment occurs instantaneously. In reality, there likely is some fire growth time where fire spreads from one side to the other (Los Angeles, 1978 and Okinawa, 2007), and fire is unlikely to engulf the entire length of the aircraft on both sides[9]. The NFPA 403 quantities appear to be sufficient for this scenario.

Table 30. Agent Suppression Quantities for Engulfed Aircraft

CAT	Suppression to Isoflux Distance—Full Length	Suppression to Isoflux Distance—Half Length	NFPA Q_1	Gallon of AFFF to Suppress Aircraft Footprint (length times wingspan)	NFPA Q_2	NFPA $Q_1 + Q_2$	CFR Q_T
9	4630	2315	2619	5957	4451	7070	6000
8				4967	3185	5280	4000
7				2864	2045	3630	3000
6	2336	1168	1245	1775	1245	2490	1500
5				1030	647	1510	*
4	509	255	468	807	247	740	*

*500 lb of powder/halon or TAU with 450 lb of PKP and 100 gal of AFFF solution.

Capability to totally extinguish the aircraft footprint may be important from two aspects. Fuel tanks in the wing may be exposed to fire and rupture, adding to both the pool and three-dimensional fire threat (Okinawa, 2007). Also, evacuation slides may be exposed to the pool fire. To date, no aircraft have been identified where deployed slides extend beyond the aircraft wing. The suppression of this large area is considered as part of "establish safe area" in the performance criteria, i.e., a Q_2 objective. Extinguishment of the footprint area should provide a safe area for slide deployment, if occupants are trapped. Some have argued that this fire area

[9] This refers to cases in which there is adequate ARFF response. See the loss history when aircraft are totally destroyed by fire.

should be associated with Q_1/PCA. It need not be part of Q_1, since occupants should deploy slides and evacuate only where there is no fire (unexposed side of the aircraft in a typical scenario); or they should wait until the fire threat is controlled by the Q_1 agent discharge. There have been situations where the last remaining ambulatory occupants have exited the aircraft while ARFF combats the pool fire. Situations where most occupants wait for ARFF arrival have not been identified in the loss history.

The exposure to fuel tanks is time- and threat-dependent. Even a small fire exposure can cause fuel line or tank rupture before ARFF arrival (Okinawa, 2007, and reference 9). The threat scenario is similar to exposure to the fuselage; moderate exposure can result in failure, even with rapid ARFF response (Manchester, 1985). Again, securing a large footprint area to prevent fuel rupture and associated cascading damage is appropriately considered an "establish safe area" performance objective; otherwise, it is addressed as Q_1 in the close-in attack or as a secondary agent requirement.

Agent quantities required to suppress the aircraft footprint are shown in table 28. NFPA 403 $Q_1 + Q_2$ agent quantities are sufficient to suppress the footprint areas. Interestingly, the CFR agent quantities for several categories are almost the same as the agent calculated for the footprint area. No documentation is available to verify if the two concepts are related. It appears that the CFR quantities may have been established directly as a result of providing sufficient AFFF to cover the aircraft footprint area. The differences in CATs 8 and 6 may be attributable to increased length "creep" for new aircraft model variants, as described in section 5.1.1.

6.2.2 Composite Exterior Extinguishment.

The wide-spread range in estimating extinguishment requirements indicates that further work is required to quantify the requirement for commercial aviation applications. The results will be highly dependent on

- the material and, particularly, the number of laminate layers.
- the material's propensity for surface burning, sustained burning in the absence of flame, and smoldering composite combustion
- the time exposure of the external fire threat.

Boeing representatives have indicated that the B-787 composite fuselage material meets ICAO and FAA fire properties requirements and that the material does not sustain combustion or aid in the spread of flame [66]. No specific test data has been made available for this report.

The GLARE material may not sustain exterior flame spread because of its aluminum exterior skin. Again, large-scale fire data is lacking. In particular, in both cases, data on sustained combustion without an exposure fire was not identified.

The key to any agent requirement is the extent to which exposed composites will support flame spread and combustion, particularly after the exposing flame is removed. If the composite does not sustain burning after the exposure is removed (e.g., pool fire is extinguished), then agent requirements will likely be limited to cooling and overhaul to accomplish final extinguishment. Within the limitations described in section 6.2.1.1, existing Q_2 and Q_3 agent quantities would likely be sufficient for cooling and overhaul, recognizing that backup water supplies will be required. NFPA 403 Section 5.3.3 specifies these backup agent requirements in general terms. This would be no different than extinguishing other existing Class A combustibles, which may be exposed in an accident where the fuselage is fractured; e.g., stored luggage, exposed interior finish combustible structural elements, and wires/cabling.

Time may be an important factor; it appears that a 2- to 5-minute exposure time may be the critical time when composite combustion can become self-sustained. If the composite fuselage and wing material sustains combustion and spreads fire, then additional agent, above existing Q_1/Q_2 quantities, may be required.

Given the estimates in table 25, insufficient evidence exists to determine if additional Q_2 agent is required for aircraft having all-composite fuselages. Data gathered from testing actual materials may indicate that the composite poses no more threat than existing combustibles. If 0.30 gpm/ft^2 is the minimum needed for suppression of flaming fire of one-quarter of the fuselage, about one-third the current CAT 8 Q_3 capacity may be used in composite suppression. If, however, 4 gal/ft^2 is actually required for total extinguishment of composites, additional Q_2 agent will most likely be required. For example, for an aircraft the size of the B-787, in which one-quarter of its fuselage is involved, 11,000 gallons of agent may ultimately be required for total extinguishment. This is more than the entire amount of the current Q allocation for CAT 8. This shows the potentially large quantity, which may ultimately be required to totally extinguish smoldering composite combustion. Q_2 quantities should be adjusted to accommodate any additional agent determined by testing to be required for composite fire suppression. It is expected that this data will be available before the B-787 is introduced into widespread commercial use.

The suggestion for additional agent is tempered by the fact that existing aircraft already have some exterior composites and substantial interior Class A fuel load (including composites). The extra threat may result from an external structure which is all, or mostly, composite material.

6.3 INTERIOR FIREFIGHTING.

A major crash in which the fuselage integrity is compromised and an interior fire occurs has been a major challenge for ARFF responders. FAA researchers' efforts to reduce fire growth characteristics of interior materials will mitigate the potential for rapid fire growth. Depending on the severity of the crash, a large pool fire could develop that would immediately put occupants at risk where the fuselage is open to the fire. Any interior firefighting in this scenario will be challenging; the notion of rapidly mounting an aggressive interior manual attack to save more than just a few nonambulatory passengers seems implausible. This assessment is based on the loss history; i.e., most surviving occupants self-evacuate, or are ambulatory and evacuate as ARFF combats the fire. The challenges to fire fighters entering a crashed aircraft are daunting: they must access the aircraft high above the ground if the wheels have not collapsed; occupants may be exiting through ingress routes used by fire fighters; the access aisles, under the best circumstances, are restricted, and the confined space may result in rapid untenability, affecting firefighting efforts.

This pessimistic outlook does negate the performance goal established in section 6.1: provide sufficient firefighting agent and capabilities to assure the ability of responders to perform rescue of nonambulatory survivors and recover victims. A specific requirement is to establish a safe area for continuous postcrash rescue and recovery efforts and to affect final extinguishment of all exterior and interior fires. Establishing explicit agent requirements is coupled with other related aspects, such as response time, access, and equipment. These factors are discussed in sections 6.3.2 through 6.3.4.

6.3.1 Response Time.

The ARAC report [33] states that "an interior aircraft fire produces an atmosphere that is immediately dangerous to life and health." With this in mind, fire fighters attempting to mount an aggressive manual interior attack are at an immediate disadvantage. Untenable conditions may have occurred within the time required to respond and secure any exterior fire. Assuming this is an unknown, the requirement to have manual firefighting agent, now designated as Q_3, at the scene within 4 minutes is a reasonable, practical goal for an indirect attack (i.e., penetrator nozzle).

It is unclear whether a manned interior attack can be mounted in this time frame. Unless responders arrive fully dressed in personal protective equipment that can be used for interior attack, some dressing time will be required. After the control of any exterior fire, personnel will have to don self-contained breathing apparatus (SCBA) and appropriate protective gear before accessing the aircraft. This could take several minutes. Normally, however, ARFF personnel respond fully dressed in proximity protective clothing (reflective ensembles that provide both exterior radiative and interior thermal protection) and SCBA. In this case, potential interior attack could be mounted more quickly after the exterior is secured. This is also a tactical decision to be made by the on-scene incident commander. If there is no exterior fire, responders can immediately transition to an interior fire attack posture. Sufficient agent will be available from the initial response (i.e., Q_1), with sufficient backup agent to secure external conditions (i.e., unignited fuel spill).

6.3.2 Access to the Aircraft Interior.

Getting inside the aircraft is a primary limitation to mounting a rapid manual interior attack. Access to the current fleet of commercial aircraft inventory is already difficult. It is exacerbated by multideck aircraft; e.g., the B-747 and A380. Neither NFPA 414 nor CFR explicitly require ladders on ARFF vehicles, although most ARFF vehicles have some form of ladder. But scaling a ladder or entering the small over-wing emergency exit is a less-than-optimum entry technique that exposes fire fighters to a serious slip and fall potential. Fire fighters can easily slip off the wing while trying to make entry. For the double-deck aircraft, an access vehicle or specialized equipment is the only practical method to mount an interior attack. The tactic of gaining access via deployed egress slides is not considered reliable or feasible.

NFPA 414 [67] has drafted criteria for access vehicles; the FAA recommends the use of NFPA 414 in AC 150/5220-10D [68]. Some type of access vehicle can improve fire fighter safety and potentially increase the effectiveness of fire suppression operations when multideck aircraft are involved, considering the difficulties described.

6.3.3 Indirect Attack Equipment.

Use of indirect attack equipment, specifically a boom-mounted, aircraft skin-penetrating nozzle, or HRET, has the greatest chance of success in rapidly cooling the interior cabin to save nonambulatory occupants. The piercing nozzle technique was proposed 3 decades ago [69]. FAA personnel and ARFF vehicle manufacturers, after analyzing major life loss incidents from 1970 through 1985, began serious developmental efforts [70 and 71]. Aircraft skin-penetrating nozzles mounted on booms can be used by a single ARFF vehicle operator to apply agent into the aircraft interior. Using this device is a tactical decision made by the on-scene senior fire officer in conditions where there is a serious interior fire. In these cases, most, if not all, ambulatory occupants evacuate, and there is a delay in mounting a manned, manual, interior attack. The general tactic is to apply agent between the known or perceived interior fire location (aft, mid, or forward) and the nearest available emergency exit.

Cherry [34] conducted an evaluation of firefighting technologies for improving occupant survivability during postcrash fires. The HRET with skin-penetrating nozzle was evaluated in terms of potential lifesaving capability. The evaluation was based on a review of world-wide accidents involving passenger and passenger/cargo turboprop and turbojet aircraft (more than 30 seats). Of the 2473 accidents reviewed, 84 accidents were of interest. These accidents, which involved smoke and fire, were survivable but involved fatalities. Determinations whether the equipment could positively affect fire extinguishment, heat reduction, and improvement of the cabin tenability in terms of assisting in evacuation or rescue was based on judgment. Data were adjusted for improvements in aircraft survivability requirements, for accidents in which data were insufficient, and for the overall improvement (decrease) in the number of major accidents over the past 25 years. It was estimated that the HRET has the potential to save approximately 12 lives per year worldwide, with a 90-percentile estimate range of 5 to 17 lives per year.

NFPA 414 currently provides criteria for HRETs with aircraft skin-penetrating nozzle technology, which is recommended in the FAA AC [68].

The existing aircraft skin-penetrating nozzle technology has limitations. Use of this technology has been reported to be successful in one situation (2003, Memphis, TN, cargo airplane), questionable in two situations (2005, Teterboro, NJ, Part 135 aircraft and 2006, Lexington, KY, Part 121 aircraft), and unsuccessful in a fourth incident (2006, Philadelphia, PA, cargo airplane). Pierce [72] has identified the following limitations in the use of HRET-mounted aircraft skin-penetrating nozzle technology:

- It cannot be used on the section of fuselage that is obstructed by the wing.
- It must be used practically perpendicular to the aircraft fuselage.
- It eliminates the usefulness of the vehicle's main turrets because of proximity to the aircraft.
- It works best when piercing the fuselage about 18 to 24 inches above the windows. They are not useful if penetration is into the overhead carry-on compartment.

- If aviation fuel is under the ARFF vehicle, foam blanket integrity must be maintained.

- ARFF vehicles may be committed to a fixed position adjacent to an aircraft wing potentially filled with fuel.

- It raises the center of gravity of the ARFF vehicle increasing the potential for rollover; however, ARFF trucks with HRET have passed appropriate tilt-table tests.

- Current commercially available HRET may have difficulty extending to the upper deck of a B-747 or A380 fuselage: new designs are becoming available with a reach in the 50- to 60-ft range. The FAA has initiated research on a new 65-ft HRET capable of reaching upper decks of multideck aircraft.

- Deployed exit slides (particularly with the A380) may limit access to the fuselage.

- It does not provide fire fighter access to the cabin for continued rescue/recovery operations. The FAA has initiated research on airstairs equipped with firefighting capabilities.

- It may need modifications to penetrate composite fuselage materials.

It must be emphasized that this equipment is tactically used where significantly degrading conditions dictate immediate cooling of the cabin interior. The limitations and relatively unimpressive real-world use to date of this technology indicates that operators must preplan and train on the use of this equipment. The FAA includes allowances for aircraft skin-penetrating nozzle training devices in AC 150/5220-10D, and progressive ARFF departments have developed detailed tactics and procedures [73].

For multideck aircraft, i.e., B-747 and A380, HRET with aircraft skin-penetrating nozzles offers a safe and reliable means to facilitate fire attack on upper decks. Incorporating this technology where inaccessible aircraft operate, e.g., CAT 5 and above, can increase fire fighter safety by reducing the dependency on ladders to conduct interior fire suppression or rescue.

For aircraft that are accessible from the ground, hand-held piercing nozzles are an alternative option for interior suppression.

<u>6.3.4 Interior Firefighting Agent Quantities</u>.

Agent, equipment, or tactics to mount an aggressive interior fire attack must be tempered by the potential opportunity to affect lifesaving actions. Section 5.2.3 shows, under the best conditions, how aircraft immersed in a pool fire afford limited scenarios for ARFF to affect the outcome. Risk benefit decisions have been made that external pool fire extinguishment is an appropriate ARFF goal; this is included in the performance requirements established in section 6.1.

Improved, indirect interior firefighting was the subject of a study by Cherry [34]. It is relevant to revisit the fire loss data reviewed in that report. Of the 2473 accidents reviewed, 84 fatal accidents were identified in which there was an opportunity to assist survivors. Of these, 15 were identified in which the HRET could have provided benefit, with a maximum estimate of 371 potential lives to save. Of these, one accident accounted for 200 of the potential "saves." The use of the HRET, which can generally be implemented much faster than a manned fire attack, was estimated to be able to offset at least half of these fatalities. There will be situations where the HRET will be ineffective (e.g., overshoot into a ravine (Toronto, 2005) or near/in water (New York, 1992 and Little Rock, 1999). In many of these situations, fire fighters mounting a potential interior attack will be faced with similar time-delaying challenges. The FAA decisions to improve burnthrough protection and reduce interior flame spread as life safety improvements compliment the ARFF response. These improvements support the stated performance goal of preventing interior ignition. Indirect firefighting equipment, access equipment, and appropriate amounts of agent, both immediately available and in reserve, can have a significant effect on improving survivability, especially in the case of multideck aircraft. Ultimately, victims may need to be recovered. The on-scene incident commander can make the tactical decision on whether to mount an interior fire attack and how aggressive this attack should be.

The NFPA Q_3 methodology provides basic interior firefighting agent quantities. The Q_3 agent can be presumed to be applied via hand lines or a penetrator nozzle.

6.4 REVISED AGENT REQUIREMENT SUMMARY.

6.4.1 Historical Basis and Current Status.

The development of agent requirement methodologies has evolved from the 1950s through 1960s to the present. EASAMS proposed a methodology based on overall length and weight of an aircraft. This was the criteria in the original NFPA 403 requirements. These criteria evolved to aircraft length and passenger load and, finally, to the aircraft dimensions only, recognizing that the fire hazard related to area rather than the total fuel quantity, passenger load, or gross aircraft weight.

Other attempts to revise methods have had limited success. For example, the USAF was critical of NFPA 403 requirements, as applied to large-frame aircraft [35], but large-aircraft characteristics were undefined, and there were no quantitatively based recommendations to improve or revise the current method. Additionally, some have mistakenly associated the concept of cutting a rescue path [41 and 74] with the TCA/PCA concept of first protecting the aircraft fuselage.

In this report, the ARFF performance goals and associated requirements were clearly re-established in section 6.1 before there was any attempt to quantify agent quantities. These performance goals track closely with NFPA requirements, but they are explicitly defined for this analysis. Performance goals and requirements are the necessary guides when consideration is given to agent quantities. The analysis in sections 5 and 6 confirmed and quantitatively validated the NFPA concept.

6.4.2 Quantities for Exterior Pool Fire Suppression and Extinguishment of Exterior Fires (Q_1 and Q_2).

Performance requirements remain the same as those stated in section 6.1.

After a detailed, quantitative analysis, it was established that existing NFPA 403 Q_1 correlates with performance requirement 1, and Q_2 related to requirement 2, and partially to requirements 3 and 4. While adjustments may be made to the total quantities and the allocations to Q_2 and Q_3, this current methodology is acceptable and appropriate.

The current NFPA designations of Q_1 for the first performance requirement and Q_2 for the second and third requirements were found to be appropriate. With the inclusion of secondary agent requirements and resupply of agent, these Q agent designations are technically valid and, to the maximum extent possible, quantifiable.

This addresses the limitation of the CFR quantities, which seem to address the Q_1 fuselage integrity factor only. To meet the additional performance goals established herein, additional agent per NFPA is required for establishing and maintaining a safe area and providing agent for final extinguishment, which potentially may include interior firefighting and recovery.

Based on the findings of this report, CFR agent requirements are particularly lacking in two FAA indices, FAA Index A (NFPA CAT 5 and below) and FAA Index E for large aircraft (where NFPA has an additional CAT 10). NFPA 403 agent quantities for these categories more closely agree with the results of the calculations in this report.

Several qualifications and clarifications are needed. The exterior pool fire analysis demonstrated the sensitivity of the agent calculations to the time of ARFF arrival and the proximity of the aircraft to the threat. Some caution must be used when interpreting the results with respect to real-life conditions. As noted, immediate, full immersion may result in rapid aircraft interior ignition. The I.N.C.P. designation (aircraft interior ignition cannot be prevented) does not mean ARFF has no chance of success, rather, the very conservative assumptions (immediate fuel ignition and fire intensity and unlimited spill size) may limit chances of successful ARFF operations. Likewise, the arrival time differences are manifested primarily in the differences in the assumed offset of the initial spill size. For more rapid ARFF response, interior ignition prevention can be achieved for fires closer to the aircraft.

Additional analysis was performed to overcome these calculation limitations by assessing maximum threatening fire areas on one or both sides of the aircraft, and for downwind fire conditions. Although there were some outliers in the data, the majority of these situations were adequately addressed by NFPA Q_1, Q_2, or Q_T agent quantities. In some situations, it was estimated that the total amount of NFPA 403 agent might be needed (including Q_3). It could be argued that Q_2 agent quantity should then be increased. Agent quantities for these few situations, and the absolute worst-case downwind situation, are compensated by the conservativeness of the following analysis assumptions:

- Ignition in the aircraft interior is the “failure” time, although there may be some fire growth time before there are untenable conditions.

- The thinnest aluminum skin was assumed, which would result in the quickest melt/heat transfer times.

- A maximum flame-to-aircraft view factor was assumed (which results in maximum heat transfer to the aircraft).

- Suppression of the pool fires was assumed to require 0.13 gpm/ft^2 of AFFF, although test fires have been extinguished at half this rate.

- For most situations, involvement of the entire length of the aircraft was assumed. Historically, this is a rare event. Additionally, the loss history of firefighting activities (section 4.10) confirms that, historically, agent quantities are sufficient for the exterior fire scenario.

- The entire fuselage length is included in the agent calculation, not just the occupied area of the fuselage.

The agent quantities in this analysis were generally calculated to four significant figures. Given the variables involved, this is too precise a calculation. The calculations should be considered reasonable to the nearest 100 gallons. The NFPA rounds to the nearest 10 gallons. There is the practical matter that commercial ARFF vehicles have specific capacities and both NFPA 403 and CFR mandate a minimum number of vehicles. Precision in the exact agent quantity becomes less important when this is considered along with the calculation variables.

It could be argued that NFPA 403 Q_2 quantities should be revised, based on the calculations in this report. Based on the conservative nature of the analysis, as described above, and the incident data, which indicates that agent for pool fire extinguishment has historically been adequate, there appears to be no compelling reason to revise the quantities in NFPA 403. However, the NFPA 403 Technical Committee may consider outlier scenarios or agent quantities to be critical. The NFPA 403 methodology has been shown here to be technically valid. The committee process allows for expert qualitative judgment in establishing requirements. Given the range of variables involved, this process serves a useful purpose. There is no compelling need to establish more formal calculation methods in NFPA 403 at this time; future revisions can consider methods in this report to revise agent quantities as necessary.

Adjustments to Q_2 for structural composites and debris field scenarios will rely on fire test data as it becomes available. Moderate- and large-scale aircraft structural composite test data is currently lacking to permit a sufficient assessment of the need for any additional agent needed for these scenarios. Despite this lack of available data, limited laboratory-scale experiments conducted provided some advanced composite characteristics. This data allowed for the estimate conducted in this report.

6.4.3 Agent for Extinguishment of Interior Fires (Q_3).

Agent quantity for potential interior attack was analyzed in section 6.3. The concept of Q_3 was validated, and to the maximum extent, quantified for interior firefighting capability, and as a potential supplement to exterior extinguishment. The NFPA 403 Q_3 quantities were judged to be appropriate based on limited quantification methods available. There is some potential crossover between Q_2 quantities to secure the ground fire area and Q_3 interior attack; for example:

- Hand lines may be used on an exterior situation to affect final extinguishment of shielded fires.
- Agent may be used in an HRET, which technically is a Q_3 interior attack, but may be performed in concert with final extinguishment of ground fires, debris, or smoldering fuselage.
- Agent may be used to extinguish exterior Class A combustibles.

Interior firefighting agent in NFPA 403 for CATs 5 to 8 aircraft is estimated to be sufficient. Additional agent may be required for CATs 9 and 10. Given the difficulty in mounting an aggressive manned interior attack, it appears prudent to retain the NFPA 403 Q_3 agent quantities. Further data is required to better quantify the potential for additional Q_2 agent requirements based on combustible composites and on indirect interior firefighting equipment, tactics, and techniques.

6.4.4 Final Extinguishment and Securing of the Fire Area.

Final extinguishment was addressed primarily as a function of Q_2, with Q_3 potentially contributing, depending on the fire scenario. The scenarios considered most realistic and plausible were evaluated. Final extinguishment is not readily quantified beyond the Q_2/Q_3 estimates since an unlimited pool fire size was assumed. The safety factors inherent in the calculations should provide sufficient agent for security in the fire area until reserve water is brought to the scene (the ARFF vehicles have 100% onboard resupply of AFFF). The absolute worst-case scenario was not addressed since it cannot be readily quantified. The following worst-case scenarios come to mind:

- Terrorist attack (This may be similar to a nonsurvivable scenario if large explosive devices are used.)
- Crash of two large aircraft, e.g., at the intersection of runways
- Crash of a large aircraft at or near the terminal where multiple large, fueled aircraft are parked during passenger boarding and debarking

Any of these scenarios may lead to situations beyond the capacity of first responding ARFF. It is important to have a preplanned water capacity available for an extreme event. NFPA 403 requires that each airport conduct and document a needs analysis to determine a minimum 100% water resupply capability. Specific requirements for that resupply are not stated in NFPA 403, but specifics may help airports to better preplan this capability. The FAA AC on agents, AC 150/5210-6D, does not discuss water resupply. Regardless, resupply will undoubtedly be needed in the event of a major accident, as observed in some cases in the accident review.

6.4.5 Airport Categories.

Since the fire threat is directly associated with the aircraft length, it is appropriate that this type of classification be retained. It could be argued that the width of the aircraft was not used as part of the hazard analysis, but it was a component of the footprint calculation performed as a check of the fuselage and occupant threat calculation.

It has been suggested that airport categorization revert back to simpler characterizations; i.e., aircraft having single aisle, multi-aisle aircraft, and multideck variables that define categories. This is similar to the original basis described in section 3.4, where airports were classified based on commercial aircraft service. Again, the important relationship is the length of the fuselage, and developers of prior criteria recognized this and changed to the approach using length.

It has also been suggested that the use of the total length of an aircraft should be revised to the occupied length of the fuselage [65]. This could reduce the overall length in the current calculations by as much as 30 feet or more. Changing to this approach is discredited in this report. The current method is easy to calculate and is readily available. Judgment is required to define the occupied area. Some aircraft have fuel tanks in the tail section. As noted in the hazard analysis, there are some outliers in terms of total agent quantity. The inclusion of the entire length in the calculation method contributes to the safety factors identified in section 6.4.2. In section 5.3.3, it was suggested that additional Q_2 agent might be required for aircraft having large amounts of composites. This may ultimately result in the recategorization of specific aircraft.

Since the fire threat is directly associated with the aircraft length, it is appropriate that this type of aircraft classification be retained. CFR requirements stop at Index E, which includes any aircraft at least 200 feet in length. The NFPA categories, which essentially mirror ICAO categories, provide specific categories for aircraft up to 295 feet. Because of their increased volume, multideck aircraft could be considered analogous to two aircraft on top of each other. Increasing the height by adding decks does not increase the overall length, which would increase the amount of required agent; therefore, a safety factor can be accommodated by considering all multideck aircraft in the next higher index until sufficient data is available to adequately characterize the hazard. This ensures that the A380 is included in CAT 10 (it would be CAT 9 based on a total length of 238.61 ft, but CAT 10 based on a width of just over 23 ft). It also provides an additional level of safety for high-capacity B-747 aircraft.

6.4.6 Response Time and Remission Factor.

The 1-minute fire control time established for Q_1 is reasonable, practical, and appropriate. Substantially reducing this time is likely to be technologically impractical. The analysis showed the sensitivity of the "success" for fuselage protection to ARFF arrival time. Paradoxically, less agent is required for a slower arrival time. This is attributable to the rapid potential failure time of a fuselage and associated fire offset distances for success (see the companion report). Compensation was made for this phenomenon by calculating agent requirements for the aircraft footprint and full fire area needed to prevent occupant injury outside the aircraft. The current 2-minute response time in NFPA 403 is based on what is practical [1]. It was shown that the

Lindemann assumption [17] of 2 minutes before the onset of hazardous conditions is optimistic in some scenarios.

The adoption of the 4-minute burnthrough requirement appears to provide a dramatic benefit for occupants for the survivable, intact fuselage fire scenario. This requirement was adopted despite concerns that there was insufficient benefit from a cost basis. With the introduction of newly certified aircraft into the commercial fleet, the time for fire and smoke penetration from an exterior fire should be proportionally increased. Rapid response becomes more important for the scenarios where the fuselage is breached. This falls outside the stated performance goal, since occupants are immediately threatened. In other words, the scenario may be more like a nonsurvivable crash. ARFF will respond in the same manner, with some lower probability of preventing injury or death.

The ARFFRWG panel members suggested that an additional time criteria be established for ARFF response to pre-announced incidents. A qualitative review of the incidents in appendix D, where ARFF had a potential impact, does not show a substantial percentage of incident prenotification. This does not necessarily include response to minor incidents, which could develop into major incidents. From the data and analysis in this report, there is an insufficient technical basis to modify the current NFPA 403 response time criteria.

Since the hazard analysis is quantitative, the remission factor does not change the outcome. There is no hazard basis to invoke a remission factor; the potential hazard is independent of the number of operations. Remission under Part 139 can be very significant, especially if remission allows an index reduction from Index B to Index A (NFPA and ICAO CAT 6 to CAT 5). Consider, for example, an Index B (CAT 6) airport where the category is based on an Airbus A320 aircraft; if on a daily basis that aircraft had only four landings and four takeoffs, then remission could be permitted back to Index A (CAT 5). Part 139 only requires either 500 lb of powder/halon or a TAU with 450 lb of PKP and 100 gallons of AFFF solution. The analysis shows that the Part 139 requirement for Index A is inadequate in this scenario.

6.4.7 The ARFF Equipment.

To meet the performance goal of potentially affecting final interior extinguishment and continue with rescue and recovery efforts, access to aircraft and indirect firefighting were identified as key elements for effective ARFF performance. The FAA currently recommends the use of NFPA 414 in AC 150/5220-10D, with modifications. According to NFPA 414 interior access vehicles must have minimum suppression agents provided (Index A capability). The vehicle must provide access to sill heights of between 7 feet and up to at least the lower sills of the largest aircraft operating. This is consistent with the analysis in section 6.3.3.

Some airports already include modified airstairs in their ARFF vehicle fleet for the very purpose of aircraft access. Whether this capability is achieved by using dedicated ARFF equipment, or some combination of dedicated, structural firefighting, or airport support equipment, the opportunity currently exists for airports to help the airport fire service improve its safety and effectiveness. Equipment improvements, both for access and indirect firefighting equipment, should focus on the challenges identified in section 6.3.

History has shown that ARFF services that have established detailed tactical procedures on the use of specialized equipment and frequently train on those procedures are more effective in actual emergencies. Developing and promulgating standard tactics and procedures for using access and indirect firefighting equipment can improve firefighting efficiency in agent application.

6.4.8 Emergency Planning.

Emergency planning is critical to the success of ARFF response to a major accident. The CFR currently requires an airport to conduct an emergency preparedness exercise to review the required emergency plan every 12 months and to hold a full-scale airport exercise every 3 years (14 CFR 139.325 g and h). Increased frequency of these exercises has the potential to enhance preparedness, as observed in Sioux City (1987), Toronto (2005), and Heathrow (2008).

Airport emergency plans should specifically address aircraft access potential, rescue, interior firefighting, victim recovery, and water resupply. Although AC 150/5200-31 identifies water resupply in the incident command chart [75], no details are provided. Identification of equipment, sources of that equipment, and timing for its arrival should be considerations of the emergency plan.

7. NEW TECHNOLOGIES AND COMPLEMENTARY AGENTS.

7.1 EXAMPLES OF NEW TECHNOLOGIES.

The U.S. Air Force Research Laboratory (AFRL) has done extensive research and development of novel ARFF-related firefighting techniques in an attempt to develop smaller, light-weight, air-transportable ARFF vehicles that can be easily carried on cargo aircraft, such as the USAF C-130.

AFRL research has focused on the following technologies:

- Ultra-High Pressure (UHP) System—This system uses high-pressure positive displacement plunger pumps to deliver AFFF at a nominal pump discharge pressure of 1500 psi. Turret residual pressures are in the 1100- to 1200-psi range, which, in effect, causes AFFF to be delivered as a foam "mist." The applied foam has the characteristics of conventional AFFF delivery, creation of a foam blanket and aqueous film formation on the fuel surface, plus the added fire suppression features of small droplet mist, namely cooling, flame stripping, and oxygen displacement via water vapor formation.

- Compressed Air Foam System (CAFS)—In a CAFS, air is injected under pressure into AFFF solution between the pump and the nozzle, so the expanded foam discharges from the nozzle. This allows greater control over the resultant foam expansion ratio and provides a uniform, more expanded foam delivery to the fuel surface.

- Combined Agent Fire Fighting System (CAFFS)—Recent tests have focused on the patented HydroChem® technology where dry-chemical agent, typically PKP, and AFFF are discharged through a concentric nozzle design. PKP is discharged through a central orifice while AFFF, or CAFS, is discharged through the annular opening around the central dry-chemical orifice. When flowing simultaneously, the AFFF/CAFS discharge carries the PKP in the center core of the discharge stream providing greater dry-chemical discharge range then if discharged separately.

- Tri/Quad Agent Systems—As a refinement of the twin-agent concept widely used for flammable liquid firefighting for over 30 years, recent delivery systems have been developed to discharge three or four agents (water, AFFF, dry-chemical, and gaseous/halogenated agents) either simultaneous or consecutively, often through a single nozzle, which provides the nozzle man the option of easily selecting the desired agent for the particular fire scenario.

7.1.1 Recent Test Results.

Two recent AFRL reports [20 and 76] document tests performed with UHP, CAFS, and CAFFS at Tyndall Air Force Base. Tests were conducted on fuel fires on a water substrate, fuel on gravel, fuel on soil/sod, and fuel on a hard surface. Because most tests over the years have been conducted with fuel on water; e.g., Geyer and Naval Research Laboratory tests, the fuel-on-water test results are described below.

Agent extinguishment tests were conducted against three different-sized JP-8 fires: 880, 3500, and 5100 ft^2. Comparative data was generated against the performance of the primary USAF crash truck, the P-19. Agent flow rates were as follows:

- P-19 250/500-gpm AFFF
- UHP 70- to 100-gpm AFFF
- CAFS 250- to 560-gpm AFFF
- CAFFS 125- to gpm AFFF/3-pps dry chemical
- CAFFS 220-gpm AFFF/7.5-pps dry chemical

A total of 114 fuel-on-water fire tests were conducted. The results are shown in table 31.

Table 31. The USAF New Technology Tests [20]

Extinguishing Method	Number of Test Fires	Mean Application Density (gal/ft^2)
P-19	22	0.044
UHP	20	0.014
CAFS	27	0.028
CAFFS	27	0.027

Considering only the performance of the UHP, as indicated in table 31, the UHP delivery method produced a mean application density based on pool fire extinguishment of 0.014 gal/ft^2 compared to a mean application density with the conventional P-19 of 0.044 gal/ft^2.

Under the methodologies used by both NFPA and ICAO, Q_1 is calculated by multiplying the PCA by an "assumed AFFF application density" of 0.13 gal/ft^2, which provides a margin of safety of at least two compared to AFFF test performance.

It was concluded in section 3.3.2 that the AFFF application density of 0.13 gal/ft^2 is reasonable for determining Q_1 and provides an adequate margin of safety. Similarly, section 3.3.3 discussed the evolution and rationale for Q_2, derived as a function of Q_1, as currently tabulated in NFPA 403.

7.1.2 Equivalency With Conventional AFFF Delivery for Pool Fire Suppression.

If a new AFFF delivery method, or an entirely new technology, is to be accepted as a replacement for the *Q* quantities currently tabulated in NFPA 403, it would be intuitively prudent to require the agent quantities to show equivalent fire performance based on actual fire tests. Further, the alternative AFFF application method, or new technology, should contain the same margin of safety that is inherent in conventional AFFF delivery, as previously discussed.

Based on the cited USAF tests [20], calculating a comparable margin of safety for UHP systems would yield an "assumed UHP AFFF application density" of 0.041 gal/ft^2, as shown in table 32.

Table 32. Comparison of UHP and Conventional AFFF

AFFF Delivery Method	Mean Application Density (gal/ft^2)	Margin of Safety vs Assumed Application Density (gal/ft^2)	Assumed Application Density for Calculating Q_1 (gal/ft^2)
P-19	0.044	2.95	0.13
UHP	0.014	2.95	0.041

7.1.3 Burnback Equivalency.

An additional criterion for accepting alternative technologies should be a demonstration of comparable burnback resistance. However, for any alternative technology that uses MIL SPEC AFFF, such as the technologies cited above, there is an inherent resistance to burnback imparted since the agent qualifies to the specification. This requires successfully passing the burnback test following the successful extinguishment of a gasoline fire. The burnback test involves a postfire extinguishment assessment using the MIL-F-24385F 28- or 50-ft^2 fire test.

> "After the gasoline fire is extinguished, the AFFF solution application continues until 3 gallons are discharged onto the 50 square feet of gasoline, resulting in a total solution application density of 3/50 = 0.06 gal/ft^2. After a 60 second wait, a burning pan (12 inches in diameter with 2 inch sides, containing 1 gallon of

gasoline) is placed in the center of the fueled area. Once fire has spread outside of the pan, the pan is removed. Burnback time is the time when 12.5 ft^2 (25% of the original area) is involved in flame. The minimum allowable burnback time specified in the MIL SPEC is 6 minutes." [21]

Burnback tests were conducted on the UHP system [76]. Tests were conducted for a UHP-delivered application density of 0.05 gal/ft^2 on a JP-8 fire (175 gallons of AFFF solution discharged over a 3500-ft^2 fire area). After extinguishment, two 12-inch stovepipes were placed in the burn area and the foam inside the stovepipes was scooped out. At 3 minutes after extinguishment, the residual fuel within one of the stovepipes was ignited and allowed to burn for 60 seconds. After the 60-second burn period, the stovepipe was removed and the fire was allowed to spread. Burnback resistance was defined as the time after the 60-second burn period for the fire to self-extinguish. Burnback resistance for the first stovepipe was 5 minutes 25 seconds. After sitting for 8 minutes, to measure the effect of an extended foam drainage period, the residual fuel in the second stovepipe was ignited and burnback was determined the same as with the first stovepipe. The burnback time for the second stovepipe was 3 minutes 36 seconds, which, similar to the first stovepipe, was the time at which the foam blanket resealed itself and completely extinguished the fire.

The burnback tests with the UHP system shows a burnback margin of safety inherent in MIL SPEC AFFF, in that, the MIL SPEC burnback test is run on gasoline, while most fuels encountered in ARFF scenarios will be kerosene-based (Jet A, Jet A-1, and JP-8). At 0.06-gal/ft^2 application density on gasoline, the passing criteria for the MIL SPEC test allows up to 25% of the original fire area to burnback in 6 minutes. In the UHP burnback test on JP-8, although the application density was less, there was no burnback at 6 minutes because the fire had self-extinguished.

The UHP burnback test was run at a higher application density than the UHP mean extinguishment application density based on 20 extinguishment tests, as shown in table 32 (0.05 versus 0.014 gal/ft^2). Burnback performance at the lower application density is unknown. Additionally, as discussed in section 5, there is concern about the possible combustibility of composites contained in new aircraft. If composites do not self-extinguish upon removal of the exposing pool fire, then the potential exists for burning chunks of composite material to fall into the previously extinguished pool of fuel. Such a scenario would make burnback resistance an important parameter, though the concern is tempered somewhat where MIL SPEC AFFF is used.

7.1.4 The UHP Equivalency to Conventional AFFF.

UHP would appear to meet the standard performance criteria for fire control of pool fires. Burnback equivalency to conventional AFFF is not clear (note, except for MIL SPEC small-scale burnback criteria, this measure has not been quantified). Effectiveness on residual Class A combustibles and usefulness for interior attacks has not been quantified. Discharge equipment quality control parameters and limits are not well established at this point.

7.2 COMPLEMENTARY AGENTS.

Secondary agents have not been emphasized in this report. NFPA 403 currently requires that complementary agents be based on International Standards Organization-qualified PKP.

Concerns with new technology include

- lack of specificity relative to the definition of CAFS (There is some conflicting data on CAFS performance, which may be attributable to a lack of a standard definition of the CAFS.)

- recent efforts on combined agent techniques focusing on the HydroChem method where PKP is discharged in the center of the AFFF stream (Reported superiority of simultaneous PKP/AFFF discharge have shown reduction in AFFF application rates, but failed to consider the mass flow equivalent amount of AFFF that could replace the PKP.)

- stream reach

Geyer performed extensive tests on three-dimensional fire suppression [13 and 14]. Performance criteria could be established using these tests as a basis. Other standard three-dimensional tests for aviation purposes have been proposed by the FAA and the USAF. The fire threats are considerably different.

The challenge of developing a standard test, as the U.S. Military has found, is quantifying the threat and associated performance level (e.g., extinguishment time and minimum agent flow rate). Baselining to Halon 1211 performance was problematic because no halon alternative has demonstrated equivalent performance.

It seemed reasonable, at this point, to list or require approval of alternative complementary agents for proposed ARFF use. Example lists or approval agencies in the U.S. include Underwriters Laboratories, Inc. or FM Global. This would provide minimum quality control assurance for accepting agents. This is a reasonable step until a specialized test method for evaluating the comparative value of new agent technologies is developed.

8. CONCLUSIONS.

The work detailed in this report led to the following conclusions.

- The performance goals of National Fire Protection Association (NFPA) 403 are embodied in the scope, definitions, and annex material. This has resulted in requirements based on the Theoretical Critical Area (TCA)/Practical Critical Area (PCA) concept.

    - Maintaining the fuselage integrity of an aircraft involved in an accident appears to be the primary basis of the Q_1 agent quantity that must be immediately applied to a fire.

- The Q_2 quantity provides final fire extinguishment so occupants can move away from the accident area. The multiples used to calculate Q_2 agent as a function of Q_1 apparently relate to the original TCA/PCA relationship and the product of the fuselage length and wingspan.

- Accident data indicates there is a high degree of survivability for even the most serious accidents.

  - When occupants are ambulatory (no traumatic injuries), they tend to self-evacuate without assistance.

  - When accidents involve traumatic injuries (i.e., fatal crashes), ARFF may assist in evacuating some occupants.

  This was confirmed in a review of the most recent major accidents.

- There were only 27 major accidents identified over the period from 1992 to the time of this analysis involving large occupant load in which Aircraft Rescue and Firefighting (ARFF) provided potential assistance, indicating the low probability of such an accident. Even under the most favorable response scenarios, ARFF response may have limited effectiveness because of potential rapid breach of the fuselage (by fire or by impact) and resulting rapidly deteriorating cabin conditions.

- The trends identified in earlier studies relating to the size of airport accident fires and associated agent use were observed in the updated accident review.

  - The fire size in most accidents is less than the product of the fuselage length times wingspan, and is usually 50% or less of this area. In exceptional cases, the fire may involve the entire aircraft area.

  - ARFF personnel may use much more agent than the Code of Federal Regulations (CFR) or NFPA 403 requires, but the amount of agent generally used for initial fire control appears to be within the required amounts.

- Emergency planning appears to be an important element for successful ARFF responses to major accidents.

- There is no general correlation of the fuel and passenger loads between aircraft within and across the airport categories. The only trend is a general increase in these loads and the length and width, as the categories increase.

- In an aircraft accident, there is no quantitative method to predict how much fuel will spill, when it will ignite, at what rate it might spill, or what total quantity may be involved. Therefore, an approach in which the fire size is assumed to be of unlimited size was adopted in the fire hazard analysis, and the agent required to protect occupants was calculated.

- Interior aircraft ignition may not be prevented if the aircraft is totally immersed in fire, even with a rapid (less than 2 minutes) ARFF response. The current assumption that there may be 2 minutes before occupants are threatened is optimistic for the analyzed scenarios of interest in this report.

- Prevention of interior ignition is sensitive to the proximity of fire to the aircraft, ARFF response, and aircraft fuselage characteristics. Agent quantities were estimated for these variables.

- The new FAA 4-minute burnthrough criteria dramatically reduce the chances of interior ignition for the intact crash scenario. It will, however, be some time before the requirements are fully implemented throughout the commercial aircraft fleet.

- Understanding the threat posed by the potential, large-surface area involvement of composite material suffers from a lack of data.

    - A low-end quantity of 300 gallons was estimated when one-quarter of the fuselage is burning.

    - When a wing is also involved, the composite has a high heat release rate, and fire fighters are inefficient in attacking the fire and applying agent (over 5500 gallons might be required).

    - Further data is required to adequately quantify this agent requirement.

- Combating fires around large aircraft offer potential challenges including potential debris and obstructions from deployed exit slides.

- Explicit performance goals and associated requirements consistent with these goals should serve as the basis for determining agent requirements.

- The current NFPA designations of Q_1, Q_2, and Q_3 for the established performance goals and associated requirements were found to be appropriate.

    - Although there are some outliers in the data, the majority of the analyzed scenarios are adequately addressed by NFPA Q_1, Q_2, or Q_T agent quantities. The outliers are compensated for by the conservative nature of the analysis and associated assessments of fully engulfed aircraft.

    - The Q_1 and Q_2 amounts in NFPA 403 are valid.

    - The Q_3 quantities were judged to be appropriate based on the limited quantification methods available. Additional agent may be needed for NFPA categories (i.e., airport category) (CAT) 9 and 10, but this depends on other factors, such as the ability to mount and sustain an interior attack within a crashed fuselage. The NFPA Q_3 methodology provides basic interior firefighting agent quantities. Any additional quantification of interior firefighting agent relies on the ability to effectively use existing capabilities.

- The agent quantities required in the CFR directly relate to Q_1 quantities. Currently, no additional agent is required based on the established performance goal for Q_1 .

- There is no compelling reason to revise the quantities in NFPA 403 for existing aircraft, unless the NFPA 403 Technical Committee considers an outlier scenario/quantity as being critically important. Q_2 quantities may need to be adjusted based on further testing of the composite fire threat from new aircraft.

• A major crash where the fuselage integrity is compromised and an interior fire occurs has been a significant challenge for ARFF responders.

  - A large pool fire could develop that would immediately put occupants at risk where the fuselage is open to the fire.

  - Any interior firefighting in this scenario will be challenging, at best.

  - The FAA efforts to reduce fire growth characteristics of interior materials and improve fuselage burnthrough resistance will mitigate the potential for rapid fire growth, though it will be some time before these improvements are fully implemented.

  - Access is the primary limitation to mounting a rapid manual interior attack.

  - Use of indirect attack equipment, specifically an aircraft skin-penetrating nozzle, or high-reach extendable turret, has the greatest chance of success in rapidly cooling the interior cabin to save nonambulatory occupants.

• The important relationship in aircraft categorization is the length of the fuselage, which is directly associated with the performance goals and associated requirements.

• Since the hazard analysis is quantitative, the CFR-permitted remission factor does not change the outcome. There is no hazard basis to invoke a remission factor; the potential hazard is independent of the number of operations.

• Access to aircraft and indirect firefighting were identified as key elements for effective ARFF performance and improving fire fighter safety.

• New agent technologies were assessed. The test results of an UHP AFFF system were reviewed. It is very promising in terms of reduced water capacity for suppression of pool fires. Burnback and Class A extinguishment performance need to be better understood.

9. REFERENCES.

1. National Fire Protection Association, "Standard for Aircraft Rescue and Fire-Fighting Services at Airports," various editions, NFPA 403, Quincy, Massachusetts.

2. U.S. Federal Register, "Part 139—Certification of Airports," Amendment No. 139-26, Code of Federal Regulations, February 10, 2004.

3. International Civil Aviation Organization (ICAO), "Aerodromes—Annex 14: Amendments 8 and 9," Vol. 1, Fourth Edition, International Civil Aviation Organization, Canada, July 2004.

4. International Civil Aviation Organization (ICAO), "Airport Services Manual—Part 1 Rescue and Firefighting," Document 9137·AN/898, Third Edition, International Civil Aviation Organization, Canada, 1990.

5. FAA AC 150/5210-6D, "Aircraft Fire Extinguishing Agents," U.S. Department of Transportation, July 8, 2004.

6. Cohn, B.M and Campbell, J.A., "Minimum Needs for Airport Fire Fighting and Rescue Services," Report No. AS-71-1, Federal Aviation Administration, Airports Service, Washington, DC, January 1971.

7. EASAMS, "Aerodrome. Fire and Rescue Services," DORA Report 7201, prepared by EASAMS Ltd. and Civil Aviation Authority (CAA), London, UK, May 1972.

8. ARFFRWG, "ARFF Requirements Working Group (ARFFRWG) Notice of Proposed Rulemaking Final Recommendation to ARAC 14 CFR Part 139 Subpart D," Federal Aviation Administration, Washington, DC, March 2004.

9. Scheffey, J.L., Darwin, R.L., and Hunt, S., "Analysis of Suppression Effects on Aviation Fuel Fires Around an Aircraft," FAA report DOT/FAA/AR-11/27, November 2011.

10. Hewes, B.V., "Report of the First Meeting of the ICAO Rescue and Firefighting Panel (ICAO RFFP I)," Montreal, Canada, March 10-20, 1970.

11. International Civil Aviation Organization (ICAO), "Rescue and Firefighting Panel, Report of the Second Meeting," Document 9036 RFFP II, Montreal, June 5-16, 1972.

12. Geyer, G.B., "Effect of Ground Crash Fire on Aircraft Fuselage Integrity," Report No. NA-69-37 (Replaced RD-69-46), U.S. Department of Transportation, Federal Aviation Administration, December 1969.

13. Geyer, G.B., "Evaluation of Aircraft Ground Firefighting Agents and Techniques," AGFSRS 71-1, National Aviation Facilities Experimental Center, Atlantic City, New Jersey, February 1972.

14. Geyer, G.B., "Equivalency Evaluation of Firefighting Agents and Minimum Requirements at U.S. Air Force Airfields," FAA report DOT/FAA/CT-82/109, Federal Aviation Administration, Washington, DC, June 30, 2005.

15. Sarkos, C., Hill, R., and Howell, W., "Development and Application of a Full Scale Wide Body Test Article to Study the Behavior of Interior Materials During a Postcrash Fuel Fire," *Advisory Group for Aerospace Research and Development*, Aircraft Fire Safety, AGARD Lecture Series 123, Oslo, Norway, 1982, pp. 21.

16. Marker, T.R., "Full-Scale Test Evaluation of Aircraft Fuel Fire Burnthrough Resistance Improvements," FAA report DOT/FAA/AR-98/52, January 1999.

17. Lindemann, T., "Aircraft Fire Fighting in Three Minutes or Less," *Industrial Fire World*, Vol. 5, No. 1, January-March 1990, pp. 6, 22-24.

18. Scheffey, J.L., Darwin, R.L., Leach, W., Fallis, S., and Williams, F.W., "Performance Analysis of Foam Agents Required to Combat Liquid Fuel Hazards," NRL/MR/6180-02-8608, Naval Research Laboratory, Washington, DC, March 21, 2002.

19. Scheffey, J.L. and Wright, J., "Analysis of Test Criteria for Specifying Foam Firefighting Agents for Aircraft Rescue and Firefighting," FAA report DOT/FAA/CT-94/04, August 1994.

20. McDonald, M.J., Dierdorf, D., Kalberer, J.L., and Barrett, K., "Fire Extinguishing Effectiveness Tests," Report No. AFRL-ML-TY-TR-2004-4554, Air Force Research Laboratory, Tyndall Air Force Base, Panama City, Florida, November 2004.

21. U.S. Military Specification, MIL-F-24385F, Department of the Navy, Washington, DC, 1992.

22. UL 162, "Standard for Foam Equipment and Liquid Concentrates," Underwriters Laboratories, Inc., Northbrook, Illinois (1994, with revisions through 1999).

23. Geyer, G., Neri, L., and Urban, C., "Comparative Evaluation of Firefighting Foam Agents," Report No. FAA/RD-79-61, Federal Aviation Administration, Washington, DC, August 1979.

24. Hewes, B.V., "F.A.R. Part 139 and the CFR Story," Air Line Pilots Association, Rescue and Fire Committee, July 31, 1978.

25. National Transportation Safety Board, "Cabin Safety in Large Transport Aircraft," NTSB Report No. AAS-81-02, NTSB, Washington, DC, September 9, 1981.

26. National Transportation Safety Board, "Survivability of Accidents Involving Part 121 U.S. Air Carrier Operations, 1983 Through 2000," Report No. NTSB/SR-01/01, NTSB, Washington, DC, August 22, 2001.

27. David, R., “Location of Aircraft Accidents/Incidents Relative to Runways,” FAA report DOT/FAA/AOV 90-1, Washington, DC, July 1, 1990.

28. Huggins, P. (unpublished), “Location of Undershoots, Overshoots, and Veer-Offs,” unpublished data provided by the Airline Pilots Association, May 2009.

29. Flight Safety Foundation, “In Aircraft Fueling, Fire Prevention Requires Strict Compliance With Routine Procedures,” *Airport Operations*, Vol. 27, No. 2-3, March-June 2001.

30. Sarkos, C.P., “Fire Test Analysis of Past Transport Aircraft Accidents: Manchester, 1985 and Valujet, 1996,” NFPA International Conference on Aviation, Fire Protection,” University of Maryland, College Park, sponsored by NFPA’s Aviation Section, September 21-24, 1998.

31. U.K. Department of Transport, “Appendices 1-21,” Ref No. Dd 291306 CIS 2/89, UK, 1986.

32. Webster, H., “Fuel Fire Penetration Test and Destruction of a Transport Aircraft,” FAA report DOT/FAA/AR-96/48, December 1996.

33. Omans, L., “Aircraft Incident Case Histories, Lessons Learned,” presentation at the “ARAC ARFF Committee Meeting,” Pittsburgh, Pennsylvania, May 2002.

34. Cherry & Associates Limited, “An Evaluation of Technologies for Aircraft Cabin Firefighting and Improving Occupant Survivability During Post-Crash Fires,” 0581/R/000396/KK, Issue 2, prepared for UK Civil Aviation Authority, R.G.W. Cherry & Associates Limited, Hertfordshire, UK, October 2007.

35. Hall, G.F., Partin, B.R., and Storm, J.H., “Large Frame Aircraft (LFA) Fire Fighting Validation, TCA/PCA Methodology Evaluation,” U.S. Air Force, Fire Research Group, Tyndall Air Force Base, Panama City, Florida, January 1995.

36. Cherry & Associates Limited, “Aircraft Accident Fire Survivability Data,” 1712/R/000266/KK, Issue 2, prepared for Federal Aviation Administration, R.G.W. Cherry & Associates Limited, Hertfordshire, UK, January 2005.

37. Hewes, B.V., “Air Carrier Crash Fire Response,” Air Line Pilots Association, Rescue and Fire Committee, February 4, 1993.

38. Conroy, M., “British Airport Authority Firefighters Test Their Training (BAA fire service responds to a Boeing 777 crash at Heathrow),” *NFPA Journal*, July 2008, www.nfpa.org/journal/portal.asp.

39. Huggins, P., “Survey of Airports for Fire Extinguishing Agent Quantities,” Memo, Air Line Pilots Association, July 2, 1991.

40. Karter, M.J., "NFPA's Recent Survey Gives us a Clearer Picture of Aircraft Rescue and Firefighting Resources Across the United States," *NFPA Journal*, May/June 1999.

41. Phillips, T.J., "Airbus 380 Meeting the Challenge in 2006," *International Forum on Airport Emergency and Risk Management*, Singapore Aviation Academy (SAA), January 11, 2005.

42. Gandhi, S. and Lyon, R.E., "Health Hazards of Combustion Products From Aircraft Composite Materials," FAA report DOT/FAA/AR-98/34, September 1998.

43. USAF, Technical Order 00-105E-9, Chapter 3, "Hazardous Materials and Mishap Hazards," December 31, 2008, Revision 14, "Mojave Composite Burn."

44. USAF Training Course (undated), "Mishap Composite Awareness," Training Course prepared by the United States Air Force (USAF) Advanced Composites Office.

45. National Fire Protection Association, "Guide for Aircraft Rescue and Firefighting Operations," 2008 Edition, NFPA 402, Quincy, Massachusetts.

46. Pora, J., "Advanced Materials and Technologies for A380 Structure."

47. Stilp, T., "Introduction to A380 RFF Characteristics," *Disabled Aircraft Recovery & Airport Rescue Fire Fighting Workshop*, Toulouse, France, April 11-12, 2006.

48. Gottuk, D.T. and White, D.A., "Liquid Fuel Fires," *SFPE Handbook of Fire Protection Engineering*, Third Edition, Chapter 2-15, National Fire Protection Association, Quincy, Massachusetts, 2002, pp. 2-337 to 2-357.

49. Mansfield, J.A. and Linley, L.J., "Measurement and Statistical Analysis of Flame Temperatures From Large Fuel Spill Fires," NWCTP 7061, Naval Weapons Center, China Lake, California, January 1991.

50. Cherry & Associates Limited, "A Benefit Analysis for Cabin Water Spray Systems and Enhanced Fuselage Burnthrough Protection," CAA paper 2002/04, Civil Aviation Authority, Safety Regulation Group, April 7, 2003.

51. U.S. Federal Register, "Improved Flammability Standards for Thermal/Acoustic Insulation Materials Used in Transport Category Airplanes, 14 CFR Part 25, et al.," *Federal Register*, Vol. 65, No. 183, September 20, 2000, pp. 56991-57022.

52. Klems, T., "Update on Airbus Fire Safety Research and Development," *Aircraft Fire and Cabin Safety Conference Lisbon*, Airbus S.A.S., August 2, 2005.

53. Federal Aviation Administration, "Full-Scale Composite Toxicity Test," Unreleased Video, FAA William J. Hughes Technical Center Cabin Fire Safety Research Group, 2007.

54. Quintiere, J.G., Walters, R.N., and Crowley, S., "Flammability Properties of Aircraft Carbon-Fiber Structural Composite," FAA report DOT/FAA/AR-07/57, October 2007.

55. Sorathia, U., "Improving the Fire Performance Characteristics of Composite Materials for Naval Applications," *AMPTIAC Quarterly*, Vol. 7, No. 3, 2003.

56. Creedy, K., "Composite Safety Concerns are Red Herrings," *Aviation Today*, December 2007.

57. Yarlagadda, S., Chatterjee, A., Gillespie, J.W., Kiel, J.C., Dierdorf, D.S., and McGraw, D.J., "Post-Fire Damage Assessment of a Composite Wingbox," AFRL-ML-TY-TP-2004-4516, Air Force Research Laboratory, Tyndall Air Force Base, Panama City, Florida, May 2004.

58. Tyson, J.H., Childress, J., Fontenot, J.S., and Wildman, G.L., "Carrier-Deck Fire Response of Graphite-Epoxy Composite Material," NAWCWD TP 6713, Naval Weapons Center, China Lake, California, May 1986.

59. Wright, M.T., Luers, A.C., Darwin, R.L., Scheffey, J.L., Bowman, H.L., Davidson, R.A., and Gogley, E.J., "Composite Materials in Aircraft Mishaps Involving Fire: A Literature Review," NAWCWD TP 8552, Naval Air Warfare Center Weapons Division, China Lake, California, June 2003.

60. U.S. Air Force, Impact Analysis, H2. Mishap Number 261766, Mishap Aircraft: B-2A, 89-0127, Investigator: Diane Baker, February 23, 2008.

61. Scheffey, J.L. and Williams, F.W., "The Extinguishment of Fires Using Low Flow Water Hose Streams–Part I," *Fire Technology*, Vol. 27, No. 2, May 1991, pp. 128-144.

62. Rashbash, D.J., "The Extinction of Fire With Plain Water: A Review," *Proceedings 1st International Symposium*, Hemisphere Publishing Co., New York, New York, 1986.

63. Budnick, E.K., Forssell, E.W., Nelson, H.E., and Wong, J.T., "Fire Performance and Suppressibility of Composite Materials, Phase II Final Report," Report HAI 92-1071/ SBIR Phase II Final Report AF87-068, prepared for United States Air Force, Tyndall Air Force Base, Panama City, Florida, August 17, 1993.

64. Frank, J.A., "Characteristics and Hazards of Water and Water Additives for Fire Suppression," Section 17/Chapter 3, *NFPA Fire Protection Handbook*, 20th Edition, Cote, A.E. (ed.), Quincy, Massachusetts, 2008, pp. 17-31–17-43.

65. Society of Fire Protection Engineers, "Engineer's Guide to Fire Department Intervention," Society of Fire Protection Engineers, Bethesda, Maryland, draft, 2005.

66. Krause, R., "Boeing 787 Dreamliner Update," presentation to the Aircraft Rescue and Firefighting Working Group, Las Vegas, Nevada, September 5, 2008.

67. NFPA 414, "Standard for Aircraft Rescue and Fire-Fighting Vehicles," 2007 Edition, Quincy, Massachusetts, August 17, 2006.

68. Federal Aviation Administration, "Guide Specification for Aircraft Rescue and Firefighting Vehicles," AC 150/5220-10D, FAA Airport Engineering Division AAS-100, Washington, DC, September 19, 2007.

69. O'Neill, J., Urban, C., and Geyer, G., "Preliminary Assessment of the Effectiveness of a Ballistically Powered Aircraft Skin Penetrator Nozzle in Extinguishing an Aircraft Cabin Fire With Aqueous Film-Forming Foam," Ltr Report No. NA-79-55-LR, FAA National Aviation Facilities Experimental Center, Atlantic City, New Jersey, October, 1979.

70. Wright, J.A., "Aircraft Rescue and Fire Fighting Efficiency Relates to the Use of New Technology, "Is it Time to Recalculate ARFF Index Requirements?" ARFF Technical Services, Inc., Red Lion, Pennsylvania.

71. Bagot, K. and Subbotin, N., "High-Reach Extendable Turrets With Skin-Penetrating Nozzle," FAA report DOT/FAA/AR-05/53, November 2005.

72. Pierce, D.M., "Aircraft Interior Access Vehicles for ARFF," *International Airport Review*, June 16, 2006.

73. Larsen, D., "Penetrate…Why, When, Where," presentation to the Aircraft Rescue and Firefighting Working Group, Las Vegas, Nevada, September 5, 2008.

74. Coalition for Airport and Airplane Passenger Safety, "Surviving the Crash, The Need to Improve Lifesaving Measures at Our Nation's Airports," Coalition for Airport and Airplane Passenger Safety, Washington, DC, February 11, 2008.

75. FAA AC 150/5200-31C, "Airport Emergency Plan," U.S. Department of Transportation, June 16, 2009.

76. Menchini, C.P., Kalberer, J.L., Dierdorf, D., McDonald, D.J., Cozart, K.S., and Abildgaard, A.C., "The Development and Design of a Prototype Ultra High Pressure P-19 Firefighting Vehicle," Applied Research Associates, Tyndall Air Force Base, Panama City, Florida, AFRL-ML-TY-2007-4525, February 2007.

APPENDIX A—AIRCRAFT CHARACTERISTICS

Airport Category	Aircraft	Overall	Fuselage			Wingspan	Single Wing Length	Height				Single Wing Area	Fuel Load			Passenger load			
		Length	*Length*	*height*	*width*			*Ground to bottom of fuselage: max (min)*	*Ground to bottom of lowest passenger door: max (min)*	*Ground to bottom of highest passenger door: max (min)*	*Ground to the highest point: max (min)*		*Total*	*In Wing*	*Other*	*Maximum possible*	*Upper Deck*	*Lower Deck*	*Range*
4 Length up to 80 ft	ATR 42-200	74.37 ft 22.67 m				80.61 ft 24.57 m							1680 gal 6359.49 L 11256 lbs 5105.69 kg	1680 gal 6359.49 L 11256 lbs 5105.69 kg	0 gal 0 L 0 lbs 0 kg	50	0	50	44 - 50
	Bombardier Dash 8	73 ft 22.25 m			6.66 ft 2.03 m	85 ft 25.91 m	39.17 ft 11.94 m				24.57 ft 7.49 m		834.7 gal 3159.68 L 5592.49 lbs 2536.74 kg	834.7 gal 3159.68 L 5592.49 lbs 2536.74 kg	0 gal 0 L 0 lbs 0 kg	39	0	39	37 - 39
5 Length up to 90 ft	ATR 72-500	89.17 ft 27.18 m			9.42 ft 2.87 m	88.75 ft 27.05 m	39.67 ft 12.09 m				25.08 ft 7.65 m		1540.5 gal 5831.43 L 10321.35 lbs 4681.74 kg	1540.5 gal 5831.43 L 10321.35 lbs 4681.74 kg	0 gal 0 L 0 lbs 0 kg	74	0	74	62 - 74
	Bae ATP	85.33 ft 26.01 m			8.2 ft 2.5 m	100.5 ft 30.63 m	46.15 ft 14.07 m				24.6 ft 7.5 m		1681 gal 6363.28 L 11262.7 lbs 5108.73 kg	1681 gal 6363.28 L 11262.7 lbs 5108.73 kg	0 gal 0 L 0 lbs 0 kg	68	0	68	68
	Bae 146 Srs 100	85.83 ft 26.16 m	50.58 ft 15.42 m	11.25 ft 3.43 m	10.67 ft 3.25 m	86.42 ft 26.34 m	37.88 ft 11.54 m				28.25 ft 8.61 m		3099 gal 11730.99 L 20763.3 lbs 9418.18 kg	3099 gal 11730.99 L 20763.3 lbs 9418.18 kg	0 gal 0 L 0 lbs 0 kg	80	0	80	70 - 80
	Canadair CRJ-100ER	87.83 ft 26.77 m			8.83 ft 2.69 m	69.58 ft 21.21 m	30.38 ft 9.26 m				20.42 ft 6.22 m	520 sq ft 158.5 sq m	2134.51 gal 8080 L 14301.22 lbs 6486.99 kg	2134.51 gal 8080 L 14301.22 lbs 6486.99 kg	0 gal 0 L 0 lbs 0 kg	50	0	50	50
	Convair 340	74.67 ft 22.76 m				91.75 ft 27.97 m					26.92 ft 8.2 m		1550 gal 5867.39 L 10385 lbs 4710.61 kg	1550 gal 5867.39 L 10385 lbs 4710.61 kg	0 gal 0 L 0 lbs 0 kg	52	0	50	52
	Convair 440	81.5 ft 24.84 m				91.75 ft 27.97 m					26.92 ft 8.2 m		1730 gal 6548.76 L 11591 lbs 5257.65 kg	1730 gal 6548.76 L 11591 lbs 5257.65 kg	0 gal 0 L 0 lbs 0 kg	52	0	52	52
	Dash 8 DHC-8	73 ft 22.25 m	29.86 ft 9.1 m		6.66 ft 2.03 m	84.94 ft 25.89 m	39.14 ft 11.93 m				24.57 ft 7.49 m		834.78 gal 3159.99 L 5593.03 lbs 2536.98 kg	834.78 gal 3159.99 L 5593.03 lbs 2536.98 kg	0 gal 0 L 0 lbs 0 kg	39	0	39	37-39
	Fairchild Packet	77.08 ft 23.5 m				106.5 ft 32.46 m					26.33 ft 8.03 m		32910 gal 124577.9 L 220497 lbs 100016.85 kg	32910 gal 124577.9 L 220497 lbs 100016.85 kg	0 gal 0 L 0 lbs 0 kg	42	0	42	42
	Fokker Fellowship F-27 MK 500	82.21 ft 25.06 m				95.15 ft 29 m					28.6 ft 8.72 m		2368 gal 8963.86 L 15865.6 lbs 7196.59 kg	2368 gal 8963.86 L 15865.6 lbs 7196.59 kg	0 gal 0 L 0 lbs 0 kg	56	0	56	52-56
	Fokker F-50	82.83 ft 25.25 m				95.17 ft 29.01 m					27.33 ft 8.33 m		1356.79 gal 5136.01 L 9090.49 lbs 4123.42 kg	1356.79 gal 5136.01 L 9090.49 lbs 4123.42 kg	0 gal 0 L 0 lbs 0 kg	58	0	58	50 - 58
	Grumman Gulfstream II	79.92 ft 24.36 m				77.83 ft 23.72 m					24.5 ft 7.47 m		3306 gal 12514.57 L 22150.2 lbs 10047.27 kg	3306 gal 12514.57 L 22150.2 lbs 10047.27 kg	0 gal 0 L 0 lbs 0 kg	19	0	19	8 - 19
	NAMC Ys-11	107 ft 32.61 m				93.5 ft 28.5 m					24.5 ft 7.47 m		1290.59 gal 4885.41 L 8646.95 lbs 3922.23 kg	1290.59 gal 4885.41 L 8646.95 lbs 3922.23 kg	0 gal 0 L 0 lbs 0 kg	119	0	119	97-119

Airport Category	Aircraft	Overall	Fuselage			Wingspan	Single Wing Length	Height				Single Wing Area	Fuel Load			Passenger load			
		Length	*Length*	*height*	*width*			*Ground to bottom of fuselage: max (min)*	*Ground to bottom of lowest passenger door: max (min)*	*Ground to bottom of highest passenger door: max (min)*	*Ground to the highest point: max (min)*		*Total*	*In Wing*	*Other*	*Maximum possible*	*Upper Deck*	*Lower Deck*	*Range*
6 Length up to 126 ft	Airbus A320	123.26 ft 37.57 m	102.07 ft 31.11 m	13.58 ft 4.14 m	12.96 ft 3.95 m	111.25 ft 33.91 m	49.15 ft 14.98 m	5.91 ft (5.69 ft) 1.8 m (1.73 m)	11.31 ft (11.12 ft) 3.45 m (3.39 m)	11.64 ft (11.31 ft) 3.55 m (3.45 m)	39.08 ft (38.72 ft) 11.91 m (11.8 m)	432.59 sq ft 131.85 sq m	25337 gal 95910.98 L 169757.9 lbs 77001.73 kg	25337 gal 95910.98 L 169757.9 lbs 77001.73 kg	0 gal 0 L 0 lbs 0 kg	164	0	164	164
	BAC One Eleven Except Srs 500	93.5 ft 28.5 m				88.5 ft 26.97 m					24.5 ft 7.47 m		3731.34 gal 14124.67 L 25000 lbs 11339.93 kg	3731.34 gal 14124.67 L 25000 lbs 11339.93 kg	0 gal 0 L 0 lbs 0 kg	89	0	89	
	BAC One Eleven Srs 500	107 ft 32.61 m				93.5 ft 28.5 m					24.5 ft 7.47 m					119	0	119	97-119
	Bae 146 Srs 200	93.67 ft 28.55 m				86.42 ft 26.34 m					28.25 ft 8.61 m					112	0	112	85 - 112
	Boeing 737-100	94 ft 28.65 m	90.58 ft 27.61 m	13.17 ft 4.01 m	12.33 ft 3.76 m	93 ft 28.35 m	40.33 ft 12.29 m	4.25 ft (3.83 ft) 1.3 m (1.17 m)	9.08 ft (9 ft) 2.77 m (2.74 m)	10.42 ft (10.25 ft) 3.18 m (3.12 m)	37.17 ft (36.83 ft) 11.33 m (11.23 m)	465.88 sq ft 142 sq m	3545 gal 13419.28 L 23751.5 lbs 10773.62 kg	3545 gal 13419.28 L 23751.5 lbs 10773.62 kg	0 gal 0 L 0 lbs 0 kg	118	0	118	103 - 118
	Boeing 737-200	100.17 ft 30.53 m	93 ft 28.35 m	13.17 ft 4.01 m	12.33 ft 3.76 m	93 ft 28.35 m	40.33 ft 12.29 m	4.25 ft (3.83 ft) 1.3 m (1.17 m)	8.58 ft (8.08 ft) 2.62 m (2.46 m)	9.17 ft (9 ft) 2.79 m (2.74 m)	37.25 ft (36.83 ft) 11.35 m (11.23 m)	457.94 sq ft 139.58 sq m	59570 gal 225496.98 L 399119 lbs 181039.31 kg	59570 gal 225496.98 L 399119 lbs 181039.31 kg	0 gal 0 L 0 lbs 0 kg	130	0	130	0 - 130
	Boeing 737-300	109.58 ft 33.4 m	105.58 ft 32.18 m	13.17 ft 4.01 m	12.33 ft 3.76 m	94.75 ft 28.88 m	41.21 ft 12.56 m	4.58 ft (4.17 ft) 1.4 m (1.27 m)	8.75 ft (8.58 ft) 2.67 m (2.62 m)	9.08 ft (8.58 ft) 2.77 m (2.62 m)	36.58 ft (36.33 ft) 11.15 m (11.07 m)	472.4 sq ft 143.99 sq m	6295 gal 23829.17 L 42176.5 lbs 19131.15 kg	6295 gal 23829.17 L 42176.5 lbs 19131.15 kg	0 gal 0 L 0 lbs 0 kg	149	0	149	128 - 149
	Boeing 737-400	119.58 ft 36.45 m	115.58 ft 35.23 m	13.17 ft 4.01 m	12.33 ft 3.76 m	94.75 ft 28.88 m	41.21 ft 12.56 m	4.58 ft (4.17 ft) 1.4 m (1.27 m)	8.75 ft (8.58 ft) 2.67 m (2.62 m)	9.08 ft (8.58 ft) 2.77 m (2.62 m)	36.58 ft (36.33 ft) 11.15 m (11.07 m)	475.9 sq ft 145.05 sq m	6295 gal 23829.17 L 42176.5 lbs 19131.15 kg	6295 gal 23829.17 L 42176.5 lbs 19131.15 kg	0 gal 0 L 0 lbs 0 kg	168	0	168	146 - 168
	Boeing 737-500	101.75 ft 31.01 m	97.75 ft 29.79 m	13.17 ft 4.01 m	12.33 ft 3.76 m	97.75 ft 29.79 m	42.71 ft 13.02 m	4.58 ft (4.17 ft) 1.4 m (1.27 m)	8.75 ft (8.58 ft) 2.67 m (2.62 m)	9.08 ft (8.58 ft) 2.77 m (2.62 m)	36.58 ft (36.33 ft) 11.15 m (11.07 m)	462.76 sq ft 141.05 sq m	6295 gal 23829.17 L 42176.5 lbs 19131.15 kg	6295 gal 23829.17 L 42176.5 lbs 19131.15 kg	0 gal 0 L 0 lbs 0 kg	132	0	132	108 - 132
	Boeing 737-600	102.5 ft 31.24 m	97.75 ft 29.79 m	13.17 ft 4.01 m	12.33 ft 3.76 m	112.58 ft 34.32 m	50.13 ft 15.28 m	4.75 ft (4.25 ft) 1.45 m (1.3 m)	9 ft (8.5 ft) 2.74 m (2.59 m)	10.17 ft (10.17 ft) 3.1 m (3.1 m)	41.67 ft (41.58 ft) 12.7 m (12.67 m)	748.58 sq ft 228.17 sq m	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	0 gal 0 L 0 lbs 0 kg	130	0	130	108 - 130
	Boeing 737-700	110.33 ft 33.63 m	105.58 ft 32.18 m	13.17 ft 4.01 m	12.33 ft 3.76 m	112.58 ft 34.32 m	50.13 ft 15.28 m	4.75 ft (4.25 ft) 1.45 m (1.3 m)	9 ft (8.5 ft) 2.74 m (2.59 m)	10.17 ft (9.67 ft) 3.1 m (2.95 m)	41.58 ft (40.83 ft) 12.67 m (12.45 m)	578.45 sq ft 176.31 sq m	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	0 gal 0 L 0 lbs 0 kg	148	0	148	0 - 148
	Caravelle SE210	101.73 ft 31.01 m			9.74 ft 2.97 m	112.5 ft 34.29 m	51.38 ft 15.66 m				28.6 ft 8.72 m		5679.7 gal 21500 L 38053.99 lbs 17261.19 kg	5679.7 gal 21500 L 38053.99 lbs 17261.19 kg	0 gal 0 L 0 lbs 0 kg	105	0	105	80 - 105
	Carvair AT98	102.67 ft 31.29 m				117.5 ft 35.81 m					29.83 ft 9.09 m		1991.67 gal 7539.29 L 13344.19 lbs 6052.89 kg	1991.67 gal 7539.29 L 13344.19 lbs 6052.89 kg	0 gal 0 L 0 lbs 0 kg	22	0	22	0 - 22
	Comet 4C	112 ft 34.14 m				115 ft 35.05 m					30 ft 9.14 m		7045 gal 26668.23 L 47201.5 lbs 21410.47 kg	7045 gal 26668.23 L 47201.5 lbs 21410.47 kg	0 gal 0 L 0 lbs 0 kg	119	0	119	56 - 119
	DC9 - 10, 20	104.4 ft 31.82 m	92.1 ft 28.07 m	11.83 ft 3.61 m	11 ft 3.35 m	89.4 ft 27.25 m	39.2 ft 11.95 m	3.67 ft (3.25 ft) 1.12 m (0.99 m)	7.75 ft (7.17 ft) 2.36 m (2.18 m)	9.42 ft (9.42 ft) 2.87 m (2.87 m)	27.58 ft (27.42 ft) 8.41 m (8.36 m)	448.56 sq ft 136.72 sq m	20704 gal 78373.17 L 138716.8 lbs 62921.57 kg	20704 gal 78373.17 L 138716.8 lbs 62921.57 kg	0 gal 0 L 0 lbs 0 kg	90	0	90	0 - 90
	DC9 - 30	119.3 ft 36.36 m	107 ft 32.61 m	11.83 ft 3.61 m	11 ft 3.35 m	93.3 ft 28.44 m	41.15 ft 12.54 m	3.33 ft (3.08 ft) 1.02 m (0.94 m)	7.67 ft (7.17 ft) 2.34 m (2.18 m)	8.83 ft (8.58 ft) 2.69 m (2.62 m)	27.75 ft (27.5 ft) 8.46 m (8.38 m)	500.81 sq ft 152.65 sq m	22441 gal 84948.43 L 150354.7 lbs 68200.49 kg	22441 gal 84948.43 L 150354.7 lbs 68200.49 kg	0 gal 0 L 0 lbs 0 kg	127	0	127	155 - 127

Airport Category	Aircraft	Overall	Fuselage			Wingspan	Single Wing Length	Height				Single Wing Area	Fuel Load			Passenger load			
		Length	*Length*	*height*	*width*			*Ground to bottom of fuselage: max (min)*	*Ground to bottom of lowest passenger door: max (min)*	*Ground to bottom of highest passenger door: max (min)*	*Ground to the highest point: max (min)*		*Total*	*In Wing*	*Other*	*Maximum possible*	*Upper Deck*	*Lower Deck*	*Range*
6 Length up to 126 ft	DC9-40	125.6 ft 38.28 m	113.3 ft 34.53 m	11.83 ft 3.61 m	11 ft 3.35 m	93.3 ft 28.44 m	41.15 ft 12.54 m	3.58 ft (3.25 ft) 1.09 m (0.99 m)	7.58 ft (7.17 ft) 2.31 m (2.18 m)	9.5 ft (9.08 ft) 2.9 m (2.77 m)	28.42 ft (28 ft) 8.66 m (8.53 m)	599.67 sq ft 182.78 sq m	19073 gal 72199.16 L 127789.1 lbs 57964.79 kg	19073 gal 72199.16 L 127789.1 lbs 57964.79 kg	0 gal 0 L 0 lbs 0 kg	128	0	128	125 - 128
	Embraer 170	98.08 ft 29.9 m	63.75 ft 19.43 m	32.33 ft 9.86 m	11 ft 3.35 m	85.33 ft 26.01 m	31.92 ft 9.73 m				32.33 ft 9.86 m		3070.74 gal 11624 L 20573.93 lbs 9332.28 kg	3070.74 gal 11624 L 20573.93 lbs 9332.28 kg	0 gal 0 L 0 lbs 0 kg	78	0	78	78
	Embraer 175	103.92 ft 31.67 m	69.58 ft 21.21 m	11 ft 3.35 m	9.92 ft 3.02 m	94.25 ft 28.73 m	42.17 ft 12.85 m				32.33 ft 9.85 m		4234 gal 16027.43 L 28367.8 lbs 12867.56 kg	4234 gal 16027.43 L 28367.8 lbs 12867.56 kg	0 gal 0 L 0 lbs 0 kg	86	0	86	86
	Embraer 190	121.67 ft 37.08 m	84.5 ft 25.76 m	11 ft 3.35 m	9.92 ft 3.02 m	94.25 ft 28.73 m	42.17 ft 12.85 m				33.75 ft 10.29 m		4234 gal 16027.43 L 28367.8 lbs 12867.56 kg	4234 gal 16027.43 L 28367.8 lbs 12867.56 kg	0 gal 0 L 0 lbs 0 kg	106	0	106	106
	Fokker Fellowship F-28, MK 2000	82.21 ft 25.06 m				95.15 ft 29 m	47.57 ft 14.5 m				28.6 ft 8.72 m		2368 gal 8963.86 L 15865.6 lbs 7196.59 kg	2368 gal 8963.86 L 15865.6 lbs 7196.59 kg	0 gal 0 L 0 lbs 0 kg	56	0	56	52-56
	Fokker F100	116.5 ft 35.51 m			10.83 ft 3.3 m	92.08 ft 28.07 m	40.63 ft 12.38 m				27.83 ft 8.48 m		3520.8 gal 13327.68 L 23589.36 lbs 10700.07 kg	3520.8 gal 13327.68 L 23589.36 lbs 10700.07 kg	0 gal 0 L 0 lbs 0 kg	122	0	122	85 - 122
	Ilyushin IL-18	122.67 ft 37.39 m				124.33 ft 37.9 m					33.33 ft 10.16 m		7926 gal 30003.17 L 53104.2 lbs 24087.92 kg	7926 gal 30003.17 L 53104.2 lbs 24087.92 kg	0 gal 0 L 0 lbs 0 kg	100	0	100	75 - 100
	L 100-20 Hercules	97.75 ft 29.79 m				132.58 ft 40.41 m					38.25 ft 11.66 m		9530 gal 36074.97 L 63851 lbs 28962.64 kg	9530 gal 36074.97 L 63851 lbs 28962.64 kg	0 gal 0 L 0 lbs 0 kg	92	0	92	92
	Lockheed Electra L188	104.5 ft 31.85 m	65 ft 19.81 m	6 ft 1.83 m	9 ft 2.74 m	99 ft 30.18 m	45 ft 13.72 m				32.08 ft 9.78 m		5520 gal 20895.47 L 36984 lbs 16775.84 kg	5520 gal 20895.47 L 36984 lbs 16775.84 kg	0 gal 0 L 0 lbs 0 kg	127	0	127	99 - 127
	Lockheed Super Constellation 1049A	116.17 ft 35.41 m				126.17 ft 38.46 m					24.75 ft 7.54 m					109	0	109	62 - 109
	Trident HS 121, Srs 2E	114.75 ft 34.98 m	0 ft 0 m	0 ft 0 m	0 ft 0 m	28.9 ft 8.81 m	14.45 ft 4.4 m	0 ft (0 ft) 0 m (0 m)	0 ft (0 ft) 0 m (0 m)	0 ft (0 ft) 0 m (0 m)	27 ft 8.23 m		7685.8 gal 29093.92 L 51494.86 lbs 23357.93 kg	7685.8 gal 29093.92 L 51494.86 lbs 23357.93 kg	0 gal 0 L 0 lbs 0 kg	115	0	115	115
	Tupolev Tu-124	100.33 ft 30.58 m				83.83 ft 25.55 m					26.5 ft 8.08 m		4441.79 gal 16814 L 29759.99 lbs 13499.05 kg	4441.79 gal 16814 L 29759.99 lbs 13499.05 kg	0 gal 0 L 0 lbs 0 kg	56	0	56	56
	Tupolev Tu-134A	121.67 ft 37.08 m				95.08 ft 28.98 m					29.5 ft 8.99 m		3485 gal 13192.16 L 23349.5 lbs 10591.27 kg	3485 gal 13192.16 L 23349.5 lbs 10591.27 kg	0 gal 0 L 0 lbs 0 kg	84	0	84	72 - 84
	Vickers Vanguard 950	122.83 ft 37.44 m				118.58 ft 36.14 m					34.92 ft 10.64 m		6289.55 gal 23808.54 L 42139.99 lbs [illegible]	6289.55 gal 23808.54 L 42139.99 lbs [illegible]	0 gal 0 L 0 lbs [illegible]	139	0	139	139

Airport Category	Aircraft	Overall	Fuselage			Wingspan	Single Wing Length	Height				Single Wing Area	Fuel Load			Passenger load			
		Length	*Length*	*height*	*width*			*Ground to bottom of fuselage: max (min)*	*Ground to bottom of lowest passenger door: max (min)*	*Ground to bottom of highest passenger door: max (min)*	*Ground to the highest point: max (min)*		*Total*	*In Wing*	*Other*	*Maximum possible*	*Upper Deck*	*Lower Deck*	*Range*
7 Lengths up to 160 ft	Bac VC 10	158.67 ft 48.36 m				146.17 ft 44.55 m					39.5 ft 12.04 m		21590 gal 81727.04 L 144653 lbs 65614.21 kg	21590 gal 81727.04 L 144653 lbs 65614.21 kg	0 gal 0 L 0 lbs 0 kg	151	0	151	151
	Boeing 707-120	145.08 ft 44.22 m	138.83 ft 42.32 m	14.25 ft 4.34 m	12.33 ft 3.76 m	130.83 ft 39.88 m	59.25 ft 18.06 m	4.92 ft (4.5 ft) 1.5 m (1.37 m)	10.25 ft (10.08 ft) 3.12 m (3.07 m)	10.5 ft (9.92 ft) 3.2 m (3.02 m)	41.67 ft (41.58 ft) 12.7 m (12.67 m)	1084.78 sq ft 100.78 sq m	17330 gal 65601.19 L 116111 lbs 52667.64 kg	17330 gal 65601.19 L 116111 lbs 52667.64 kg	0 gal 0 L 0 lbs 0 kg	172	0	172	137 - 174
	Boeing 707-220	144.5 ft 44.04 m	138.83 ft 42.32 m	14.25 ft 4.34 m	12.33 ft 3.76 m	130.83 ft 39.88 m	59.25 ft 18.06 m	4.92 ft (4.5 ft) 1.5 m (1.37 m)	10.25 ft (10.08 ft) 3.12 m (3.07 m)	10.5 ft (9.92 ft) 3.2 m (3.02 m)	41.67 ft (41.58 ft) 12.7 m (12.67 m)	1084.78 sq ft 100.78 sq m	17330 gal 65601.19 L 116111 lbs 52667.64 kg	17330 gal 65601.19 L 116111 lbs 52667.64 kg	0 gal 0 L 0 lbs 0 kg	172	0	172	137 - 174
	Boeing 707-320	152.92 ft 46.61 m	145.5 ft 44.35 m	14.25 ft 4.34 m	12.33 ft 3.76 m	142.42 ft 43.41 m	65.05 ft 19.83 m	5.08 ft (4.5 ft) 1.55 m (1.37 m)	10.5 ft (9.92 ft) 3.2 m (3.02 m)	10.67 ft (10.33 ft) 3.25 m (3.15 m)	42.17 ft (41.92 ft) 12.85 m (12.78 m)	1158.48 sq ft 107.63 sq m	23820 gal 90168.51 L 159594 lbs	23820 gal 90168.51 L 159594 lbs	0 gal 0 L 0 lbs	189	0	189	141 - 189
	Boeing 707-320B	152.92 ft 46.61 m	145.5 ft 44.35 m	14.25 ft 4.34 m	12.33 ft 3.76 m	145.75 ft 44.42 m	66.71 ft 20.33 m	5.08 ft (4.5 ft) 1.55 m (1.37 m)	10.5 ft (9.92 ft) 3.2 m (3.02 m)	10.67 ft (10.33 ft) 3.25 m (3.15 m)	42.08 ft (41.83 ft) 12.83 m (12.75 m)	1158.48 sq ft 107.63 sq m	23855 gal 90301 L 159828.5 lbs 72497.78 kg	23855 gal 90301 L 159828.5 lbs 72497.78 kg	0 gal 0 L 0 lbs 0 kg	189	0	189	141 - 189
	Boeing 707-320C	152.92 ft 46.61 m	145.5 ft 44.35 m	14.25 ft 4.34 m	12.33 ft 3.76 m	145.75 ft 44.42 m	66.71 ft 20.33 m	5.08 ft (4.5 ft) 1.55 m (1.37 m)	10.5 ft (9.92 ft) 3.2 m (3.02 m)	10.67 ft (10.33 ft) 3.25 m (3.15 m)	42.08 ft (41.83 ft) 12.83 m (12.75 m)	1158.48 sq ft 107.63 sq m	23855 gal 90301 L 159828.5 lbs 72497.78 kg	23855 gal 90301 L 159828.5 lbs 72497.78 kg	0 gal 0 L 0 lbs 0 kg	189	0	189	141 - 189
	Boeing 707-420	152.92 ft 46.61 m	145.5 ft 44.35 m	14.25 ft 4.34 m	12.33 ft 3.76 m	142.42 ft 43.41 m	65.05 ft 19.83 m	5.08 ft (4.5 ft) 1.55 m (1.37 m)	10.5 ft (9.92 ft) 3.2 m (3.02 m)	10.67 ft (10.33 ft) 3.25 m (3.15 m)	42.17 ft (41.92 ft) 12.85 m (12.78 m)	1158.48 sq ft 107.63 sq m	23820 gal 90168.51 L 159594 lbs 72391.41 kg	23820 gal 90168.51 L 159594 lbs 72391.41 kg	0 gal 0 L 0 lbs 0 kg	189	0	189	141 - 189
	Boeing 720	136.17 ft 41.5 m	130.5 ft 39.78 m	14.25 ft 4.34 m	12.33 ft 3.76 m	130.83 ft 39.88 m	118.5 ft 36.12 m	4.67 ft (4.58 ft) 1.42 m (1.4 m)	10 ft (9.33 ft) 3.05 m (2.84 m)	10.33 ft (10.17 ft) 3.15 m (3.1 m)	41.42 ft (40.5 ft) 12.62 m (12.34 m)	1107.61 sq ft 102.9 sq m	16130 gal 61058.69 L 108071 lbs 49020.72 kg	16130 gal 61058.69 L 108071 lbs 49020.72 kg	0 gal 0 L 0 lbs 0 kg	156	0	156	131-156
	Boeing 720B	136.75 ft 41.68 m	130.5 ft 39.78 m	14.25 ft 4.34 m	12.33 ft 3.76 m	130.83 ft 39.88 m	118.5 ft 36.12 m	4.75 ft (4.5 ft) 1.45 m (1.37 m)	9.83 ft (9.33 ft) 3 m (2.84 m)	10.33 ft (10.17 ft) 3.15 m (3.1 m)	41.17 ft (40.58 ft) 12.55 m (12.37 m)	1107.61 sq ft 102.9 sq m	16130 gal 61058.69 L 108071 lbs 49020.72 kg	16130 gal 61058.69 L 108071 lbs 49020.72 kg	0 gal 0 L 0 lbs 0 kg	156	0	156	131 - 156
	Boeing 727-100	133.17 ft 40.59 m	116.17 ft 35.41 m	13.17 ft 4.01 m	12.33 ft 3.76 m	108 ft 32.92 m	47.83 ft 14.58 m	5.42 ft (4.25 ft) 1.65 m (1.3 m)	9.67 ft (8.17 ft) 2.95 m (2.49 m)	9.67 ft (8.17 ft) 2.95 m (2.49 m)	34.25 ft (31.75 ft) 10.44 m (9.68 m)	747.4 sq ft 227.81 sq m	7680 gal 29071.96 L 51456 lbs 23340.3 kg	7680 gal 29071.96 L 51456 lbs 23340.3 kg	0 gal 0 L 0 lbs 0 kg	129	0	129	106 - 129
	Boeing 727-100C	133.17 ft 40.59 m	116.17 ft 35.41 m	13.17 ft 4.01 m	12.33 ft 3.76 m	108 ft 32.92 m	47.83 ft 14.58 m	5.42 ft (4.25 ft) 1.65 m (1.3 m)	9.67 ft (8.17 ft) 2.95 m (2.49 m)	9.67 ft (8.17 ft) 2.95 m (2.49 m)	34.25 ft (31.75 ft) 10.44 m (9.68 m)	747.4 sq ft 227.81 sq m	7680 gal 29071.96 L 51456 lbs 23340.3 kg	7680 gal 29071.96 L 51456 lbs 23340.3 kg	0 gal 0 L 0 lbs 0 kg	129	0	129	0 - 129
	Boeing 727-200	153.17 ft 46.69 m	136.17 ft 41.5 m	13.17 ft 4.01 m	12.33 ft 3.76 m	108 ft 32.92 m	47.83 ft 14.58 m	5.42 ft (3.83 ft) 1.65 m (1.17 m)	10.08 ft (8 ft) 3.07 m (2.44 m)	10.08 ft (8 ft) 3.07 m (2.44 m)	34.92 ft (31.58 ft) 10.64 m (9.63 m)	705.88 sq ft 215.15 sq m	10585 gal 40068.58 L 70919.5 lbs 32168.89 kg	10585 gal 40068.58 L 70919.5 lbs 32168.89 kg	0 gal 0 L 0 lbs 0 kg	189	0	189	134 - 189
	Boeing 737-800	129.5 ft 39.47 m	112.58 ft 34.32 m	13.17 ft 4.01 m	12.33 ft 3.76 m	112.58 ft 34.32 m	50.13 ft 15.28 m	4.75 ft (4.25 ft) 1.45 m (1.3 m)	9 ft (8.5 ft) 2.74 m (2.59 m)	10.25 ft (9.75 ft) 3.12 m (2.97 m)	41.42 ft (40.58 ft) 12.62 m (12.37 m)	635.16 sq ft 193.6 sq m	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	0 gal 0 L 0 lbs 0 kg	184	0	184	160 - 184
	Boeing 737-900	138.17 ft 42.11 m	133.42 ft 40.67 m	13.17 ft 4.01 m	12.33 ft 3.76 m	112.58 ft 34.32 m	50.13 ft 15.28 m	4.75 ft (4.25 ft) 1.45 m (1.3 m)	9 ft (8.5 ft) 2.74 m (2.59 m)	10.25 ft (9.75 ft) 3.12 m (2.97 m)	41.42 ft (40.58 ft) 12.62 m (12.37 m)	657.84 sq ft 200.51 sq m	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	6875 gal 26024.71 L 46062.5 lbs 20893.83 kg	0 gal 0 L 0 lbs 0 kg	189	0	189	177 - 189
	Canadair CL-44J	136.92 ft 41.73 m				142.33 ft 43.38 m					36.67 ft 11.18 m					189	0	189	160 - 189
	Convair 880	129.33 ft 39.42 m				120 ft 36.58 m					36.08 ft 11 m		10770 gal 40768.88 L 72159 lbs 32731.13 kg	10770 gal 40768.88 L 72159 lbs 32731.13 kg	0 gal 0 L 0 lbs 0 kg	110	0	110	88 - 110
	Convair 990 Coronado	139.42 ft 42.49 m				120 ft 36.58 m					39.5 ft 12.04 m					121	0	121	96 - 121

Airport Category	Aircraft	Overall	Fuselage			Wingspan	Single Wing Length	Height				Single Wing Area	Fuel Load			Passenger load			
		Length	*Length*	*height*	*width*			*Ground to bottom of fuselage: max (min)*	*Ground to bottom of lowest passenger door: max (min)*	*Ground to bottom of highest passenger door: max (min)*	*Ground to the highest point: max (min)*		*Total*	*In Wing*	*Other*	*Maximum possible*	*Upper Deck*	*Lower Deck*	*Range*
	Douglas DC8 srs 10 to 50	150.7 ft 45.93 m	146.25 ft 44.58 m	13.55 ft 4.13 m	12.25 ft 3.73 m	142.4 ft 43.4 m	65.08 ft 19.83 m	6.59 ft (5.96 ft) 2.01 m (1.82 m)	11.17 ft (10.52 ft) 3.4 m (3.21 m)	13.09 ft (12.08 ft) 3.99 m (3.68 m)	43.43 ft (42.14 ft) 13.24 m (12.84 m)	1182.22 sq ft 360.34 sq m	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	0 gal 0 L 0 lbs 0 kg	177	0	177	0-177
	Douglas DC8-55	150.7 ft 45.93 m	146.25 ft 44.58 m	13.55 ft 4.13 m	12.25 ft 3.73 m	142.4 ft 43.4 m	65.08 ft 19.83 m	6.59 ft (5.96 ft) 2.01 m (1.82 m)	11.16 ft (10.52 ft) 3.4 m (3.21 m)	13.19 ft (12.08 ft) 4.02 m (3.68 m)	43.56 ft (42.14 ft) 13.28 m (12.84 m)	1182.22 sq ft 360.34 sq m	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	0 gal 0 L 0 lbs 0 kg	189	0	189	0-189
	Douglas DC8-62	157.5 ft 48.01 m	152.9 ft 46.6 m	13.55 ft 4.13 m	12.24 ft 3.73 m	148.4 ft 45.23 m	68.08 ft 20.75 m	6.5 ft (5.94 ft) 1.98 m (1.81 m)	11.2 ft (10.5 ft) 3.41 m (3.2 m)	13.33 ft (12.05 ft) 4.06 m (3.67 m)	43.74 ft (42.11 ft) 13.33 m (12.83 m)	1177.78 sq ft 358.99 sq m	24275 gal 91890.87 L 162642.5 lbs 73774.2 kg	24275 gal 91890.87 L 162642.5 lbs 73774.2 kg	0 gal 0 L 0 lbs 0 kg	189	0	189	0-189
	Douglas DC9-50	133.58 ft 40.72 m	121.25 ft 36.96 m	11.83 ft 3.61 m	11 ft 3.35 m	93.35 ft 28.45 m	41.18 ft 12.55 m	3.67 ft (3.33 ft) 1.12 m (1.02 m)	15.33 ft (14.67 ft) 4.67 m (4.47 m)	15.33 ft (14.67 ft) 4.67 m (4.47 m)	28.75 ft (25.25 ft) 8.76 m (7.7 m)	447.05 sq ft 136.26 sq m	5039 gal 19074.69 L 33761.3 lbs 15314.03 kg	5039 gal 19074.69 L 33761.3 lbs 15314.03 kg	0 gal 0 L 0 lbs 0 kg	135	0	135	0 - 135
	Embraer 195	126.83 ft 38.66 m	92.42 ft 28.17 m	11 ft 3.35 m	9.92 ft 3.02 m	94.25 ft 28.73 m	42.17 ft 12.85 m				34.5 ft 10.52 m		4268.06 gal 16156.36 L 28596 lbs 12971.07 kg	4268.06 gal 16156.36 L 28596 lbs 12971.07 kg	0 gal 0 L 0 lbs 0 kg	118	0	118	
	Trident HS 121	131.17 ft 39.98 m				98 ft 29.87 m					28.21 ft 8.6 m					179	0	179	115 - 179
	Tupolev Tu-104A	127.42 ft 38.84 m				113.33 ft 34.54 m					39 ft 11.89 m					100	0	100	50 - 100
	Tupolev TU-154	157 ft 47.85 m				123.25 ft 37.57 m					37.42 ft 11.4 m		13079.55 gal 49511.49 L 87633 lbs 39750.09 kg	13079.55 gal 49511.49 L 87633 lbs 39750.09 kg	0 gal 0 L 0 lbs 0 kg	180	0	180	114 - 180
	Boeing 757-200	155.25 ft 47.32 m	154.08 ft 46.96 m	13.17 ft 4.01 m	12.33 ft 3.76 m	124.83 ft 38.05 m	56.25 ft 17.15 m	8 ft (7.33 ft) 2.44 m (2.24 m)	13.17 ft (12.42 ft) 4.01 m (3.78 m)	13.58 ft (12.75 ft) 4.14 m (3.89 m)	45.08 ft (44.25 ft) 13.74 m (13.49 m)	846.43 sq ft 257.99 sq m	11276 gal 42684.3 L 75549.2 lbs 34268.91 kg	11276 gal 42684.3 L 75549.2 lbs 34268.91 kg	0 gal 0 L 0 lbs 0 kg	228	0	228	186 - 228
8 Length up to 200 ft	Airbus A300 - 600	177.25 ft 54.03 m	177.25 ft 54.03 m	18.416 ft 5.64 m	18.416 ft 5.64 m	147.083 ft 44.84 m	64.33 ft 19.6 m	Less than: 10.08 ft 3.07 m	15.083 ft 4.6 m	18 ft 5.5 m	54.25 ft 16.54 m	2800 sq ft 260 sq m	16060 gal 73000 L	13640 gal 62000 L	Tail Tank: 1353 gal 6150 L Cargo: 1067 gal 4850 L	298	0	298	266-298
	Airbus A310 - 300	153.08 ft 46.66 m	150.58 ft 45.9 m	18.5 ft 5.64 m	19 ft 5.79 m	144 ft 43.89 m	62.5 ft 19.05 m	6.42 ft (6.04 ft) 1.96 m (1.84 m)	14.88 ft (14.5 ft) 4.54 m (4.42 m)	15.89 ft (15.33 ft) 4.84 m (4.67 m)	52.32 ft (51.5 ft) 15.95 m (15.7 m)	#DIV/0!	19944 gal 75496.25 L 133624.8 lbs 60611.85 kg	19944 gal 75496.25 L 133624.8 lbs 60611.85 kg	0 gal 0 L 0 lbs 0 kg	265	0	265	243 - 265
	Airbus A330 - 200	191.5 ft 58.37 m		18.5 ft 5.64 m	17.33 ft 5.28 m	197.83 ft 60.3 m	90.25 ft 27.51 m	6.7 ft (6.03 ft) 2.04 m (1.84 m)	15.19 ft (14.56 ft) 4.63 m (4.44 m)	5.74 ft (5.35 ft) 1.75 m (1.63 m)	18.23 ft (17.71 ft) 5.56 m (5.4 m)		36744 gal 139091.17 L 246184.8 lbs 111668.76 kg	36744 gal 139091.17 L 246184.8 lbs 111668.76 kg	0 gal 0 L 0 lbs 0 kg	253	0	253	253
	Airbus A340-200	194.92 ft 59.41 m		18.5 ft 5.64 m	18.5 ft 5.64 m	197.83 ft 60.3 m	89.67 ft 27.33 m	7.02 ft (6.33 ft) 2.14 m (1.93 m)	15.02 ft (14.43 ft) 4.58 m (4.4 m)	18.69 ft (17.74 ft) 5.7 m (5.41 m)	55.86 ft (54.71 ft) 17.03 m (16.68 m)		37153 gal 140639.4 L 248925.1 lbs 112911.76 kg	37153 gal 140639.4 L 248925.1 lbs 112911.76 kg	0 gal 0 L 0 lbs 0 kg	303	0	303	228 - 303
	Airbus A340-600	247 ft 75.29 m	241 ft 73.46 m	17.5 ft 5.33 m	17.3 ft 5.27 m	208.17 ft 63.45 m	95.43 ft 29.09 m	8.72 ft (7.99 ft) 2.66 m (2.44 m)	15.67 ft (14.88 ft) 4.78 m (4.54 m)	18.69 ft (17.77 ft) 5.7 m (5.42 m)	58.84 ft (57.74 ft) 17.93 m (17.6 m)		55195 gal 208935.8 L 369806.5 lbs 167743.23 kg	55195 gal 208935.8 L 369806.5 lbs 167743.23 kg	0 gal 0 L 0 lbs 0 kg	380	0	380	
	BAC Super VC 10																		
	Boeing 747 SP	184.75 ft 56.31 m	176.75 ft 53.87 m	0 ft 0 m	21.33 ft 6.5 m	195.67 ft 59.64 m	87.17 ft 26.57 m	9.67 ft (9 ft) 2.95 m (2.74 m)	16.33 ft (15.67 ft) 4.98 m (4.78 m)	17 ft (16.33 ft) 5.18 m (4.98 m)	65.83 ft (65.08 ft) 20.07 m (19.84 m)	2096.28 sq ft 638.95 sq m	50734 gal 192049.08 L 339917.8 lbs 154185.8 kg	50734 gal 192049.08 L 339917.8 lbs 154185.8 kg	0 gal 0 L 0 lbs 0 kg	299	45	254	270 - 299

Airport Category	Aircraft	Overall	Fuselage			Wingspan	Single Wing Length	Height				Single Wing Area	Fuel Load			Passenger load			
		Length	Length	height	width			Ground to bottom of fuselage: max (min)	Ground to bottom of lowest passenger door: max (min)	Ground to bottom of highest passenger door: max (min)	Ground to the highest point: max (min)		Total	In Wing	Other	Maximum possible	Upper Deck	Lower Deck	Range
8 Length up to 200 ft	Boeing 767-200	159.17 ft 48.51 m		17.75 ft 5.41 m	16.5 ft 5.03 m	156.08 ft 47.57 m	69.79 ft 21.27 m	6.75 ft (5.67 ft) 2.06 m (1.73 m)	14.5 ft (13.33 ft) 4.42 m (4.06 m)	14.67 ft (13.42 ft) 4.47 m (4.09 m)	52.92 ft (51.17 ft) 16.13 m (15.6 m)		24140 gal 91379.84 L 161738 lbs 73363.92 kg	24140 gal 91379.84 L 161738 lbs 73363.92 kg	0 gal 0 L 0 lbs 0 kg	245	0	245	174 - 275
	B767-300	180.25 ft 54.94 m	180.25 ft 54.97 m	17.75 ft 5.41 m	16.5 ft 5.03 m	156.083 ft 47.57 m	69.79 ft 21.27 m	6.833 ft (5.833 ft) 2.08m (1.78 m)	14.75 ft (13.5 ft) 4.5 m (4.11 m)	N/A	52.916 ft (50.66 ft) 16.13 m (15.44 m)	3050 sq ft 283.3 sq m	16700 gal 63216 L 111890 lb 50753 kg			299	0	299	237-299
	B787-8	186.08 ft 56.72 m	183.42 ft 55.91 m	19.42 ft 5.92 m	18.92 ft 5.77 m	197.25 ft 60.12 m	89.17 ft 27.18 m	5.75 ft (0 ft) 1.75 m (0 m)	14.17 ft (0 ft) 4.32 m (0 m)	15.83 ft (0 ft) 4.83 m (0 m)	55.5 ft 16.92 m		33528 gal 126917.29 L 224637.6 lbs 101895.01 kg	33528 gal 126917.29 L 224637.6 lbs 101895.01 kg	0 gal 0 L 0 lbs 0 kg	375	0	375	224 - 375
	Douglas DC 8-61	187.4 ft 57.12 m	182.9 ft 55.75 m	13.55 ft 4.13 m	12.25 ft 3.73 m	142.4 ft 43.4 m	65.08 ft 19.83 m	7 ft (6.38 ft) 2.13 m (1.95 m)	11.3 ft (10.51 ft) 3.44 m (3.2 m)	13.1 ft (12.05 ft) 3.99 m (3.67 m)	43.23 ft (41.98 ft) 13.17 m (12.79 m)	1259.26 sq ft 383.82 sq m	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	0 gal 0 L 0 lbs 0 kg	259	0	259	177 - 259
	Douglas DC 8-61 F	187.4 ft 57.12 m	182.9 ft 55.75 m	13.55 ft 4.13 m	12.25 ft 3.73 m	142.4 ft 43.4 m	65.08 ft 19.83 m	6.95 ft (6.38 ft) 2.12 m (1.95 m)	11.11 ft (10.53 ft) 3.39 m (3.21 m)	13.08 ft (12.13 ft) 3.99 m (3.7 m)	43.19 ft (42.08 ft) 13.16 m (12.83 m)	1259.26 sq ft 383.82 sq m	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	23393 gal 88552.14 L 156733.1 lbs 71093.71 kg	0 gal 0 L 0 lbs 0 kg	0	0	0	0
	Douglas DC 8-63	187.4 ft 57.12 m	182.9 ft 55.75 m	13.55 ft 4.13 m	12.25 ft 3.73 m	148.4 ft 45.23 m	68.08 ft 20.75 m	6.87 ft (6.37 ft) 2.09 m (1.94 m)	11.13 ft (10.48 ft) 3.39 m (3.2 m)	12.9 ft (12.16 ft) 3.93 m (3.71 m)	43 ft (42.12 ft) 13.11 m (12.84 m)	1259.26 sq ft 383.82 sq m	24275 gal 91890.87 L 162642.5 lbs 73774.2 kg	24275 gal 91890.87 L 162642.5 lbs 73774.2 kg	0 gal 0 L 0 lbs 0 kg	259	0	259	177 - 259
	Douglas DC 8-63F	187.4 ft 57.12 m	182.9 ft 55.75 m	13.55 ft 4.13 m	12.25 ft 3.73 m	148.4 ft 45.23 m	68.08 ft 20.75 m	6.94 ft (6.37 ft) 2.12 m (1.94 m)	11.19 ft (10.48 ft) 3.41 m (3.2 m)	13.01 ft (12.16 ft) 3.96 m (3.71 m)	43.13 ft (42.12 ft) 13.14 m (12.84 m)	1259.26 sq ft 383.82 sq m	24275 gal 91890.87 L 162642.5 lbs 73774.2 kg	24275 gal 91890.87 L 162642.5 lbs 73774.2 kg	0 gal 0 L 0 lbs 0 kg	0	0	0	0
	Douglas DC 10-10	182.26 ft 55.55 m	170.5 ft 51.97 m	19.75 ft 6.02 m	19.75 ft 6.02 m	155.33 ft 47.35 m	67.79 ft 20.66 m	7.33 ft (7.17 ft) 2.24 m (2.18 m)	15.25 ft (15.17 ft) 4.65 m (4.62 m)	15.75 ft (15.5 ft) 4.8 m (4.72 m)	57.5 ft (57.33 ft) 17.53 m (17.48 m)	1590.08 sq ft 484.66 sq m	21763 gal 82381.92 L 145812.1 lbs 66139.98 kg	21763 gal 82381.92 L 145812.1 lbs 66139.98 kg	0 gal 0 L 0 lbs 0 kg	399	0	399	215 - 399
	Douglas DC 10-30	181.6 ft 55.35 m	170.5 ft 51.97 m	19.75 ft 6.02 m	19.75 ft 6.02 m	165.33 ft 50.39 m	72.79 ft 22.19 m	7.42 ft (7.33 ft) 2.26 m (2.24 m)	15.33 ft (15.08 ft) 4.67 m (4.6 m)	15.83 ft (15.75 ft) 4.83 m (4.8 m)	57.58 ft (57.17 ft) 17.55 m (17.42 m)	1636.36 sq ft 498.76 sq m	36650 gal 138735.34 L 245555 lbs 111383.09 kg	36650 gal 138735.34 L 245555 lbs 111383.09 kg	0 gal 0 L 0 lbs 0 kg	399	0	399	215 - 399
	Douglas DC 10-40	182.216 ft 55.54 m	170.5 ft 51.97 m	19.75 ft 6.02 m	19.75 ft 6.02 m	165.33 ft 50.39 m	72.79 ft 22.19 m	8.33 ft (7.33 ft) 2.54 m (2.24 m)	16.083 ft (15.083 ft) 4.9 m (4.6 m)	16.916 ft (15.75 ft) 5.16 m (4.8 m)	58.583 ft (57.166 ft) 17.86 m (17.42 m)	3958 sq ft 367.7 sq m	36652 gal 137509 L			399	0	399	255-399
	Ilyushin IL-62																		
	Ilyushin IL-86																		
	Lockheed L-1011 Tristar																		
	Tupolev TU-114																		
9 Length up to 250 ft	Airbus A330 - 300	209 ft 63.7 m	0 ft 0 m	18.5 ft 5.64 m	17.33 ft 5.28 m	197.83 ft 60.3 m	90.25 ft 27.51 m	2.74 ft (2.45 ft) 0.84 m (0.75 m)	14.92 ft (4.41 ft) 4.55 m (1.34 m)	18.93 ft (17.75 ft) 5.77 m (5.41 m)	56.36 ft (54.85 ft) 17.18 m (16.72 m)	#DIV/0!	25765 gal 97531.13 L 172625.5 lbs 78302.46 kg	25765 gal 97531.13 L 172625.5 lbs 78302.46 kg	0 gal 0 L 0 lbs 0 kg	295	0	295	0
	Airbus A340-300	208.67 ft 63.6 m	208.67 ft 63.6 m	18.5 ft 5.64 m	18.5 ft 5.64 m	197 ft 60.3 m	89.25 ft 27.20 m				55.25 ft 16.85 m	3892 sq ft 361 sq m	37380 gal 141500 L			335	0	335	295-335
	Airbus A340-600	247 ft 75.29 m	241 ft 73.46 m	17.5 ft 5.33 m	17.3 ft 5.27 m	208.17 ft 63.45 m	95.43 ft 29.09 m	8.72 ft (7.99 ft) 2.66 m (2.44 m)	15.67 ft (14.88 ft) 4.78 m (4.54 m)	18.69 ft (17.77 ft) 5.7 m (5.42 m)	58.84 ft (57.74 ft) 17.93 m (17.6 m)		55195 gal 208935.8 L 369806.5 lbs 167743.23 kg	55195 gal 208935.8 L 369806.5 lbs 167743.23 kg	0 gal 0 L 0 lbs 0 kg	380	0	380	380
	B-777-300	242.33 ft 73.86 m	239.75 ft 73.08 m	18.25 ft 5.58 m	20.33 ft 6.2 m	199.9166 ft 60.93 m	89.79 ft 27.37 m	10 ft (9.25 ft) 3.05 m (2.81 m)	16.416 ft (15.416 ft) 5 m (4.71 m)	18.166 ft (17.33 ft) 5.54 m (5.28 m)	61.5 ft (60.416 ft) 18.76 m (18.42 m)	4605 sq ft 427.8 sq m	44700 gal 169210 L 299490 lb 135880 kg		158 cu ft in fwd cargo, 158 cu ft in aft cargo, 600 cu ft in bulk cargo	451	0	451	368-451

Airport Category	Aircraft	Overall	Fuselage			Wingspan	Single Wing Length	Height				Single Wing Area	Fuel Load			Passenger load			
		Length	Length	height	width			Ground to bottom of fuselage: max (min)	Ground to bottom of lowest passenger door: max (min)	Ground to bottom of highest passenger door: max (min)	Ground to the highest point: max (min)		Total	In Wing	Other	Maximum possible	Upper Deck	Lower Deck	Range
9 Length up to 250 ft	B-747-200	231.83 ft 70.66 m	225.166 ft 68.6 m	25.583 ft 7.82 m	21.33 ft 6.5 m	195.66 ft 59.64 m	87.17 ft 26.57 m	6.75 ft (6.25 ft) 2.08 m (1.88 m)	17.5833 ft (15.25 ft) 5.36 m (4.65 m)	17.166 ft (15.66 ft) 5.23 m (4.78 m)	64.25 ft (60.166 ft) 19.58 m (18.34 m)	5500 sq ft 511 sq m	53986 gal 204335 L 351310 lb 159323 kg	52410 gal 198370 L 351150 lb 159250 kg	1576 gal 5965 L 160 lb 73 kg	480	32	420	452-480
	Boeing 747-400	229.17 ft 69.85 m	225.17 ft 68.63 m		21.33 ft 6.5 m	213 ft 64.92 m	95.83 ft 29.21 m	7.92 ft (6.83 ft) 2.41 m (2.08 m)	16.92 ft (15.5 ft) 5.16 m (4.72 m)	25.92 ft (24.67 ft) 7.9 m (7.52 m)	64 ft (61.58 ft) 19.51 m (18.77 m)		53985 gal 204355.45 L 361699.5 lbs 164065.92 kg	50685 gal 191863.6 L 339589.5 lbs 154036.88 kg	3300 gal 12491.86 L 22110 lbs 10029.04 kg	624	85	539	0 - 624
	MD-11		192.416 ft 58.6 m	21.583 ft 6.28 m	19.75 ft 6 m	170.5 ft 51.97 m	75.38 ft 22.97 m	8.416 ft (7.66 ft) 2.57 m (2.38 m)	16.25 ft (15 ft) 4.94 m (4.57 m)	17.416 ft (15.75 ft) 5.31 m (4.81 m)	58.83 ft (56.75 ft) 17.93 m (17.31 m)	3648 sq ft 338.9 sq m	38615 gal 146155 L			410	0	410	385-410
10 Length 250 ft and above	A380-800	239.5 ft 73 m	230.97 ft 70.4 m	27.6 ft 8.41 m	23.43 ft 7.142 m	261.65 ft 79.75 m	119.11 ft 36.30 m	5.4 ft 1.6 m	16.6 ft 5.07 m	26 ft 7.92 m	79.3 ft 24.18 m	9100 sq ft 845 sq m	81890 gal 310000 L	75630 gal 286300 L	6260 gal 23700 L	840	199	356	555-840
	A380-900	239.5 ft 73 m																	
	AN-225	275.6 ft 84 m	275.6 ft 84 m			290.16 ft 88.4 m					59.3 ft 18.1 m	9743.7 sq ft 905 sq m	661375 lb 300000 kg			76	0	76	6-76
	Boeing 747-8	250.67 ft 76.4 m	243.5 ft 74.22 m		20.1 ft 6.13 m	224.75 ft 68.5 m	102.33 ft 31.19 m				63.5 ft 19.35 m		64225 gal 243118.07 L 430307.5 lbs 195186.33 kg			467	48	419	467

APPENDIX B—AIRCRAFT RESCUE AND FIREFIGHTING EFFECTIVENESS DATA [B-1]

Table B-1. Aircraft Crash Fire Information (Compiled From National Fire Protection Association Files and Other Sources, as Provided in Table 2 From Gage Report [B-1])

Aircraft	Date	Location	Occupants	Injured	Fatalities	Crash-Fire Effectiveness Escape/Rescue	Crash-Fire Effectiveness Property Saved	Remarks
Caravelle	1/19/60	Ankara Turkey	42	1	41	No	No	Aircraft believed destroyed on impact.
B-707	5/9/60	N.Y.-Kennedy	109	8	0	Possibly	Yes	
Viscount	1/7/60	London	59	0	0	Escaped before arrival	Yes	Response delayed by fog
CV-880	5/23/60	Atlanta	4	0	4	No	No	Survivability doubtful, also inadequate equip.
Electra	9/14/60	NY-LaGuardia	76	6	0	Escaped unaided	Yes	
B-707	6/16/61	Portela, France	119	0	0	Undetermined	Undetermined	
DC-8	7/11/61	Denver, Co.	122	80	18	No	No	Inadequate equipment
B-707	7/27/61	Hamburg Ger.	41	5	0	Undetermined	Undetermined	
DC-8	9/16/61	NY-Kennedy	133	19	0	Probably	Yes	
B-707	6/3/62	Paris, Orly	132	1	130	No	No	Survivability uncertain
Viscount	1/29/63	Kansas City,Mo	8	0	8	No	No	Survivability doubtful
Vertol 107	10/14/63	NY-Kennedy	6	0	6	No	No	1½m response 10m exiting, too late
DC-8	11/6/63	London	90	4	0	Unaided	Yes	Engine fires, delayed response 23 Min
DC-8	1/19/61	NY-Kennedy	106	28	4	Unaided	No	Off field response 7½ min
Comet IV	3/22/64	Singapore	68	32	0	Probably	Yes	
B-707	7/1/64	NY-Kennedy	12	3	0	Undetermined	Yes	

Table B-1. Aircraft Crash Fire Information (Compiled From National Fire Protection Association Files and Other Sources, as Provided in Table 2 From Gage Report [B-1]) (Continued)

						Crash-Fire Effectiveness		
Aircraft	Date	Location	Occupants	Injured	Fatalities	Escape/Rescue	Property Saved	Remarks
DC-7C	9/28/64	Istanbul	97	1	0	Probably	No	
B-707	11/23/64	Rome	73	0	45	Undetermined	No	Center section tank exploded during evacuation
CV-880	9/13/65	Kansas City,Mo	4	0	0	Undetermined	Yes	
DC-7	10/16/65	Charlotte,N.C.	62	0	0	Probably	Yes	
B-727	11/11/65	Salt Lake City	91	43	36	No	Yes	Rapid cabin fire may have precluded survival, equip. & manning was grossly inadequate
Caravelle IV	2/15/66	New Delhi	80	5	0	Unaided	No	
TU 114	2/15/66	Moscow	70	0	48	Undetermined	No	
DC-8	3/4/66	Tokyo	72	8	63	Undetermined	No	
DC-8	7/4/66	Auckland NZ	5	0	0	Probably	No	
CV-880	8/26/66	Tokyo	5	0	5	No	No	
DC-8F	5/20/67	Ottawa	3	0	0	No	No	
B-707	6/13/67	Yokota AFB	10	0	0	Undetermined	Yes	Cabin fire on ground
IL-18	9/5/67	Gander	69	37	32	No	No	Access impossible off field
B-707	11/6/67	Cincinnati	36	11	0	Probably	Yes	
B-707	11/21/67	Honolulu	52	3	0	Probably	Yes	
Beechcraft	2/17/68	Columbia,S.C.	4	0	0	Possibly	Yes	
B727-QC	3/21/68	O'Hare	3	1	0	Yes	No	
DC-8	3/28/68	Atlantic City	4	2	0	Possibly	No	
DC-7B	7/7/68	Philadelphia	3	0	0	Possibly	Yes	
B-707	12/26/68	Elmendorf AFB	3	0	3	No	No	High impact

Table B-1. Aircraft Crash Fire Information (Compiled From National Fire Protection Association Files and Other Sources, as Provided in Table 2 From Gage Report [B-1]) (Continued)

Aircraft	Date	Location	Occupants	Injured	Fatalities	Crash-Fire Effectiveness: Escape/Rescue	Crash-Fire Effectiveness: Property Saved	Remarks
CV-580	12/27/68	O'Hare	45	19	26	Questionable	Not a/c	Hit into hangar, deluge sprinkler system probably controlled fire
B-707	4/8/68	London	127	38	5	Unaided	Yes	Improper Crash Fire operations increased damage & fatalities
IL-18	3/20/69	Aswan Egypt	101	9	92	Undetermined	No	
Beechcraft	2/5/69	Port Angeles, WA	10	0	10	No	No	Snow & ice delayed access to a/c
DC-3	3/20/69	New Orleans	27	10	16	No	No	20m response due to fog
Comanche	4/12/69	Tucson	3	0	3	No	No	Killed by impact
Stinson 150	7/12/69	Compton, Ca.	4	0	2	Unaided?	Not a/c	Crashed on house roof
B-707	7/26/69	Atlantic City	5	0	5	No	No	No info on fire fighting
B-720	8/7/69	Philadelphia	0	0	0	N.A.	Yes	Cabin fire on ground
DC-8	10/16/69	Stockton, Ca.	5	0	0	Unaided	No	Off rnwy, delayed response by terrain
DC-8	11/28/69	Newark	121	0	0	Unaided?	Yes	Small fire probably not immediately endangering occupants, #4 engine
DC-8	4/19/70?	Rome	75	26	0	Possibly	No	Data limited
C-54	4/14/70	Miami				Undetermined	No	Limited data

REFERENCE.

B-1. Cohn, B.M and Campbell, J.A., “Minimum Needs for Airport Fire Fighting and Rescue Services,” Report No. AS-71-1, Federal Aviation Administration, Airports Service, Washington, DC, January 1971.

APPENDIX C—LOCATION OF UNDERSHOOTS, OVERSHOOTS, AND VEEROFFS PROVIDED BY AIR LINE PILOTS ASSOCIATION, INTERNATIONAL

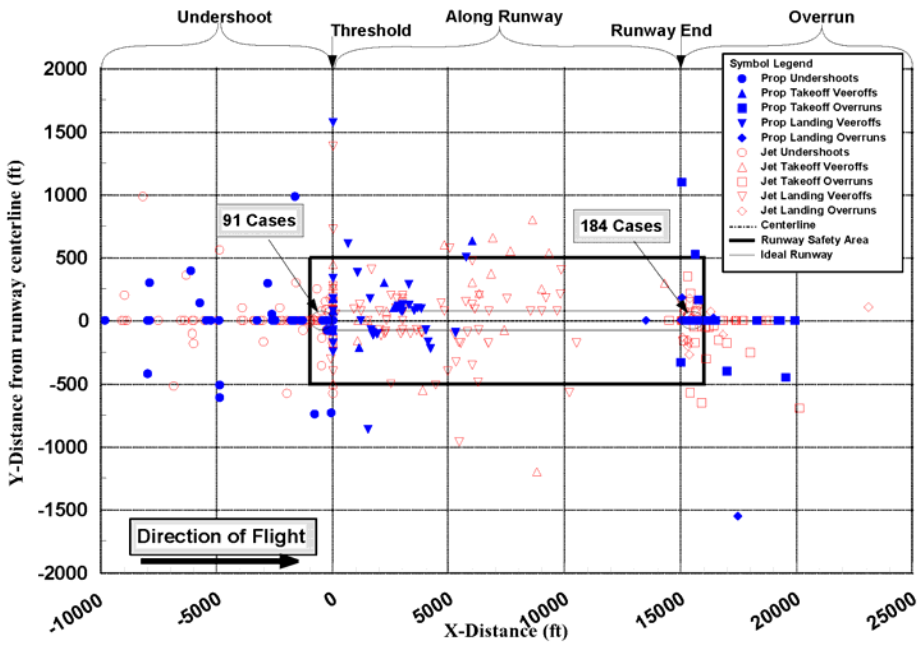

Figure C-1. Location of Landing and Takeoff Accidents

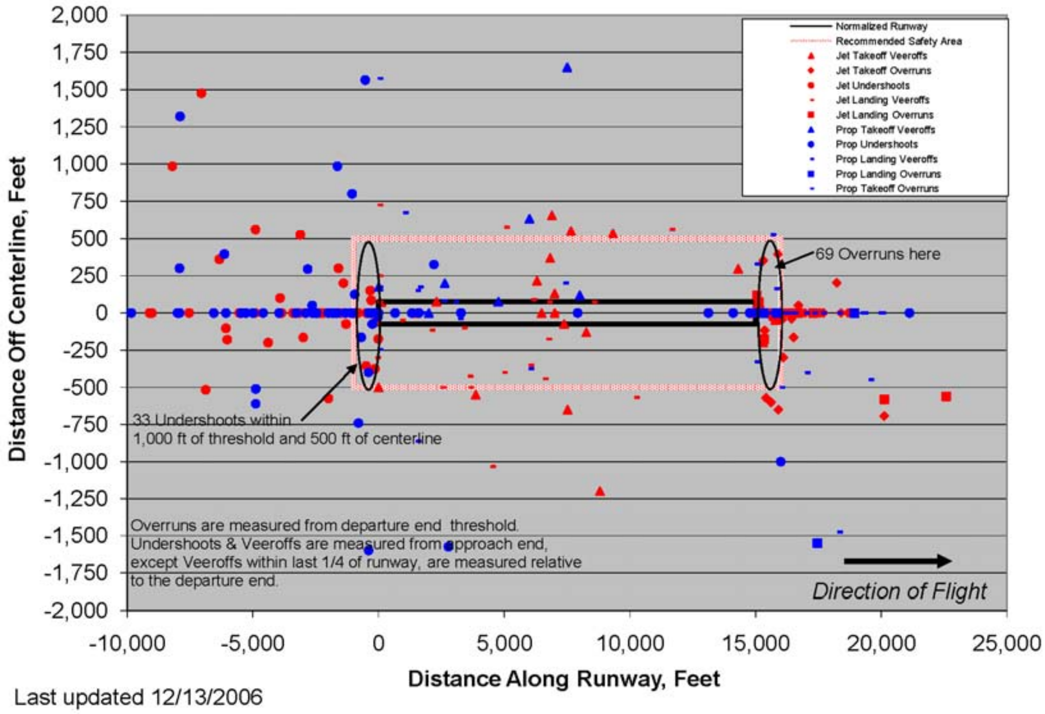

Figure C-2. Air Line Pilots Association, International Compilation of Overruns, Undershoots and Veeroffs Damage Level—Destroyed

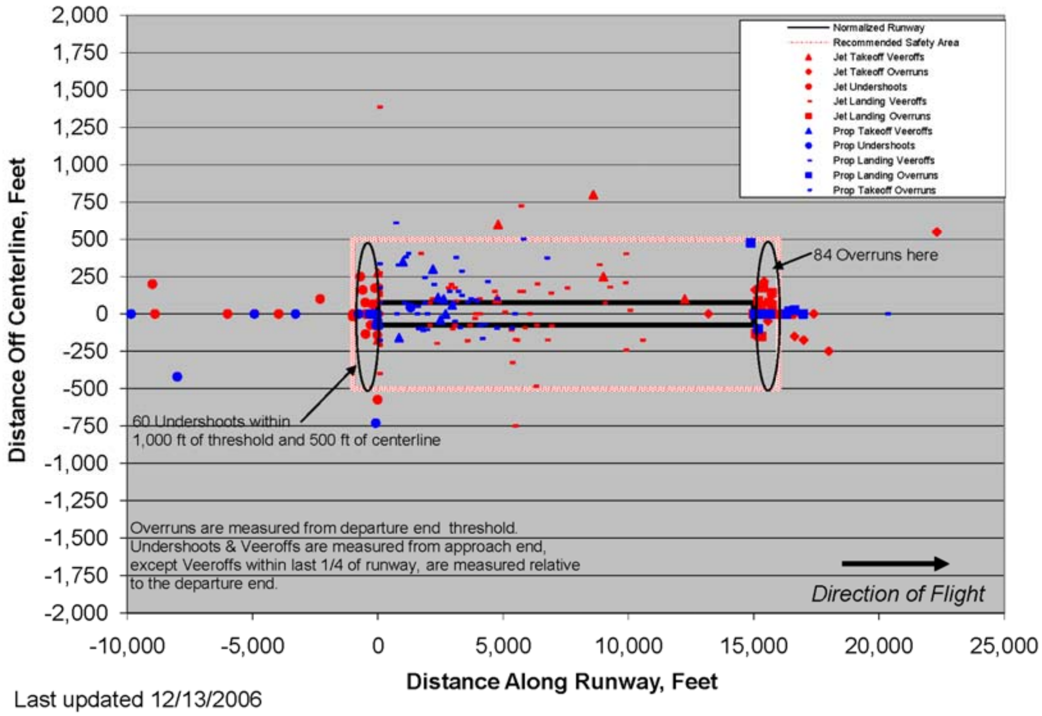

Figure C-3. Air Line Pilots Association, International Compilation of Overruns, Undershoots and Veeroffs Damage Level—Substantial

APPENDIX D—ACCIDENTS INVOLVING AIRCRAFT RESCUE AND FIREFIGHTING RESPONSE TO FIRE

Table D-1. Occurrences Which Were Nonsurvivable or in Which Aircraft Rescue and Firefighting was Ineffective

Plane Type	Date	Location (U.S. if not stated)	Occupants on the Airplane	Injured	Fatalities	Occupant Survived	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Learjet 35A	11/4/2007	Brazil	11	3	8	3	No	No	The airplane went down with a near-vertical trajectory. Impact forces killed those on board.	Non-U.S. Commercial	Climb	The pilot lost control due to a strong wind. The postcrash fire destroyed the airplane.
A320-233	7/17/2007	Brazil	186	0	186	0	No	No	The airplane crashed into a building at 100 mph and immediately exploded. Impact forces destroyed the airplane.	Non-U.S.	Takeoff	The airplane overran the runway. 18 of the fatal injuries were to persons on the ground. Fire destroyed the aircraft.
Boeing 737-400	3/7/2007	Indonesia	140	12	21	119	No	Escaped unaided	Many passengers were able to escape unaided; there was a broken door that kept those still onboard trapped. The wreckage was 300 meters off the runway.	Non-U.S.	Landing	The airplane overran the runway due to human error and was destroyed by a postcrash fire.

Table D-1. Occurrences Which Were Nonsurvivable or in Which Aircraft Rescue and Firefighting was Ineffective (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on the Airplane	Injured	Fatalities	Occupant Survived	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Bombardier CRG-100	8/27/2006	Lexington, KY	50	1	49	1	No	No	The airplane went to the wrong runway and it was too short to achieve liftoff. There was a ground fire. Wreckage was found between 265 ft to 1800 ft from the end of the runway. 6 died of thermal injuries, 11 from smoke, 23 from impact forces, and 8 from a combination of the three. The one survivor was removed from the airplane by first responders.	Part 121: Air Carrier	Takeoff	The airplane went to the wrong runway and it was too short to achieve liftoff. There was a ground fire. Wreckage was found between 265 ft to 1800 ft from the end of the runway. 6 died of thermal injuries, 11 from smoke, 23 from impact forces, and 8 from a combination of the three. The one survivor was removed from the plane by first responders.

Table D-1. Occurrences Which Were Nonsurvivable or in Which Aircraft Rescue and Firefighting was Ineffective (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on the Airplane	Injured	Fatalities	Occupant Survived	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Jetstream 32	10/19/2004	Missouri	15	2	13	2	No	Escaped unaided	Impact forces killed most passengers. The two who survived were seated near the emergency exit, but left through a hole in the fuselage before the airplane was fully engulfed in flames.	Part 121: Air Carrier	Approach	During approach, the airplane hit some trees on the airport property. The airplane was destroyed by impact and postimpact fire.
Boeing 737-2T4	3/6/2003	Tamanrassett, Algeria	103	1	102	1	No	No	ARFF responded. All but one occupant injury was fatal.	Non-U.S.	Takeoff	The airplane rashed shortly after takeoff and was destroyed by impact. There was a postcrash fire.
Beech 1900D	1/8/2003	Charlotte, NC	21	0	21	0	No	No	ARFF responded in 2 minutes. All onboard were deceased, however,	Part 121: Air Carrier	Takeoff	Weight/balance errors. Elevator malfunctions. There was a postcrash fire.
Gates Learjet 25B	11/22/2001	Pittsburgh, PA	2	0	2	0	No	No	Both passengers died. ARFF responded and cut access.	Part 91: General Aviation	Takeoff	Veered off runway on takeoff. Postcrash fire. (Seats 10)

Table D-1. Occurrences Which Were Nonsurvivable or in Which Aircraft Rescue and Firefighting was Ineffective (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on the Airplane	Injured	Fatalities	Occupant Survived	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Swearingen METRO II	6/18/1998	Montreal, Canada	13	0	13	0	No	No	ARFF responded and quickly extinguished the fire, but all passengers perished.	Part 129: Foreign	Cruise	Smoke in cockpit during cruise. Crashed during emergency landing. Post impact fire.
Airbus Industrie A300	2/16/1998	Taipei, Taiwan	196	0	196	0	No	No	The airplane crashed short of the runway into houses. Postimpact fire. Fire fighters extinguished fire and all occupants died.	Part 129: Foreign	Landing	Crashed short of runway into houses. Post impact fire.
Douglas DC-8-61	8/7/1997	Miami, FL	5	0	5 (1 ground)	1	No	No	The airplane crashed shortly after takeoff. Destroyed by postimpact fire. Fire was controlled in 15 minutes and extinguished in 30 minites.	Part 121: Air Carrier	Climb	Crashed shortly after take-off. Destroyed by post impact fire. Fire controlled in 15 mins, ext in 30 mins.

Table D-2. Occurrences Where all Occupants Evacuated Before Aircraft Rescue and Firefighting Arrived or Without Aircraft Rescue and Firefighting Assistance

Plane Type	Location	Date	Occupants on Airplane	Occupants Survived	Incident	Comments
A310	Sudan	6/10/08	203	173	Landing, veered off runway	Fire grew very large—delayed ARFF plus difficult access
Fokker 100	Iran	1/2/08	59	59	Takeoff, ran off runway	All passengers evacuated before ARFF arrived; airplane destroyed
Hawker 800XP (Part 91)	Santa Ana, CA	10/29/07	8	8	Broke fire	Fire in left main landing gear
DH 125-3A	Venezuela	6/26/06	8	8	Landing gear collapse	All passengers escaped unaided
Learjet 35A (Part 135)	Colorado	7/15/05	4	4	Hard landing runway overshoot	Substantial damage to aircraft
Bombardier CL-600-1A11 (Part 135)	Teterboro, NJ	2/2/05	13	13	Landing Overshoot	Passengers escaped unaided (one injured); substantial damage to aircraft
CL-600-2A12 (Part 135)	Montrose, CO	11/28/04	6	3	Takeoff	Survivors escaped unaided (one injured); airplane destroyed by impact and fire
DC-3	Columbia	6/21/04	22	22	Takeoff, crash 1 mile from airport	Survivors likely self-evacuated before ARFF arrived; airplane destroyed by impact and fire
DC10-10	Denver, CO	10/12/03	7	7	Aborted take-off, brake fire	Smoke from wheels; ARFF alerted
Fokker F28	Ecuador	1/17/03	78	78	Overshoot of runway on emergency landing	Fire under left wing; two injured
B777-236	Denver, CO	9/5/01	27 (remaining of 256 onboard)	26	50-120 gals of fuel spilled; 15 x 30 ft fire ball	ARFF responded in 3 minutes and immediately extinguished fire; occupants escaped unaided; moderate damage to airplane
B737-400	Thailand	3/3/01	10	9	Explosion and fire in wing	ARFF arrived after crew escaped; airplane destroyed; nine injured
DC-9	Atlanta, GA	11/29/00	97	97	Smoke/fire in cabin	Occupants escaped unaided; 13 injured
DC-9-82	Dulles, VA	11/29/00	66	66	Lightening strike caused fire/smoke	Occupants escaped unaided

Table D-2. Occurrences Where all Occupants Evacuated Before Aircraft Rescue and Firefighting Arrived or Without Aircraft Rescue and Firefighting Assistance (Continued)

Plane Type	Location	Date	Occupants on Airplane	Occupants Survived	Incident	Comments
Learjet 35A (Non-US-GA)	France	5/2/00	5	3	Crash on approach	AFFF standing by and extinguished fire; survivors escaped before ARFF arrived.
B747-267B	Saudi Arabia	3/26/00	All Crew	All	Engine fire, Extinguished by ARFF	Crew escaped unaided
MD-88	Dallas, TX	12/26/98	50	50	Engine fire, ARFF dispatched no damage reported	Most occupants escaped unaided, one injured
B747-259B	Miami, FL	12/1/98	4	4	Refueling fire extinguished by ARFF	Crew escaped unaided
ATR-42	Puerto Rico	10/25/98	27	7	Struck object while taxiing, started fire	ARFF response in 4 minutes, occupants escaped unaided, three injured
DC-8F-55	Miami, FL	11/20/97	3	3	Crash landing after in-flight engine fire; port crash fire extinguished by ARFF	Crew escaped before ARFF arrived
MD-11	Newark, NJ	7/31/97	5	5	Crash landing; ARFF responded to root-crash fire	Crew escaped unaided
DC-10-30	Puerto Rico	5/11/97	262	262	Engine fire; ARFF responded	Occupants escaped unaided
MD-82	Dallas, TX	11/23/96	119	119	Engine fire; ARFF responded in 4 minutes	Occupants escaped unaided
B737-222	Grand Rapids, MI	11/18/96	87	87	Engine fire; ARFF responded	Occupants escaped unaided; three injured
DC-10-10CF	Newburgh, NY	9/5/96	5	5	Smoke in cockpit; developed into major fire that destroyed plane	Crew escaped unaided, two injured
DC-9-32	Houston, TX	2/9/96	87	87	Cabin fire after landing gear failure	Passengers escaped unaided, 12 injured
B727-224	Panama	11/7/95	12	12	Cargo compartment fire	Crew escaped unaided, two injured
SF-340-A	Philadelphia, PA	8/17/95	31	31	Engine fire extinguished by ARFF	Occupants escaped unaided
Learjet 55 (Non-US-GA)	Spain	4/4/94	10	10	ARFF extinguished post landing fire	Occupants likely escaped unaided

Table D-2. Occurrences Where all Occupants Evacuated Before Aircraft Rescue and Firefighting Arrived or Without Aircraft Rescue and Firefighting Assistance (Continued)

Plane Type	Location	Date	Occupants on Airplane	Occupants Survived	Incident	Comments
DC-9-82	Savannah, GA	6/18/93	133	133	In flight engine fire; ARFF extinguished on landing	Occupants escaped unaided
DC-10-30	Dallas, TX	4/14/93	202	202	Overshoot on landing; ARFF responded in 1 min, extinguished fire in 50 sec; substantial damage to airplane	Occupants escaped unaided; 40 injured
L-1011	New York, NY	7/30/92	292	292	Crash on aborted takeoff; ARFF responded in about 3 minutes; extinguished fire in about 4 minutes.	All except three or four occupants evacuated before ARFF arrived; ten injured. ARFF response estimated in 260 seconds, the same time as evacuation deemed complete.
Fokker 28-4000/ Part 121	New York, NY	3/22/92	51	27	Crash on takeoff, into water at end of runway; ARFF responded in 4 min.	Most survivors escaped unaided—delayed ARFF response to the aircraft, which was in the water at end of runway.

Table D-3. Occurrences Where Aircraft Rescue and Firefighting Assisted or Possibly Assisted Aircraft Evacuation

Plane Type	Date	Location (U.S. if not stated)	Occupants on Airplane	Injured	Fatalities	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Canadair CRJ-100ER	2/14/2008	Yerevan, Armenia	21	11	0	No	Undetermined	ARFF responded. People were saved due to the prompt actions of the fire fighters.	Non-NTSB	Takeoff	Crashed on takeoff. Destroyed by postimpact fire. ARFF responded, assisted in evacuation.
Boeing 777-222	12/14/2007	Chicago	264	0	0	Yes	Undetermined	All passengers escaped. Uncertain if ARFF assisted in rescue.	Part 121: Air Carrier	Approach/ Landing	Smoke filled the passenger cabin when the airplane was 10 miles from the airport. When the smoke became heavily concentrated, an emergency was declared and the airplane landed at O'Hare International Airport. No evidence if fire was observed.
DC-9-82	9/28/2007	St. Louis, MO	143	0	0	Yes	Yes	The ARFF was waiting as the airplane landed and successfully extinguished the engine fire before the evacuation was ordered.	Part 121: Air Carrier	Climb	Left engine fire during climb led to an emergency landing where ARFF was waiting. ARFF put out the fire and then an evacuation was ordered.
Tupolev TU-134A-3	3/17/2007	Samara, Russia	57	20	6	No	Yes	After arrival, ARFF assisted in evacuation.	Non-NTSB	Landing	Landed short of the runway. Wing separated. Landed upside down and caught fire. ARFF responded and assisted in evacuation.
Bae-146-200A	10/10/2006	Norway	16	9	4	No	Undetermined	Reports are not clear when ARFF arrived, or what role they played in the evacuation.	Non-U.S.	Landing	There was a postcrash fire after the airplane overran the runway.
Tupolev TU 154M	9/1/2006	Mashad, Iran	148	119	29	No	Yes	According to article, rescue workers carried passengers out of the gutted aircraft.	Non-NTSB	Landing	Skidded off the runway, wing drug across the ground causing fire. Rescue personnel assisted in evacuation.

Table D-3. Occurrences Where Aircraft Rescue and Firefighting Assisted or Possibly Assisted Aircraft Evacuation (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on Airplane	Injured	Fatalities	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Boeing 737-400	8/31/2006	Miami	118	0	0	Yes	Yes	There was a tire fire during landing. ARFF arrived in 2 minutes and evacuation occurred. ARFF assisted in evacuation based on pictures from the scene	Part 121: Air Carrier	Landing	The tires popped and caught fire while landing. Emergency personnel responded within 2 minutes.
Tupolev TU-134	7/10/2006	Gvadeyskoye, Ukraine	20	3	0	No	Undetermined	Video shows ARFF putting out flames, nothing more.	Non-NTSB	Takeoff	Engine failure and fire on takeoff. Overran runway after aborted takeoff. ARFF responded (from pictures).
Airbus A310-300	7/8/2006	Russia	200	1	124	No	Yes	It took 2 hours to fully extinguish the blaze at the scene, including the buildings the airplane ran into. According to news reports, local emergency personnel, including fire fighters, assisted in passenger escape and rescue.	Non-U.S.	Landing	The airplane overran the end of the runway and was destroyed by impact and postcrash fire.
Airbus A320	3/5/2006	Ireland	0	0	0	Unknown	Undetermined	A fire confined to the APU broke out. ARFF responded and extinguished it. Evacuation occurred.	Non-U.S.	Taxiing	There was a fire in the APU.
Airbus A340	8/2/2005	Canada	309	12	0	No	Yes	ARFF was on the scene within 1 minute of alarm. There was extra crew because the crash occurred during a shift change. The extra ARFF crew assisted passenger evacuation.	Non-U.S.	Landing	Due to extreme weather the airplane overran the end of the runway.
Boeing B-777	8/11/2004	Houston, TX	129	0	0	Yes	Possibly	Evacuation occurred simultaneously with firefighting efforts	Part 129: Foreign	Takeoff	Smoke in the cockpit led to an emergency landing. Firefighting activities occurred with the left engine.

Table D-3. Occurrences Where Aircraft Rescue and Firefighting Assisted or Possibly Assisted Aircraft Evacuation (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on Airplane	Injured	Fatalities	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
DHC-8-4002	5/19/2004	Norway	Not stated	0	0	Yes	Possibly	There was an engine fire in-flight. ARFF was waiting for the airplane as it landed. ARFF applied foam to the left engine as the passengers evacuated the airplane.	Non-U.S.	Cruise	Engine failure and fire led to the airplane being forced to land.
Boeing MD-10-10F	12/18/2003	Memphis, TN	7	2	0	No	Possibly; NTSB report says occupants escaped unaided	Some type of rescue personnel aided in the escape of the crew.	Part 121: Air Carrier	Landing	Landing gear collapsed on landing and fire started.
Boeing 767-200ER	4/15/2002	Pusan, Korea	166	28	138	No	Possibly	Emergency personnel and soldiers/police aided in evacuation/rescue of occupants on the airplane.	Non-US	Landing	Crashed during landing. Postimpact fire.
Boeing 747-400	10/31/2000	Taipei, Taiwan	179	44	83	No	Yes	Collided with construction equipment while on wrong runway. ARFF responded within 3 mins, took 10-15 minutes to bring fire under control (720 seconds). Rescue personnel did evacuate some passengers. Reports list amounts of agents used.	Part 129: Foreign	Landing	Collided with runway construction equipment during hurricane. Postimpact fire.
Douglas MD-82	6/1/1999	Little Rock, AR	145	110	11	No	Yes	Postimpact fire. ARFF responded, extinguished exterior fire in 60 seconds and extricated the first officer (and others).	Part 121: Air Carrier	Landing	Overran runway, crashed. Postimpact fire. Passengers escaped unaided. Long response time due to miscommunication about what side of runway the crash took place.

Table D-3. Occurrences Where Aircraft Rescue and Firefighting Assisted or Possibly Assisted Aircraft Evacuation (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on Airplane	Injured	Fatalities	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Douglas DC-8-61	8/18/1993	Guantanamo Bay, Cuba	3	3	0	No	Yes	Destroyed by post impact fire. ARFF responded, extinguished fire, extricated crew. Used 275gal of AFFF, 907 lb of Halon, and 37,500 gallons of water.	Part 121: Air Carrier	Approach	Crashed during approach to naval base. Destroyed by postimpact fire. ARFF responded, extinguished fire, extricated crew. Used 275 gal of AFFF, 907 lb of Halon, and 37,500 gallons of water.
Learjet 36A	12/3/2002	Astoria, OR	4	0	0	No	Yes	ARFF and fire department extinguished fire and aided the people in evacuation.	Part 91: General Aviation	Landing	Collided with elk, overran runway. (Seats 10) Postcrash Fire.
Douglas MD-11	3/31/2002	Charlotte, NC	245	16	0	Yes	Undetermined	ARFF responded to call.	Part 121: Air Carrier	Cruise	Engine fire
Douglas DC-9-41	1/24/2002	Indianapolis, IN	75	1	0	Yes	Yes	Communicated with crew about fire and procedures. Assisted with evacuation.	Part 121: Air Carrier	Standing	Engine tail pipe fire.
Douglas MD-90	8/24/1999	Hualien, Taiwan	96	27	1	No	Undetermined	E xploded after landing. Caught fire. ARFF responded (from pic). Undetermined if they assisted in evacuation.	Part 129: Foreign	Landing	Exploded and caught fire after landing. ARFF responded.
Airbus Industrie A-300	7/9/1998	San Juan, Puerto Rico	252	28	0	Yes	Possibly	Engine fire during cruise. Not extinguished by fire bottles. Not much damage to fuselage. ARFF responded, directed passengers to exit on right side.	Part 121: Air Carrier	Cruise	Engine fire during cruise. Not extinguished by fire bottles. Not much damage to fuselage. ARFF responded, directed passengers to exit on right side.

Table D-3. Occurrences Where Aircraft Rescue and Firefighting Assisted or Possibly Assisted Aircraft Evacuation (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on Airplane	Injured	Fatalities	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Boeing 727-212	3/30/1998	Fort Lauderdale, FL	194	17	0	Yes	Yes	Engine failure/fire during takeoff. Emergency evacuation. ARFF responded and assisted in evacuation by telling passengers not to jump from wings to ground.	Part 129: Foreign	Takeoff	Engine failure/fire during takeoff. Emergency evacuation. ARFF responded and assisted in evacuation by telling passengers not to jump from the wings to the ground.
Beech 1900C	8/13/1997	Seattle, WA	1	0	0	No	Yes	Loss of control during landing. Collided with runway. Postcrash fire. ARFF responded, extinguished fire and removed pilot.	Part 135: Air Taxi and Commuter	Landing	Loss of control during landing. Collided with runway. Postcrash fire. ARFF responded, extinguished fire and removed pilot.
Douglas MD-82	4/28/1997	Tucson, AZ	123	0	0	Yes	Yes	Engine tail pipe fire. ARFF responded, extinguished fire, directed passengers to stay on airplane and directed evacuation.	Part 121: Air Carrier	Climb	Engine tailpipe fire. ARFF responded, extinguished fire, directed passengers to stay on airplane and directed evacuation.
Douglas DC-9-32	6/8/1995	Atlanta, GA	62	3	0	Yes	Yes	Engine failure on takeoff roll. Fire from engine shrapnel. ARFF arrived in 3 minutes. ARFF attacked fire inside for short period before everyone was evacuated.	Part 121: Air Carrier	Takeoff	Engine failure on takeoff roll. Fire from engine shrapnel ARFF arrived in 3 minutes. ARFF attacked fire inside for short period before everyone was evacuated.
Douglas DC-9-31	7/2/1994	Charlotte, NC	57	20	37	No	Yes	Crashed into trees during missed approach. Destroyed by postimpact fire. ARFF used 187 gal of AFFF. Assisted trapped passengers.	Part 121: Air Carrier	Approach	Crashed into trees during missed approach. Destroyed by postimpact fire. ARFF used 187 gal of AFFF. Assisted trapped passengers.

Table D-3. Occurrences Where Aircraft Rescue and Firefighting Assisted or Possibly Assisted Aircraft Evacuation (Continued)

Plane Type	Date	Location (U.S. if not stated)	Occupants on Airplane	Injured	Fatalities	Property Saved	Escape/ Rescue	Remarks	Type of Carrier Operation	First Occurrence	Comments
Douglas DC-10-30F	12/21/1992	Faro, Portugal	340	175	56	No	Undetermined	ARFF response from pictures. Undetermined what action they took.	Non-U.S.	Landing	Crashed on runway. Right wing separated. Fire started 30 second ARFF response; evacuation in 240 seconds.

Note: Yellow highlight is an incident, not an accident.

APPENDIX E—AGENT QUANTITY USAGE PROVIDED BY AIR LINE PILOTS ASSOCIATION, INTERNATIONAL

Vic Hewes 2/4/93

AIR CARRIER CRASH FIRE RESPONSE

It is the policy of the ALPA Accident Survival Committee to revise their manuals based on a study of recent accidents. Within the past 13 years, there have been a number of major aircraft crash fires which have shown that the decisions that were made by ICAO, NFPA and the FAA to reduce agent quantities below those required by the original concept have not been justified. This survey conducted by the Air Line Pilots Association confirms this fact. Accidents where statistics are available are listed below.

TABLE E-1. WATER FOR FOAM PRODUCTION

Aircraft	**Location**	**Date**	**Recommended NFPA 403**	**Used U.S. gallons**
DC-l0	Los Angeles	January 3, 1978	4,800	7,800 AFFF
DC-8-61	Athens	October 7, 1979	4,800	Unknown
L-1011	Riyadh	August 19, 1980	4,800	20,000 AFFF
B-747	Seoul	November 18, 1980	6,500	Unknown
B-727	Yap Island	November 21, 1980	3,300	3,500 AFFF
B-737	Orange County	February 17, 1981	2,200	3,000 AFFF
B-737	Orange County	February 17, 1981	2,200	13,000 Hi Ex
DC-lO	Malaga	September 13, 1982	4,800	7,500 Prot.
DC-9	Barquisimeto	March 11, 1983	2,200	7,925 Prot.
DC-9	Cincinnati	June 2,1983	2,200	7,400 P/AFFF
DC-9	Madrid	July 12, 1983	2,200	Unknown
B-727	Madrid	July 12, 1983	3,200	Unknown
B-727	Chicago	November 11, 1983	3,200	Unknown
B-737	Calgary	March 22,1984	2,200	12,000 AFFF
B-707	Edwards AFB	December I, 1984	3,300	24,000 AFFF
CY-880	March AFB	July 17,1985	3,300	59,000 AFFF
L-l011	Dallas	August 2, 1985	4,800	16,400 AFFF
B-737	Manchester	August 22, 1985	2,200	10,000 AFFF
L-l011	Colombo	May 3,1986	4,800	2,000 FFFP
Aztec	Tampa	November 6,1986	60	500 AFFF
C-212	Detroit	March 4, 1987	315	5,800 AFFF
C-212	Mayaguez	May 8,1987	315	1,000 AFFF
DC-9	Detroit	August 16, 1987	2,200	19,900 AFFF
DC-9	Denver	November 15, 1987	2,200	940 AFFF
DH-8	Seattle	April 15, 1988	600	6,000 AFFF
B-727	Dallas	August 31,1988	3,300	15,000 AFFF
B-737	E. Midlands	January 8, 1989	2,200	670 FP
DC-l0	Sioux City	July 19, 1989	4,800	15,000 AFFF

Aircraft	Location	Date	Recommended NFPA 403	Used U.S. gallons
B-727	Salt Lake City	October 14, 1989	3,300	3,000 AFFF
DC-9/B-727	Detroit	December 3, 1990	5,500	8,500 + 1,500
B-737/J-31	Los Angeles	February 6, 1991	2,800	8,000 +9,000
DC-9	Cleveland	February 17, 1991	2,200	15,000 AFFF
DC-8	Kennedy	March 12, 1991	4,800	16,000 AFFF
B-727	Bradley	May 3,1991	3,300	36,000 AFFF
A-3oo	SANAA	March 17, 1992	4,800	6,040 AFFF
L-1011	Kennedy	July 30, 1992	4,800	37,000 AFFF
DC-l0	Faro	December 20, 1992	4,800	Unknown

AFFF - Aqueous Film Forming Foam
FFFP-Film Forming Fluoroprotein
HX - High Expansion Foam
Prot - Protein Foam
FP - Fluoroprotein

All of the above quantities of agent used are approximate and were obtained from accident reports or contact with the fire fighters involved. Where actual agent quantities are missing, photographs indicate that the aircraft was mostly destroyed by fire. Every effort was made to obtain these quantities through NTSB, ICAO and other national and international sources.

United States military experience is equally significant.

TABLE E-2. MILITARY AGENT USED

Date	A/C Type	Location	Water	AFFF
Feb 1974	B-52	Beale AFB	23,200	696
Mar 1974	KC-135	McCollllell AFB	19,700	591
Jun1974	B-52	Wright-Pat APB	16,000	480
Oct 1975	KC-135	Beale AFB	5,300	159
Nov 1975	B-52H	Minot AFB	12,750	383
Nov 1976	FB-lI1A	Pease AFB	5,600	168
Mar 1977	KC-135	Griffis AFB	35,750	1,073
Apr 1977	KC-135	Beale AFB	34,150	1,025
Sept 1979	C-141	Charleston APB	13,000	390
Jan 19~O	KC-135	Plattsburg APB	30,000	900
Aug 1980	B-52	Robins AFB	58,000	1,740
Sept 1980	B-52	Grand Forks AFB	503,000	15,090
Oct 1986	C-141	Travis AFB	19,100	573
Feb 1987	KC-135	Altus AFB	21,500	645
Apr1987	L-382	Travis AFB	15,500	465
Sept 1987	KC-10	Barksdale AFB	62,670	1,880
Oct 1988	KC-135	Wurtsmith AFB	25,630	769
Nov 1988	B-1B	Dyess AFB	25,010	750

Date	A/C Type	Location	Water	AFFF
Nov 1988	B-1B	Ellsworth APB	29,340	880
Dec 1988	B-52	Sawyer AFB	12,800	384
Jan 1989	C-5	Travis AFB	8,600	258
Jul 1989	B-52	Kelly AFB	58,890	1,766
Oct 1989	KC-135	Eilson APB	32,680	980
Nov 1989	C-5	Kelly AFB	1,400	42
Dec 1989	KC-135	Pease APB	151,300	4,539

The causes for the use of these excessive amounts of agent are varied, including: slow notification of the accident, slow response due to weather conditions, poor training, poor location of the fire house, vehicle malfunctions or accidents occurring outside of the airport boundary. Most crash fires were however, located on the active runway or in the immediate vicinity.

APPENDIX F—ESTIMATED FUEL SPILL BURN TIMES [F-1]

Table F-1. Potential Fuel Spill Burn-Times for Different Size Aircraft

Aircraft Size	Fuselage Length ft	Critical Fire Area sq ft	Maximum Aircraft Fuel Capacity gal JP-4	Jet A	Aviation Gasoline	Fuel Density gal per sq ft	Estimated Fuel Burning Time min
F-104A	55	2,475	1,484	--	--	0.599	6.73
DC-3	64	2,880	--	--	688	0.238	2.33
B-47	107	12,840	18,240	--	--	1.41	15.90
DC-9-10	104	12,480	--	3,722	--	0.298	3.63
C-5A	245	29,400	49,000	--	--	1.67	18.7
747 **(older models)**	258	30,960	--	47,210	--	1.53	18.7

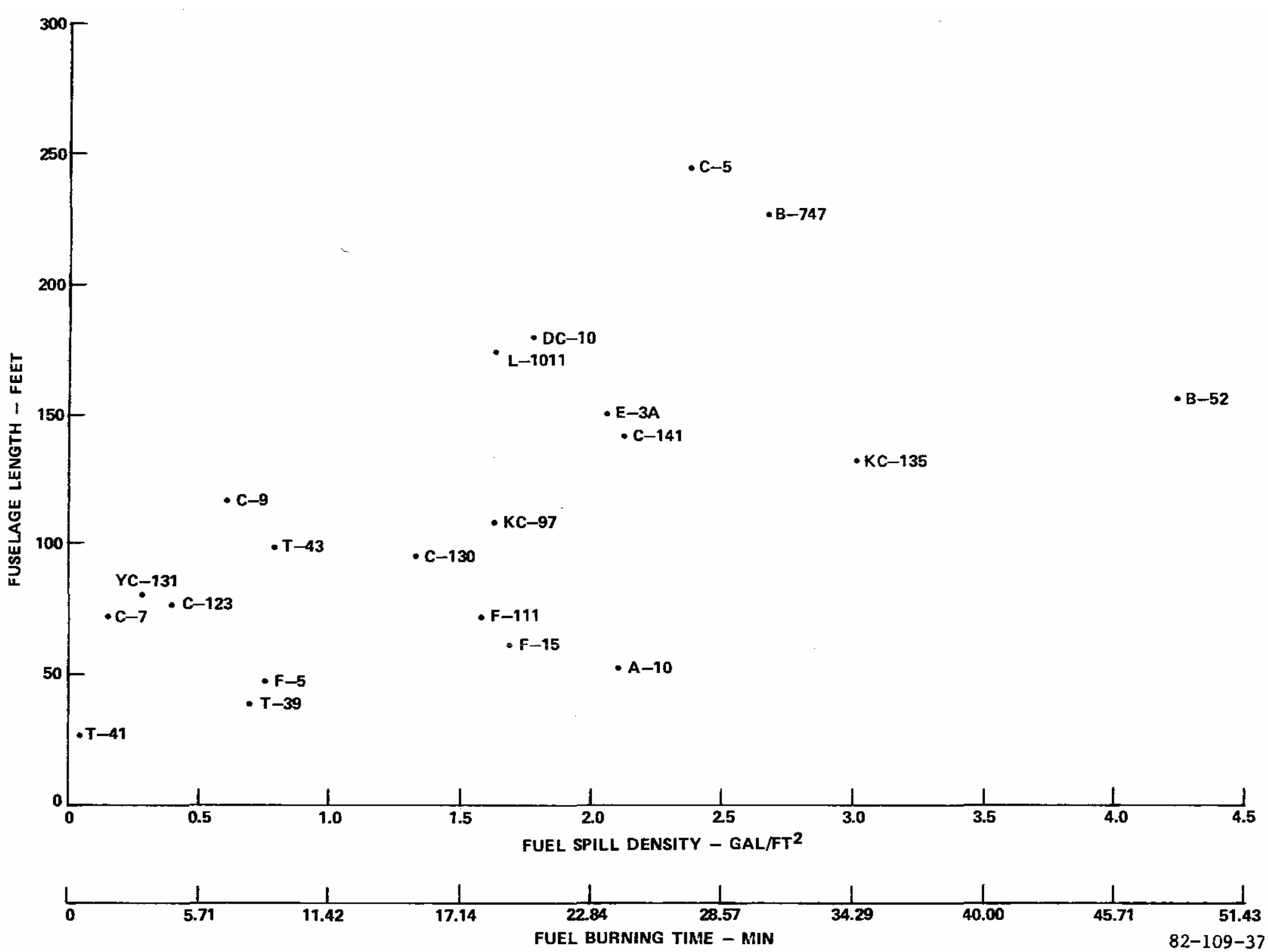

Figure F-1. Aircraft Fuselage Length as a Function of Fuel Spill Density and Burning Time for Selected Military Aircraft [F-1]

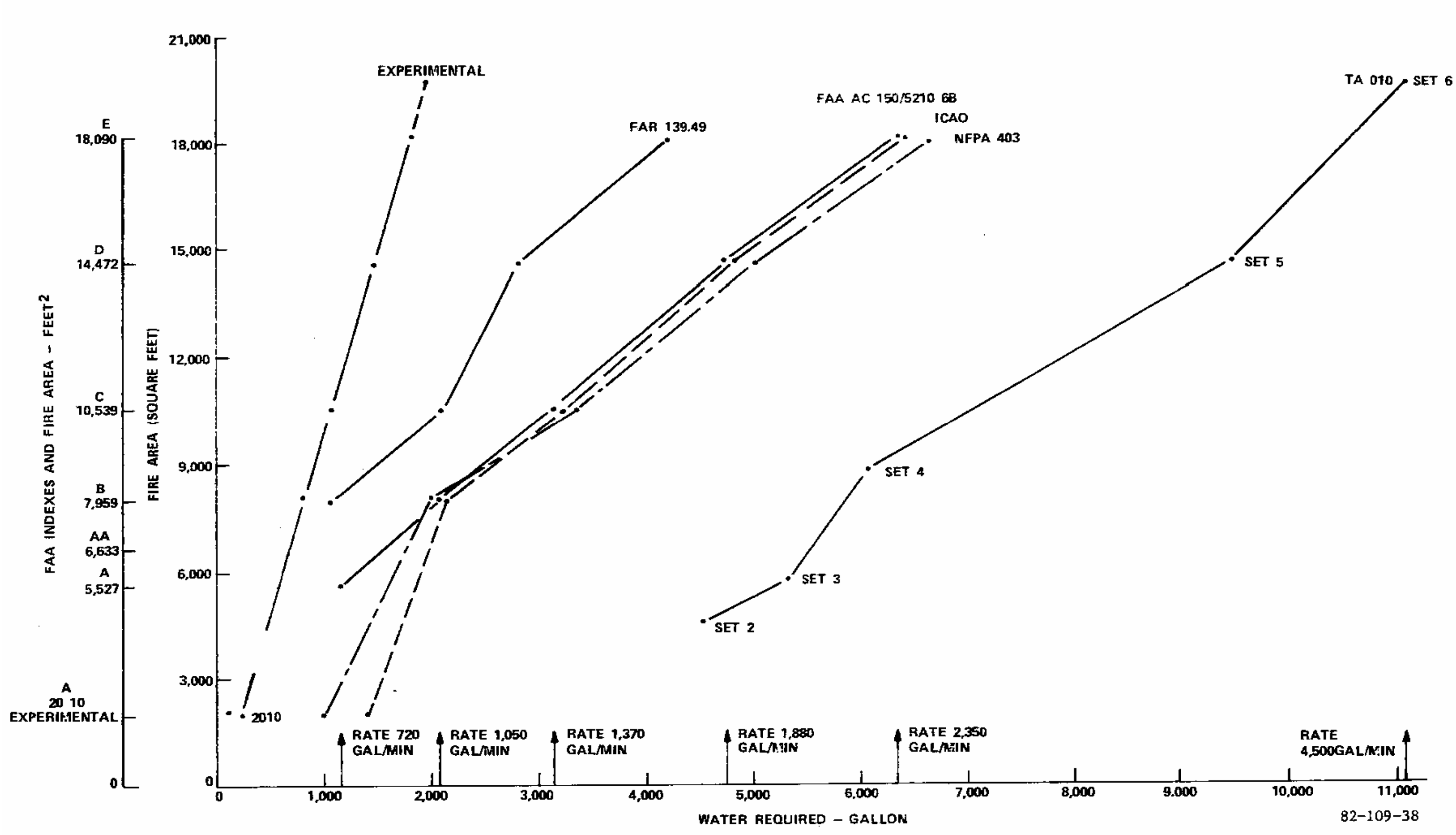

Figure F-2. Comparison of Water Quantities for the Crash Fire Rescue Services, [F-1]

REFERENCE.

F-1 Geyer, G.B., "Effect of Ground Crash Fire on Aircraft Fuselage Integrity," Report No. NA-69-37 (Replaced RD-69-46), U.S. Department of Transportation, Federal Aviation Administration, December 1969.