Status Report on an Effort to Evaluate and Develop Methodologies for Calculating Firefighting Agent Quantities Needed to Combat Aircraft Fires

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BACKGROUND

The US Federal Aviation Administration (FAA) is responsible for developing and implementing technologies which maximize the potential of aircraft passenger survivability in a post-crash environment. Aircraft size and construction is evolving to an extent where traditional crash rescue firefighting concepts may be outdated. The size of passenger aircraft is increasing, with associated increases in fuselage size, wing span, passenger capacity, and jet fuel load. Widespread use of composite materials is becoming the norm. In order to improve the effectiveness of aircraft rescue and firefighting (ARFF) resources, the FAA is reviewing the current methodology for calculating the total amount of firefighting agent required to combat aircraft fires.

AIRCRAFT FIREFIGHTING – IN THREE MINUTES OR LESS

It is important to understand the regulations and rationale which apply to ARFF. In the United States, the Federal Aviation Administration has the statutory authority to issue airport operating certificates to airports serving air carriers and establish minimum safety standards. The fire safety requirements are contained in Title 14, *Code of Federal Regulations*, Part 139 (14 CFR 139), Subpart D. FAA also issues Advisory Circulars (ARs), which are procedures for compliance with 14 CFR 139 ARFF requirements [1]. The National Fire Protection Association promulgates NFPA 403, *Standard for Aircraft Rescue and Firefighting Services at Airports* [2], through its consensus standard process. Even though NFPA 403 is not adopted verbatim by FAA, there has always been a close association between the NFPA work and US civil aviation. The International Civil Aviation Organization (ICAO), a global forum for civil aviation functioning as a United Nations Specialized Agency, also promulgates Aviation Fire Safety Standards and Guidelines [3,4].

The specification of firefighting agent quantities and associated crash firefighting and rescue (CFR) vehicles to deliver these agents was developed with the goal of saving lives in a survivable aircraft accident at or in the vicinity of an airport. The agent quantities are based on cutting a rescue path for occupant self evacuation, assuming a large jet fuel pool fire has occurred.

Captain Tom Lindemann, a longtime member of the NFPA 403 Technical Committee, provided an excellent synopsis of the ARFF rescue concept [5]. Research conducted by the FAA indicated that when an aircraft is involved in a fuel spill fire, the aluminum skin will burn through in about one minute. If the fuselage is intact, the sidewall insulation will maintain a survivable temperature inside the cabin until the windows melt in approximately three minutes. At that time the cabin temperature rapidly increases beyond a survivable temperature. Since aircraft do not have an effective means of preventing or suppressing a major cabin interior fire, the only protection that can be provided to aircraft occupants is rapid and effective fire control by ARFF personnel. He noted that firefighting vehicles built to the specifications of NFPA 414 [6] provide adequate amounts of extinguishing agent at appropriate discharge rates so that trained personnel should be able to obtain fire control in one minute. ARFF personnel must reach the accident scene within two minutes in order to prevent life safety consequences of the anticipated fuselage burn-through.

This response characteristic can be formalized in the following equation:

$$T_V + T_E \leq T_B \tag{1}$$

where:

T_V = vehicle response time (2 min)

T_E = time to extinguish pool fire (90% control) (1 min)

T_B = time pool fire exposure will burn-through the fuselage and become a threat to passengers (3 min)

Currently, there is a little latitude in adjusting these critical times without significant technological or regulatory changes. Pool fire extinguishment is based on the best, currently available primary agent, AFFF. Reducing vehicle response time would add significantly to equipment and facility requirements. The question remains whether historical methodologies used to develop agent quantities remain valid with the introduction of larger passenger aircraft.

THE PRACTICAL CRITICAL FIRE AREA (PCA) AND AGENT QUANTITY (Q)

The FAA currently utilizes an airport indexing system based on aircraft size. Table 1 compares ICAO and NFPA categorization criteria against current FAA indexes.

Table 1 – Current ARFF Index Comparison of FAA, ICAO, and NFPA[1]

FAA Index	Aircraft Length (ft.)	ICAO Cat.	Aircraft Length (ft.) up to but not including	Width (ft) up to but not including	NFPA Cat.	Aircraft Length up to but not including	Width up to but not including	Sample Aircraft
A	< 90	4	78 ft.	13.1	4	78	13.0	EMB120
A	< 90	5	91 ft.	13.1	5	90	13.0	CRJ-200; Saab 340
B	90–126	6	127 ft.	16.4	6	126	16.4	DC-9; A320; B737-300
C	126–159	7	160 ft.	16.4	7	160	16.4	B727-200; B757
D	159–200	8	200 ft.	22.9	8	200	23.0	A300; B767-300
E	> 200	9	249 ft.	22.9	9	250	23.0	A340-600; B777; B747-200;MD-11
		10	295 ft.	26.2	10	295	25.0	AN-225, A380

[1]From Aircraft Rescue and Firefighting Requirements Working Group, Draft March 2004

The historical basis of agent requirements is well documented in NFPA 403. A Rescue and Fire-Fighting Panel (RFFP) first convened by ICAO in Montreal, Canada, in 1970 developed the Theoretical Critical Area (TCA) and Practical Critical Area (PCA) concepts. The “critical area” is an area to be protected in any post-accident situation that would permit the safe evacuation of the aircraft occupants. It serves as the basis for calculating the quantities of extinguishing agents necessary to achieve protection within an acceptable period of time. Based on the logic that passenger capacity was related to length, it was agreed that the critical area should be a rectangle with dimensions relative to the length, width, and wingspan of the aircraft. Using this approach, the aircraft are grouped into a series of categories as shown in Table 1. The concept of using graduated aircraft categories as a means of assessing fire protection needs has survived to the present time with only minor revisions to reflect changes in the operating aircraft fleet.

The critical area concept for determining the level of fire-fighting agents and equipment needed to combat an aircraft accident fire is based on:

(1) The quantity of agent necessary to control or cover the fire area
(2) The rate of application of the agents to control the fire in the most effective time period

The TCA is the area adjacent to an aircraft in which fire must be controlled for the purpose of ensuring temporary fuselage integrity and providing an escape area for passengers. The theoretical critical area serves only as a means for categorizing aircraft in terms of the magnitude of the potential fire hazard in which they may become involved. It was not intended to represent the average, maximum, or minimum spill fire size associated with a particular aircraft. Data analysis of actual incidents and spill sizes indicated that a PCA of approximately two-thirds of the TCA is consistent with the objective of preventing the fire from melting through the fuselage or causing an explosion of the fuel tanks. The equipment and techniques used to discharge agent should be capable of controlling the fire in the critical area in 1 minute and of extinguishing the fire within another minute. Using available fire extinguishment test data, a single agent attack at an application rate of 0.13, 0.18 and 0.20 gpm/ft^2 for AFFF, fluoroprotein, and protein foams, respectively, was established. By multiplying the PCA corresponding to the upper limit of the airport category, times the recommended foam application rate, the recommended water quantities for foam production are calculated. The amounts required to control and to extinguish a fire are determined separately. The quantities were named and defined as follows:

Quantity $Q1$**.** The quantity required to obtain a 1-minute control time in the PCA. The formula for the water required for control (Q1) in the PCA can be expressed as:

$$Q1 = PCA \times R \times T \qquad (2)$$

where: PCA = practical critical area
R = rate of application for the specific foam
T = time of application (1 min)

Quantity $Q2$. The quantity required for continued control of the fire after the first minute or for complete extinguishment of the fire or for both. The amount of water required for $Q2$ is qualitative, and is dependent on a number of variables. Those variables (expressed as *f* in the equation below) considered of primary importance are:

(1) Maximum gross weight
(2) Maximum passenger capacity
(3) Maximum fuel load
(4) Previous experience (analysis of aircraft rescue and fire-fighting operations)

These factors are used to generate $Q2$ values for each airport category where:

$$Q2 = f \times Q1 \qquad (3)$$

Over time, changes in aircraft size have required revisions to the values of both $Q1$ and $Q2$ and the introduction of a third component, $Q3$, which make up the total quantity of water (Q) required for the production of foam. The values of *f* for $Q2$ currently range from 0 percent for Category 1 airports through 190 percent for Category 10. $Q3$ is based on the potential need for handlines to be used for interior fire fighting and ranges from 60 gpm for Category 1 airports to 500 gpm for Category 10 airports.

Summarizing, the total quantity of water (Q) is defined by NFPA 403 as follows:

$$Q = Q1 + Q2 + Q3 \qquad (4)$$

where: $Q1$ = water requirement for control of PCA
$Q2$ = water requirement to maintain control, extinguish the remaining fire, or both
$Q3$ = water requirement for interior fire fighting

The total quantities of agent are shown in Table 5.3.1 of NFPA 403. There are variations in the adopted FAA and ICAO versions of these total agent quantity guidelines, but the concepts remain essentially the same.

The next sections describe areas that are being investigated to determine if the current methodology is still applicable for large frame aircraft (LFA).

LARGE FRAME AIRCRAFT (LFA)

The introduction of LFA provides motivation to investigate the firefighting agent methodology currently used by FAA, NFPA, and ICAO. The size of the new Airbus A380 super jumbo jet is actually not much bigger than the forward section (double-decker) of the Boeing 747. Table 2 provides a comparative chart of airframe characteristics.

Table 2 – Comparison of Airframe Characteristics[2]

Aircraft	NFPA 403 CAT	Fuselage			Wing span (ft)	Height (ft)		Single Wing Area (sq ft)	Total Fuel Load (gal)	Total Max Passenger Load (people)
		Length (ft)	Height (ft)	Width (ft)		Ground to bottom of lowest door	Ground to bottom of highest door			
A320	6	123	14	13	112	11	12	1320	7885	180
B767-300	8	180	18	17	156	15	15	3050	16700	290
B787-8	8	186	19	19	197	14	16	3501	33528	224–375
DC10-40	8	182	20	20	165	16	17	3958	36652	399
A300-600	8	177	18	19	147	15	18	2800	18000	298
A340-300	9	209	19	19	198	15	17	3892	39060	335
B777-300	9	242	18	20	213	16	17	4605	44700	305–375
B747-200	9	229	26	21	196	17	17	5500	53864	480
MD11	9	192	22	20	171	15	16	3648	38615	410
A380-800	10	239	28	23	262	17	26	4600	81893	840

[2] All aircraft data is approximate, based on public-access information from the air frame manufacturers.

The key differences of the A380 with other aircraft are the passenger load and associated aviation fuel load. A load of up to 840 passengers is anticipated with the A380, compared to passenger loads of 480 and 375 for the B747 and B787, respectively. The aviation fuel load of nearly 82,000 gallons (and potentially higher) for the A380 is substantially greater than fuel loads of about 54,000 gallons for the B747 and 38,000 gallons for the B787.

Additional attributes of the A380 include the use of greater amounts of composite materials, and sixteen passenger exiting chutes required to quickly allow passenger evacuation. Using the existing NFPA 403 requirements, the A380 would be a Category 10 aircraft, which would require 14,260 gallons of AFFF discharged from vehicles totaling about 3200 gpm (plus 500 gpm for handlines) based on the current PCA calculation. This compares to the B747, a Category 9 aircraft, which requires 9570 gallons of AFFF protection, discharged at a total of about 2600 gpm (plus 250 gpm for handlines).

FUEL FIRE THREAT

The differences in aircraft fuel load are substantial. As noted previously, the firefighting fuel load per se is not the basis of protection, but rather the extinguishment of a pool fire to allow for occupant self evacuation. The PCA assumes a pool fire exposure of one side of the fuselage. The fundamental presumptions of the PCA calculation can be checked using first principles. Calculations can be performed to compare maximum fire size of a liquid fuel spill as a function of spill volume or rate [7], e.g.,

$$A_S = \frac{V}{\delta} \tag{5}$$

where: A_S = spill area

V = Volume of fuel spilled

δ = spill depth, 2.8–4 mm for a large release on concrete

Thermal radiation calculations can then be used to estimate the impact of a pool fire exposure on personnel, equipment, and materials. Thermal radiation to an item or "target" seeing the flame is calculated using the fundamental heat transfer equation:

$$Q = \varepsilon\sigma\phi T^4 \tag{6}$$

where: Q = heat flux (kW)

ε = flame emissivity (dimensionless)

σ = Stefan-Bolzmann constant, 56.7 x 10^{-12} kW/m °K

ϕ = view factor

T = flame temperature (°K)

Considerable work has been performed to simplify the calculation of heat transfer from pool fires to targets. Variables include fuel characteristics, burning rate, flame height, distance to target, wind affects, and complicated view factors. A review of this data is available in the literature. For example, a commonly used correlation has been published by the Society of Fire Protection Engineers [8].

$$\dot{q} = 15.4\left(\frac{L}{D}\right)^{-1.54} \qquad \left[\frac{kW}{m^2}\right] \tag{7}$$

where: $\dot{q}$ = heat flux to a target (kW/m^2)
D = diameter of pool fire (m)
L = distance from the center of the pool fire to the edge of a target (m)

"Targets" include passengers evacuating the aircraft, the aircraft structure, and responding ARFF personnel. The aircraft may be immersed in flame. Passengers may be at some distance from the edge of a burning pool, i.e., when the rescue path is established. The safe evacuation of passengers occurs when the incident flux from the adjacent (unextinguished) pool fire along the exit path does not exceed the threshold of pain (2.5–5kW/m^2). Calculations of the plausibility and thermal affects of fire outside the PCA can be made with respect to exit paths (slide discharge). The adequacy of the current PCA can then be established. Part of the plausibility assessment is consideration of the safety factor inherent with current agent requirements.

FIREFIGHTING AGENTS AND EQUIPMENT

Aqueous film-forming foam (AFFF) is required to be discharged at 0.13 gpm/ft^2 to provide the control of a fire in 60 seconds. In the US, AFFF at airports must meet the requirements of the US Military Specification, MIL-F-24385(F) [9]. Analysis has shown that the 0.13 gpm/ft^2 provides a substantial factor of safety for extinguishment of two-dimensional aviation fuel fires [10]. The MIL SPEC test is performed at a rate as low as 0.04 gpm/ft^2 on gasoline, with an extinguishment density of 0.033 gal/ft^2. Analysis of data for AFFF that does not meet the MIL SPEC suggests that these agents may not provide a similar safety factor. It has been shown that the current ICAO foam test method is not equivalent to the MIL SPEC requirements. There is a program underway to establish a new ICAO foam performance test which will require extinguishment of a larger test fire at the same foam discharge rate (i.e., lower effective extinguishment application rate and density). The motivation is to approve foam agents having performance similar to the US MIL SPEC. ICAO will then more closely correlate with NFPA 403.

Several new agent application techniques have recently been tested by the US Air Force [11]. The technologies include compressed air foam (CAFS), a combined agent firefighting system (CAFFS), and an ultra high pressure AFFF system (UHPS). The CAF system injects compressed air into the pressurized line between the pump and the nozzle. This results in a high expansion, more stable AFFF. Flow rates of 125 and 220 gpm were used. The CAFFS system uses CAF plus dry chemical discharged through a central orifice. Flow rates of 125/220 gpm of foam and 3/7.5 lb/sec of dry chemical were evaluated. UHPS AFFF was discharged at 1500 psi at a flow rate of 70 and 100 gpm. Baseline AFFF tests were performed at 250 and 500 gpm on test fires ranging from 877–6644 ft^2. The new agent techniques resulted in lower control/extinguishment application densities, as shown in Table 3, for fuel fires on water and gravel substrates.

Table 3 – Results of Experimental Agent Application Techniques [11]

Extinguishing Method	**Mean Extinguishment Density (gal/ft^2)**	
	Water Substrate	**Gravel**
Standard AFFF	0.044	0.064
UHPS	0.014	0.054
CAFS	0.028	0.053
CAFFS (combined agent)	0.027	0.036

There are continuing requests from industry to judge the effectiveness and applicability of new agents and equipment. Both the FAA and the US Air Force conduct experimentation on an ongoing basis [12,13].

This new technology offers the potential for either reducing agent quantity for equivalent fire performance or increasing capability for an equivalent mass of agent. There are several challenges to overcome, including: application of appropriate safety factors; establishment of small-scale approval test methods for technology such as CAFS, high pressure foam, and dual agent systems; and quantification of required performance as it relates to the fire safety objective of protecting evacuating passengers.

Access to the aircraft is an issue, particularly for a full length double-deck as on the A380. There are no current requirements to provide aerial capability to immediately access aircraft for a post-crash environment. If needed, airports provide their own supplemental vehicles. For example, a structural aerial apparatus, which is part of the normal airport structural response or mutual aid arrangement, may be called on to respond for a major incident. ARFF vehicle manufacturers are responding to demand for ARFF aerial equipment. If access is required in a survivable post-crash environment, aerial equipment is necessary for LFA as shown in Table 2. Requiring such capability would change the current philosophy of providing firefighting to establish a rescue path around and from the aircraft.

COMPOSITE MATERIALS AND POOL FIRE OBSTRUCTIONS

Composite materials are being used to a greater extent on new aircraft. In addition to use in the interior, they are being used in the fuselage and wing structures. Composites offer both an opportunity and challenge for the ARFF services. Though combustible, composites may be more thermally resistive to fire. This may extend the burn-through time of intact aircraft. This presumes that weak links such as windows are also hardened. The FAA is investigating the burn through characteristics of airframe composites.

By their nature, most aircraft composites include combustible material. These materials may exhibit char-like burning characteristics. Test data and information will be reviewed to determine if burning composites present an unrecognized fire extinguishment or re-ignition hazard. Review of data to date does not indicate that this is a serious problem [14]; there is anecdotal information which suggests firefighters have had difficulty in totally extinguishing fires involving composite materials.

Other challenges associated with LFA warrant further consideration. The large number of exit chutes from the A380 may create an obstructed pool fire. If the plastic material melts and becomes involved in the pool fire, the burning fuel may be more persistent than fires on flat surfaces. This should probably be investigated, with an eye toward possible adjustment of the $Q2$ agent quantity. The exit chute arrangement of LFA compared to smaller aircraft, and the potential impact on spill fire suppression, will be investigated. Burnback resistance of foam agents should be quantified for a "debris" field. An approach to burnback quantification of foam, using approval test data, has been described [15]. Full scale burnback resistance tests may be required.

SUMMARY

The regulatory requirements and current methodology for calculating firefighting agent quantities needed to combat aircraft fires have been described. These requirements and methodology may require revision based on newer, larger aircraft being introduced into commercial passenger service. The newer aircraft have more passengers, a greater fuel load, and more composite materials. Analytical techniques can be used to quantitatively evaluate the TCA/PCA methodology. Composites and large egress chutes may create debris in the crash area which might extend extinguishment times or require a greater degree of burnback resistance. The existing fire safety objective (cut an egress path around a burning aircraft for self-evacuating passengers) may merit revision to more formally address on-board firefighting and physical rescue of passengers in a survivable post-crash environment. New agent application techniques and equipment are being fielded to address the threats. A more formal process for recognizing these new technologies, consistent with the fire safety objectives, is appropriate for incorporation into NFPA, FAA, and ICAO standards.

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