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Performance Criteria for Aircraft Hangar Fire Protection Systems

Final Report by:

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Foreword

NFPA 409, Standard on Aircraft Hangars, has historically (until the 2022 edition) required various fire protection options using firefighting foam systems. The requirements for foam fire protection systems in NFPA 409 (e.g., low expansion, high expansion) are largely based on large-scale fire tests (~900 sq. ft. pool fire tests) conducted by FM Global in the 1970's, however it is a challenge to replicate these large-scale pool fire tests today. There have traditionally been no avenues for evaluating alternative fire protection methods for possible inclusion in NFPA 409. While systems such as water mist, compressed air foam, clean agents and other solutions have been proposed, the path to understand their effectiveness in protecting an aircraft hangar is unclear. Therefore, it is necessary to develop an alternative evaluation method that can be used to assess the performance of other technologies on the assumed aircraft hangar fire scenario. This research project proposes an evaluation method that can be used to assess the performance of alternative fire protection systems for aircraft hangar facilities and what additional research is needed to further develop performance criteria for alternative systems.

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for

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1. Introduction

Firefighting foam suppression system has historically been used as the primary fire protection strategy for aircraft hangars. In recent years, alternative fire protection methods have been proposed and studied, however, a full understanding of their effectiveness in protecting an aircraft hangar has been unclear. Thus, research was needed to clarify the existing fire protection methods and establish a performance evaluation method to assess various alternative fire protection systems for aircraft hangar applications.

The scope of this report includes:

- *Review and clarification of the technical basis of the performance criteria of fire protection systems currently permitted in NFPA 409;*
- *Overview of a risk assessment methodology for aircraft hangar facilities, including an evaluation of the applicability of alternate fire protection technologies;*
- *Development of a research plan to further investigate the effectiveness of fire protection solutions in aircraft hangars.*

Fire protection system requirements in NFPA 409 are based on the presence of a large flammable liquid fuel spill. In a recent report by Milke, et al. (2019), no fires involving fuel spills occurred in hangars in the first ten months of 2019 according to the US Coast Guard (USCG) database. Further, in a survey conducted of Fixed Based Operators and insurance carriers of incidents involving foam discharges in aircraft hangars, there were 37 fire incidents reported in a 16-year period (Milke, et al., 2019). None of the 37 fire incidents involved a fuel spill. Hence, the major motivation for requiring foam systems in hangars, i.e., fires involving fuel spills, appear to be rarely encountered fire scenarios. Further, that same survey found that false discharges of foam systems were 3.7 times more likely than discharges due to fire, resulting in appreciable damage to aircraft, buildings and the environment.

In light of the recent experience obtained with foam systems in aircraft hangars, developing an evaluation method to identify effective fire protection strategies for aircraft hangars will provide the industry with the capability to explore alternatives. The overall purpose of this report is to document an evaluation method that can be used to assess the performance of fire protection systems for aircraft hangar facilities. As part of that purpose, another goal of this project is to determine the baseline performance criteria of existing fire protection systems in aircraft hangar facilities.

2. Overview of Code Provisions for Fire Suppression Systems

This section provides an overview of provisions in existing standards or guidance documents.

The reviewed resources include:

- National Fire Protection Association (NFPA) 409, *Standard on Aircraft Hangars*
- National Aerospace Standard (NAS) 3306, *Facility Requirements for Aircraft Operations: Standard Practice*
- Factory Mutual (FM) Global Property Loss Prevention Sheet 7-93, *Aircraft Hangar, Aircraft Manufacturing and Assembly Facilities, and Protection of Aircraft Interiors During Assembly*
- United Facilities Criteria (UFC) 4-211-01, *Aircraft Maintenance Hangars*
- *International Building Code (IBC)*

2.1 NFPA 409

According to the NFPA 409 Origin and Development section, concerns for fire protection in hangars dates back to the recommendations by the National Board of Fire Underwriters (NBFU) in 1930, with revisions in 1931, 1943, 1945, and 1950 [NFPA 2022a]. In 1943, the NBFU document became NFPA Pamphlet 85 [NFPA 2022a]. During the period 1943 through 1954, these recommendations were published as NBFU Pamphlet 85. In 1951, NFPA organized a Committee on Aircraft Hangars to which the National Board of Fire Underwriters and other interested groups lent their support. The NFPA's first standard was adopted in 1954, and the NBFU adopted the same text, rescinding their earlier 1950 standard. Revisions were made in 1957 and 1958 by this NFPA Committee. In 1959, a reorganization of the NFPA aviation activities resulted in the assignment of this standard to the Sectional Committee on Aircraft Hangars and Airport Facilities.

The 1960, 1962, 1965, 1966, 1967, 1969, 1970, 1971, 1972, 1973 and 1975 editions were prepared by this sectional committee. The sectional committee was reorganized as the Technical Committee on Airport Facilities and completed a revision to NFPA 409 in 1978. The document underwent extensive editorial revision and partial technical revision in 1984 and was again revised in 1990 and 1995.

In the 2001 edition of NFPA 409, the fire protection requirements for Group I Hangars were extensively revised and new criteria was added for membrane-covered, rigid, steel frame structure hangars. In 2004 and 2011 a partial revision of the standard was performed. In the 2011 edition of NFPA 409, criteria was added to clarify where sprinklers are required for smaller hangars such as those used by general aviation entities. Unenforceable terms have also been removed to comply with the Manual of Style for NFPA Technical Committee Documents.

The 2016 edition, which was the current edition at the start of the research project, the committee re-examined many of the long-standing requirements with respect to current technologies, modern design practices, and known fire loss history [NFPA 2016]. That fresh look resulted in the relaxation of the requirements for divided water reservoirs, redundant fire pumps, and reserve supplies of foam concentrate, among others. In addition, zoning of low-level foam systems is permitted in Group I and Group II hangars, and Chapter 8 was simplified for Group III hangars.

During the development of this research report the 2022 edition of NFPA 409 was approved by the NFPA Standards Council and published. The effective date of the 2022 edition of NFPA 409 is October 22, 2021, which supersedes all previous editions. The new provisions and updates in the 2022 edition of NFPA 409 are available within the Origin and Development section of NFPA 409 and are summarized below:

- Chapter 1 contains new sections pertaining to the application of the standard and retroactivity.
- Chapter 3 includes new definitions to provide further clarification to the technical changes reflected in the 2022 edition.
- Chapter 4, *Fire Protection Approaches*, has been introduced as a new chapter in the 2022 edition, which allows for risk-based fire protection approaches for aircraft hangars, in addition to the previously allowable prescriptive approaches.
- Supplementing the new addition of the risk-based fire protection approach of Chapter 4, another new chapter, Chapter 5, *Performance-Based Design Approach*, has been introduced. This chapter provides specific guidance for performance-based practices for aircraft hangars.
- The 2022 edition of NFPA 409 now permits the use of an alternative fire protection method, ignitable liquid drainage floor assemblies, in Chapter 8.
- New and updated provisions for inspection, testing, and maintenance requirements for aircraft hangars has been outlined in Chapter 11.

Before 1985, NFPA 409 required both Group I and II hangars to be protected with water deluge systems. Aqueous Film-Forming Foam (AFFF) was first considered by the Navy (NRL) for hangar fire protection in the early 1960's. Research from the 1970's demonstrated the effectiveness of foam agents on controlling fires involving JP-4 fuel spills and addressed benefits of nozzle type and the interaction of foam and sprinkler systems [Krasner, et al., 1975][Breen, 1973][Fitzgerald, 1971]. In the 1985 edition of NFPA 409, the requirement for Group I hangars was changed to require a foam-water deluge system while Group II hangars could have either a foam-water deluge system or a sprinkler system combined with a low-level foam system. The justification provided for the change in the 1984 Report on Proposals (ROP) was "available test data has never shown water to be an effective suppressant for potentially large flammable liquid spill fires" [NFPA 1984]

In the 2001 edition, the requirements in NFPA 409 were revised to permit Group I hangars to have a choice between a foam-water deluge system or a sprinkler system combined with a low-level foam system. In the 2001 ROP, the justification for this change was "to better cover entire hangar floor area when random parking positions are used and to cut back on fire protection water demand" [NFPA 2001].

The requirements for fire suppression systems included in the 2016 edition of NFPA 409 permits multiple fire protection options for Group I to Group IV hangars. The fire protection requirements depend on the hangar classification, ranging from Group I to Group IV. The classification of a hangar into Groups I to III is dependent on the door height, floor area of largest single fire area and construction type of the building as summarized in Table 2-1.

Fire protection requirements depend on the hangar classification, number of stories and the presence of fueled versus unfueled aircraft [NFPA 2016]. For hangars containing unfueled aircraft, all Group I and II hangars and Group IV hangars with a fire area greater than 1,115 m², (12,000 ft²) a sprinkler system (either wet pipe or single-interlock preaction system) is required. Single story, Group III hangars with unfueled aircraft are not required to have a fixed fire suppression system unless hazardous operations occur in the hangar (a list of activities considered to be hazardous operations is included in section 8.8.1.2).

Table 2-1: Classification of Group I, II and III Hangars [NFPA 2022a]

	Group I	Group II	Group III
Access Door Height	> 8.5 m	≤ 8.5 m	
Type of Construction	Single Fire Area (m²)		
Type I (443) & (332)	> 3,716	2,787-3,716	≤ 2,787
Type II (222)		1,858-3,716	≤ 1,858
Type II (111), Type III (211), Type IV (2HH)		1,394-3,716	≤ 1,394
Type II (000) & Type III (200)		1,115-3,716	≤ 1,115
Type V (111)		743-3,716	≤ 743
Type V (000)		465-3,716	≤ 465

Requirements for fixed fire suppression systems in Group I to IV hangars with fueled aircraft are provided in Chapters 6 to 9 in NFPA 409 [NFPA 2022a]. An overview of the suppression system options included in those chapters is provided in Table 2-2.

A fire suppression system is required in Group IV hangars only if the fire area is 1,115 m² or greater. The options for fire suppression systems include a low-expansion foam system, a high-expansion foam system or sprinklers (again being limited to wet pipe or single-interlock preaction). Fixed fire suppression systems are not required in Group III hangars unless hazardous operations are performed in the hangar. In such cases, the requirements for Group II hangars apply.

Considering the set of requirements currently included in the 2022 edition of NFPA 409, the variation in requirements reflects an implicit difference of risk levels in different sizes of hangars (height and fire area), construction type, fueled versus unfueled aircraft, and operations within the hangar. For membrane-covered Group IV hangars, several fire protection options are available for those hangars with a hangar fire area in excess of 1,115 m² (12,000 ft²) and housing unfueled aircraft.

*Table 2-2: Fire Suppression System Options for Group I-IV Hangars with Fueled Aircraft
[NFPA 2022a]*

Fire Suppression System Options	Hangar Group			
	I	II	III	IV
Foam-water deluge system	* ^a	* ^a	* ^{a,b}	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam system	*	*	* ^b	
Combination of automatic sprinkler protection and automatic, high-expansion foam system	*	*	* ^b	
Closed-head foam-water system		*	* ^b	
Water only sprinklers, low-expansion foam or high-expansion foam				* ^c
Combination of automatic sprinkler protection and an ignitable liquid drainage floor assembly	* ^a	* ^a	* ^{a,b}	* ^c

^a Where the wing area exceeds 279 m² (3,000 ft²) supplementary protection is required because of concerns of shielding of the fire that may be provided aircraft wings.

^b Only required if hazardous operations occur in the hangar or required by local codes.

^c Only required if floor area is greater than 1,115 m²

2.2 NAS 3306

The requirements included in the 2020 edition of NAS 3306 largely agree with those in NFPA 409. NAS 3306 classifies unmanned aircraft into groups by size [NAS 2020]. The small ones (Groups 1-3) have separate guidance than the larger ones (Group 4-5). Group 4 and 5 Unmanned Aircraft hangars are treated just like manned aircraft and facilities they are in are "hangars". There are some notable exceptions where the NAS standard includes requirements for fire suppression systems where NFPA 409 does not. The exceptions are:

- In Group III hangars that house unfueled aircraft, NAS 3306 requires that such hangars be protected by an automatic sprinkler system designed for Extra Hazard Group 1 as outlined in NFPA 13.
- In Group IV hangars which have a fire area which is less than 1,115 m² (12,000 ft²) that contain more than one aircraft, a sprinkler system (either wet pipe or single-interlock preaction) is required (i.e., the same requirement as for Group IV hangars with a fire area in excess of 1,115 m²).

NAS 3306 requires that a review of the need for supplementary underwing protection be included in all hangars with multiple aircraft (as opposed to considering such in only Group I hangars in NFPA 409).

NAS 3306 also addresses hangars that store or service unmanned aircraft. The NAS document recommends that facilities storing and servicing unmanned aircraft be protected with an automatic sprinkler system.

2.3 FM Data Sheet 7-93

The classification of hangars in the FM data sheet (FM Global 2019 revision) are the same as those in NFPA 409. The recommended fire suppression system options for hangars with fueled aircraft in the FM data sheet vary somewhat from the requirements included in NFPA 409. The recommended fire suppression system options included in the FM data sheet are included in Table 2-3.

Table 2-3: Fire Suppression System Options for Group I and II Hangars [FM 2019]

Fire Suppression System Options	Hangar Group	
	I	II, III, IV
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with floor nozzles	*	*
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with monitor nozzles	*	*
Combination of automatic sprinkler protection and automatic, high-expansion foam system	*	*
For ceiling heights up to 60 ft, with supplementary low-level, low-expansion foam protection under shielded areas	*	
Foam-water deluge system at ceiling		*
Wet low-expansion foam water at ceiling only		*

2.4 UFC 4-211-01

UFC 4-211-01 outlines the following requirements for the design of overhead sprinkler systems [DoD 2017]. The hangar bay, wet pipe, dry pipe or preaction sprinklers are required. Any overhead system is required to produce an output density of 8.0 liters/m² (0.2 gpm/ft²) over the most demanding 464 m² (5,000 ft²) area. It must also provide upright quick-response sprinklers with a temperature rating of 79°C (175°F) or 93°C (200°F), if the location has a dry bulb temperature greater than 38°C (100°F).

Wet pipe systems are only permitted for geographical locations with dry bulb temperature greater than 4°C (40°F) or greater than -18°C (0°F) with the addition of a heating system. It must also vent at least 95% of the volumetric capacity of the system. Temperature sensors are to be placed throughout the given space within 200 ft of each other and within 100 ft of a wall. Dry pipe systems must provide an externally resettable automatic water control valve whereas preaction systems require a single interlock, externally resettable automatic water control valve.

For the Army and Air Force, a low-level Hi-Ex foam system is required. Hi-Ex foam systems must cover 90% of the aircraft's projected silhouette on the floor within one minute of activation and must be designed to only release the necessary system in the case of two or more present systems during a fire event.

Table 2-4: Fire Suppression System Options for Hangars (UFC 4-211-01)[DoD 2017]

Fire Suppression System Options	Hangar Group			
	I	II	III	IV
Overhead wet pipe, dry pipe or preaction sprinkler system with temperature monitoring	*	*	* ^a	*
Low level trench nozzle system (Navy)	* ^b			
Hi-Ex foam system (Army, Air Force)	*	*		*

^a Must be hydraulically designed to provide 12 Lpm/m² (0.3 gpm/ft²) over the most demanding 279 m² (3,000 ft²) area

^b Overhead sprinklers are not required in Navy tension fabric hangars.

The Navy was using MIL-SPEC AFFF but no longer includes AFFF in new projects since the passage of the 2020 National Defense Authorization Act. Trench drains and grate nozzles are still provided, and water is used as an interim solution. Low level water trench nozzle systems must provide water within 30 seconds of the activation of the system. It is required to maintain a discharge pressure between 40 psi and 45 psi at all times. The design must consider proper sizing of trenches for water flow rates, volume, and turning radius of the necessary fittings. The nozzle spray pattern is not to exceed 0.3 m (1 ft) above the hangar bay floor and should always be using nozzles of appropriate degree spray pattern as to always direct the foam/water solution onto the aircraft servicing area. The maximum spacing between trenches is 15 m (50 ft), and the minimum and maximum spacings of nozzles are 6.9 m (22.5 ft) and 8.4 m (27.5 ft), respectively.

A potential protection method not listed in UFC 4-211-01 consists of trench drains spaced 7.6 m (25 ft) apart with grate nozzles at 15 m (50 ft) spacing. With such a design, a fuel fire can be directed into a trench drain. Typically, a trench width of 0.46 m (18 in.) is used, but for hangars housing the F-35, 0.61 m (2 ft) trench width is used to accommodate duct work. The depth is at least 0.61 m (2 ft) with piping in it but may vary. A grid-iron pattern is used for the trenches so the area enclosed is 15 m (50 ft) by the depth/width of the hangar. The sprinkler system is designed in accordance with NFPA 409 but uses the 464 m² (5,000 ft²) requirement for Group II hangars instead of the 1,390 m² (15,000 ft²) requirement for Group I hangars.

Preaction sprinkler systems are to be actuated either by non-addressed, rate-compensated heat detectors with a temperature rating between 71°C (160°F) and 76° (170°F). Foam systems are required to be actuated by triple infrared (IR) optical flame detectors. Detectors need to be selected considering the fuels that are expected to be present in the hangar bay.

2.5 International Building Code (IBC), 2018 edition

The International Building Code (IBC) establishes minimum requirements for building systems using prescriptive and performance-related provisions. It is founded on broad-based principles that make possible the use of new materials and new building designs. The 2018 edition is fully compatible with all of the International Codes (I-Codes) published by the International Code Council (ICC). The I-Codes, including this International Building Code, are used in a variety of ways in both the public and private sectors. Most industry professionals are familiar with the I-Codes as the basis of laws and regulations in communities across the U.S. and in other countries. A new version of the IBC is promulgated every 3 years.

The IBC is intended to establish provisions that adequately protect public health, safety and welfare; that do not unnecessarily increase construction costs; that do not restrict the use of new materials, products or methods of construction; and that do not give preferential treatment to particular types or classes of materials, products or methods of construction.

Many jurisdictions throughout the world have adopted the I-Codes, which through reference includes provisions to include NFPA 409. NFPA 409 is also viewed throughout the world and by many Airport Authorities, as the standard of choice to establish the minimum requirements for the proper construction and protection of aircraft hangars from fire.

The IBC classifies a commercial (non-residential) aircraft hangar used for the storage and repair of aircraft as a moderate-hazard storage occupancy (Group S-1). Section 412.3.6 requires aircraft hangars to be provided with a fire suppression system designed in accordance with NFPA 409, based on the classification for the hangar given in Table 412.3.6. A copy of IBC Table 412.3.6 is presented as Table 2-5.

Table 2 - 5: IBC Table of Hangar Fire Suppression Requirements [ICC, 2018]

[F] TABLE 412.3.6
HANGAR FIRE SUPPRESSION REQUIREMENTS^{a, b, c}

MAXIMUM SINGLE FIRE AREA (square feet)	TYPE OF CONSTRUCTION								
	IA	IB	IIA	IIB	IIIA	IIIB	IV	VA	VB
≥ 40,001	Group I	Group I	Group I	Group I	Group I	Group I	Group I	Group I	Group I
40,000	Group II	Group II	Group II	Group II	Group II	Group II	Group II	Group II	Group II
30,000	Group III	Group II	Group II	Group II	Group II	Group II	Group II	Group II	Group II
20,000	Group III	Group III	Group II	Group II	Group II	Group II	Group II	Group II	Group II
15,000	Group III	Group III	Group III	Group II	Group III	Group II	Group III	Group II	Group II
12,000	Group III	Group III	Group III	Group III	Group III	Group III	Group III	Group II	Group II
8,000	Group III	Group III	Group III	Group III	Group III	Group III	Group III	Group III	Group II
5,000	Group III	Group III	Group III	Group III	Group III	Group III	Group III	Group III	Group III

For SI: 1 foot = 304.8 mm, 1 square foot = 0.0929 m².

a. Aircraft hangars with a door height greater than 28 feet shall be provided with fire suppression for a Group I hangar regardless of maximum fire area.

b. Groups shall be as classified in accordance with NFPA 409.

c. Membrane structures complying with Section 3102 shall be classified as a Group IV hangar.

There is one exception in the IBC to Section 412.3.6. That exception states that “where a fixed base operator has separate repair facilities on site, Group II hangars operated by a fixed base operator used for storage of transient aircraft only shall have a fire suppression system, but the system is exempt from foam requirements. There are two key components to this exception: 1) the fixed based operator (FBO) shall have a separate hangar for all repair operations, and 2) the hangar shall be used for storage of transient aircraft only. If these two exceptions are met for a Group II hangar housing/storing only transient aircraft the hangar only needs sprinkler at the ceiling and a low-level foam system is not required as referenced in the 2016 edition of NFPA 409.

IBC, Section 412.3.6.1 requires Group III hangars which contain or perform hazardous operations, such as doping, hot work, fuel transfer, fuel tank repair or maintenance, spray finishing, a total fuel capacity of all aircraft within the unsprinklered single fire area in excess of 6,057 liters (1,600 gallons), or total fuel capacity of all aircraft within the maximum single fire area in excess of 28,391 liters (7,500 gallons) for a hangar with an automatic sprinkler system, to be provided with fire suppression systems as required for Group I and II hangars.

Aircraft paint hangars have specific fire safety features required as outlined in Section 412.5 of the IBC. The fire suppression requirements for paint hangars shall be as required by NFPA 409.

The IBC clearly references NFPA 409 for the fire suppression requirements for aircraft hangars. The IBC, not the *International Fire Code*, does not attempt to drive any of the specific fire suppression criteria.

2.6 Summary

The suppression system requirements included in the four documents (NFPA 409, NAS 3306, FM 7-93 and UFC 4-211-01) are summarized in Tables 2-6, Table 2-7, Table 2-7 and Table 2-9.

Table 2 - 6: Fire Suppression System Options in Group I Hangars (Fueled Aircraft)

Fire Suppression Options	NFPA 409 NAS 3306	FM 7-93	UFC 4- 211-01
Foam-water deluge system	* ^a		
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam system	*		
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with floor nozzles		*	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with monitor nozzles		*	
Combination of automatic sprinkler protection and automatic, high-expansion foam system	*	*	* ^b
Combination of automatic sprinkler protection and an ignitable liquid drainage floor assembly	* ^d		
For ceiling heights up to 18 m (60 ft), with supplementary low-level, low-expansion foam protection under shielded areas		*	
Overhead wet pipe, dry pipe or preaction sprinkler system with temperature monitoring with low level trench nozzle system			* ^c

^a Where the wing area exceeds 279 m², (3,000 ft²) supplementary protection is required because of concerns of shielding of the fire that may be provided aircraft wings.

^b Air Force

^c Navy

^d NFPA 409 [2022a]

Table 2 - 7: Fire Suppression System Options in Group II Hangars (Fueled Aircraft)

Fire Suppression Options	NFPA 409 NAS 3306	FM 7-93	UFC 4- 211-01
Foam-water deluge system	*	*	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam system	*		
Closed-head foam-water system	*		
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with floor nozzles		*	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with monitor nozzles		*	
Combination of automatic sprinkler protection and automatic, high-expansion foam system	*	*	* ^a
Combination of automatic sprinkler protection and an ignitable liquid drainage floor assembly	* ^c		
Wet low-expansion foam water at ceiling only		*	
Overhead wet pipe, dry pipe or preaction sprinkler system with temperature monitoring with low level trench nozzle system			* ^b

^a Air Force

^b Navy

^c NFPA 409 [2022a]

Table 2 - 8: Fire Suppression System Options in Group III Hangars (Fueled Aircraft)

Fire Suppression Options	NFPA 409 NAS 3306	FM 7-93	UFC 4- 211-01
Foam-water deluge system	* ^a	*	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with floor nozzles	* ^a	*	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with monitor nozzles	* ^a	*	
Combination of automatic sprinkler protection and automatic, high-expansion foam system	* ^a	*	
Combination of automatic sprinkler protection and an ignitable liquid drainage floor assembly	* ^a		
Wet low-expansion foam water at ceiling only		*	
Overhead wet pipe sprinkler system with temperature monitoring			* ^b
Overhead dry pipe sprinkler system with external automatic control valve			* ^b
Overhead preaction sprinkler system with single interlock automatic control valve			* ^b
High-expansion foam system			* ^c

^a Only required if hazardous operations occur in the hangar.

^b Hydraulically designed to provide 11 Lpm/m² (0.3 gpm/ft²) over the most demanding 279 m² (3,000 ft²) area

^c Not required

Note (NFPA 409); If a Group III hangar contains unfueled aircraft, but hazardous operations occur in the hangar such as those identified in section 8.8.1.2, the fire suppression system options are the same as those for Group II hangars.

Note (NAS 3306): EXCEPTION - In Group III hangars that house unfueled aircraft, NAS 3306 requires protection by an automatic sprinkler system designed for Extra Hazard Group 1 as outlined in NFPA 13.

Table 2 - 9: Fire Suppression System Options in Group IV Hangars (Fueled Aircraft)

Fire Suppression Options	NFPA 409 NAS 3306	FM 7-93	UFC 4- 211-01
Foam-water deluge system		*	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with floor nozzles		*	
Combination of automatic sprinkler protection and automatic, low-level, low-expansion foam with monitor nozzles		*	
Combination of automatic sprinkler protection and automatic, high-expansion foam system		*	
Wet low-expansion foam water at ceiling only		*	
Overhead wet pipe sprinkler system with temperature monitoring	* ^a		*
Overhead dry pipe sprinkler system with external automatic control valve	* ^a		*
Overhead preaction sprinkler system with single interlock automatic control valve			*
Low level trench nozzle system			*
High-expansion foam system	* ^a		*
Low level low-expansion foam system	* ^a		
Ignitable Liquid Drainage Floor Assembly	* ^a		

^a (NFPA 409) [NFPA 2022a]: Group IV hangars require a fire suppressions system only if the fire area is 1,115 m² (12,000 ft²) or greater.

Note (NAS 3306): EXCEPTION - In Group IV hangars which have a fire area which is less than 1,115 m² (12,000 ft²) that contain more than one aircraft, a sprinkler system (either wet pipe or single-interlock preaction) is required (i.e., the same requirement as for Group IV hangars with a fire area in excess of 1,115 m² (12,000 ft²)).

Note [2022a]: EXCEPTION – In Group IV hangars with a fire area in excess of 1,115 m² (12,000 ft²), with hazardous operations, automatic sprinkler system per NFPA 13 is required per NFPA 409.

Note [2022a]: EXCEPTION – In Group IV hangars with a fire area in excess of 1,115 m² (12,000 ft²) and no hazardous operations are being performed, no fire protection system is required by NFPA 409.

3. Statistics of Fuel Spills and Incidents with Foam Discharges

3.1 NFIRS Data

An analysis of the National Fire Incident Reporting System (NFIRS) data from the years 2009 through 2018 was conducted. Unfortunately, there is no property use code in NFIRS to identify the occupancy type associated with for aircraft hangars. As a result, an alternative approach was needed to identify fire incidents that occurred in hangars.

First, this data was sorted for incidents occurring in the occupancy code “Vehicle Storage, Other” (880), including airplane and boat hangars and excluding parking garages. In order to narrow this field down to incidents occurring only in aircraft hangars, a second sort was conducted for incidents involving an aircraft. This second parameter was utilized to distinguish between parking garages and hangars. A consequence of the use of the second parameter is that any fire in a hangar that did not involve an aircraft would not have been identified by this scan.

In the ten years examined, only fourteen incidents occurred under the circumstances outlined above. The year in which these incidents occurred is presented in Figure 3-1. However, there was no available data for these incidents on whether an automatic extinguishing system (AES) was present, what type of AES was installed, and if the AES operated, so no further analysis could be done relative to the performance of installed fire suppression systems.

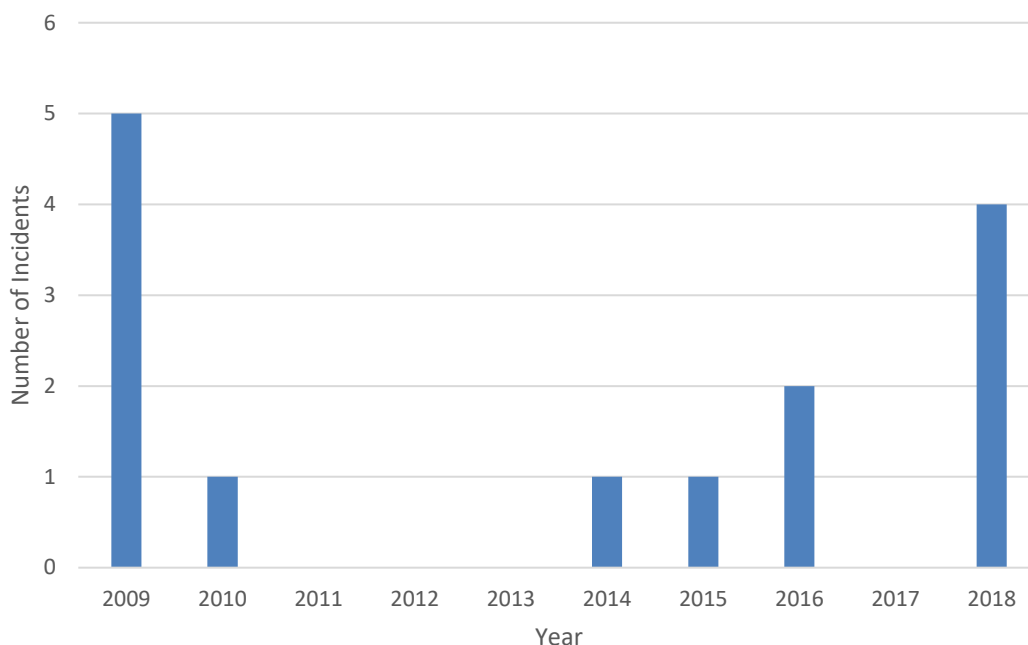


Figure 3-1: Fire Incidents in Parking Facilities that Included an Aircraft

3.2 U.S. Coast Guard Data

The United States Coast Guard (USCG) collects data on all hazardous liquid spills, including fuel spills, in the U.S. USCG data from January 2016 to December 2020 was reviewed to assess the frequency and location of fuel spills in hangars (as compared to all other locations) (USCG, 2020). The distribution of the cause of the fuel spill by year is presented in Table 3-1 and Figure

3-1. Of the 862 incidents observed during almost five full years, only 25 spills have been found to have occurred inside a hangar, resulting in an annual rate of approximately 5 incidents per year. The 25 fuel spills in hangars represents 2.9% of the total number of fuel spills. The USCG database does not identify if any fires occurred in any of the incidents involving fuel spills.

Table 3-1: Causes and Frequency of Jet Fuel Spills in 2016-2020 (USCG 2020)

Circumstance	Year					
	2016	2017	2018	2019	2020	Total
Spills Not in Hangars						
Fuel Island or Fuel Truck	24	32	52	25	31	164
Equipment Failure	77	32	50	41	24	224
Unknown (Outdoors)	50	32	31	24	23	160
Aircraft Crash	17	10	10	23	18	78
Refinery or Pipeline	3	16	20	14	13	66
Operator Error	26	22	28	31	13	120
Intentional/Improper Disposal	6	6	6	1	6	25
Total Spills not in Hangars	203	150	197	159	128	837
Spills in Hangars	3	2	4	8	8	25
Total Spills	206	152	201	167	136	862

As indicated in Table 3-1 and Figure 3-2 the leading cause of all 862 jet fuel spills in the U.S. over the last 5 years is equipment failure. The term “equipment failure” refers to a variety of events such as leakage from oil tanks, aircraft fuel tank malfunction, and failure of internal fueling lines.

The descriptions of the five incidents of fuel spills which occurred in hangars are:

- 23 of the incidents occurred when maintenance was being conducted
- 1 incident occurred when an aircraft valve was opened (the reason for the valve being opened was not reported)
- 1 incident occurred when the fuel valve was rotated (the reason for the valve being rotated was not reported)

The next most frequent causes of spills not inside of hangars are those caused by activities at a fuel island or fuel truck and then operator error. It is also noteworthy that 18.6% of incidents have an unknown cause.

Of the fuel spills inside of hangars, 92% were caused during maintenance activities and the remaining 8% were caused when a valve was accidentally opened. According to the data received, there was no indication that a fire occurred as a result of the fuel spill, nor was the foam system activated.

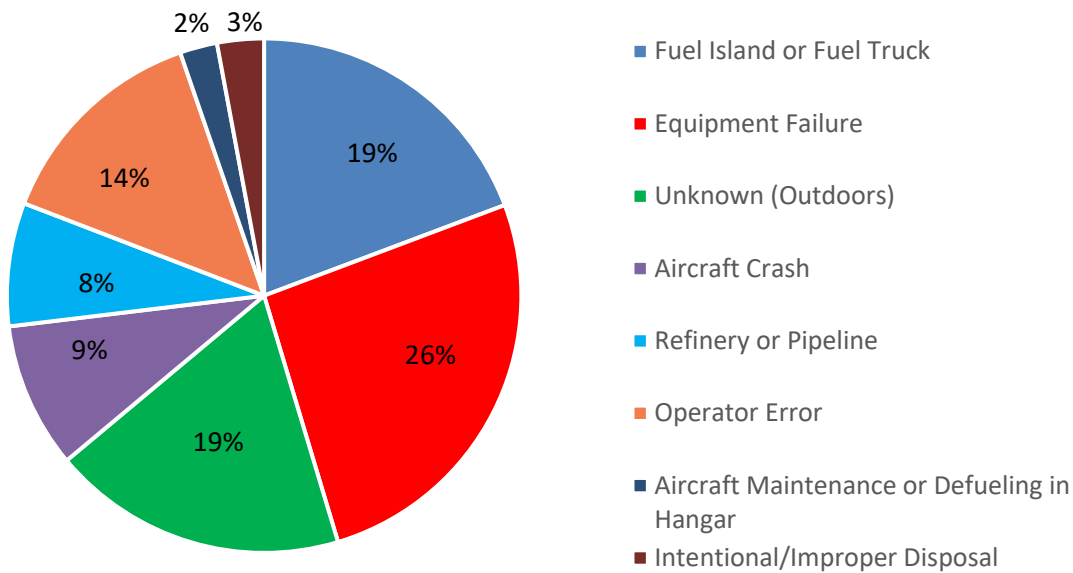


Figure 3-2: Cause of Jet Fuel Spills in 2016-2020 (USCG, 2020)

3.3 UMD Surveys

Reviewing the history of fire incidents in hangars is needed as a foundation to conducting a risk analysis. The research team has been involved in two recent studies [Milke et al., 2019][Milke et al, 2021] to document cases with foam system discharges. With NFIRS not yielding any significant results, an alternative strategy to understand the nature of fire incidents in aircraft hangars can be to use information from the performance of fire protection systems in hangars. With foam systems being the predominant form of protection in aircraft hangars for the last 30 years, results from recent surveys of incidents involving foam system discharges are presented in this report.

The research team requested incident reports of discharges of foam fire suppression systems from several insurance companies who provide coverage for either the aircraft and/or aircraft hangar, fixed based operators (FBOs), commercial airlines and the Department of Defense. A form to facilitate data reporting, The Data Collection Form, Foam Suppression System Discharge Analysis, developed by the University of Maryland (UMD), was provided to each of the participating organizations. The data form is included in Appendix A. A second survey was distributed by the Fire Protection Research Foundation to seek additional information. While similar to the form used by UMD, the FPRF form is included in Appendix B. Some incidents were also obtained directly by the research team. Damage estimates for aircraft and the building/building systems were requested in the form, along with cause of the discharge and cause of the fire.

As a result of these requests, 432 incident reports of foam fire suppression system discharges were provided to the research team. The causes of the actuation are summarized as follows:

44 incidents (10.2% of the total) involved a foam system discharge in response to a fire.
 357 incidents (82.6% of the total) involved a foam system discharge with no fire being present.
 31 incidents (7.2% of the total) involved a foam system discharge due to an unknown cause.

A second survey, the “Hangar Foam Fire Suppression Survey,” was distributed to the members of the National Air Transportation Association (NATA). The 72 respondents that completed the survey operated 118 aircraft hangars, 26 which have foam systems installed. One respondent had a fire (pooled fuel), though the foam system did not discharge. 9 respondents reported they had experienced inadvertent discharges. This second survey will be discussed in section 3.4.

Reviewing the dates of the incidents included in the Department of Defense (DoD) database, incidents appear to be reported sporadically from the 1960’s until 2004. In 2004 to 2021, there are more regular entries of foam discharges in hangars suggesting that more attention was being given to entering any incident involving a foam discharge or the information on incidents was more readily retrieved from the DoD database or records kept by insurance companies, FBOs and commercial airlines. As such, the remainder of the analysis in this report will focus on the 386 foam discharge incidents with a confirmed cause (fire versus no fire being present) that occurred within the 17-year period of 2004 to 2021.

An additional 17 incidents were reported via the FPRF survey (the operator of the hangar was not included in the FPRF survey). The incidents reported via this survey occurred in 2017 to 2021. Of the 17 responses, one of the responses indicated that the suppression system activated as a result of a fire. That fire involved a gas-powered forklift vehicle. In these incidents, there were a total of four injuries in two of the incidents (it is unclear where either of these incidents involved a fire).

A summary of the incident reports of foam system discharges from 2004 to 2021 is included in Table 3-2.

Table 3-2: Summary of All Incidents Obtained in UMD, 2004-2021

	UMD			Total
	FBO	DoD	Commercial	
Discharge due to fire	36	4	4	44
Accidental discharge	113	203	41	357
Unknown cause	0	31	0	31
Total	149	238	45	432

The distribution of the accidental discharges and discharges in response to fire for both surveys is presented in Figure 3-3. While the annual number of responses due to fire is relatively steady, the annual increase in the accidental discharges from 2009-2015 is noteworthy, the number of incidents per year has been decreasing since 2015. The annual average number of accidental discharges with a known cause from 2004 to 2021 is 21 discharges per year, while there were 2.6 foam system discharges in response to fire per year. The ratio of accidental discharges to those in response to a fire is approximately 8 to 1.

A distribution of the year in which incidents involving accidental discharges occurred by the operator of the hangar is included in Figure 3-3. The trend line provided in the figure indicate a steady annual rate of fire incidents n increasing frequency of these incidents in hangars operated by DoD, commercial airlines and FBOs, with the greatest slope being for the DoD hangars.

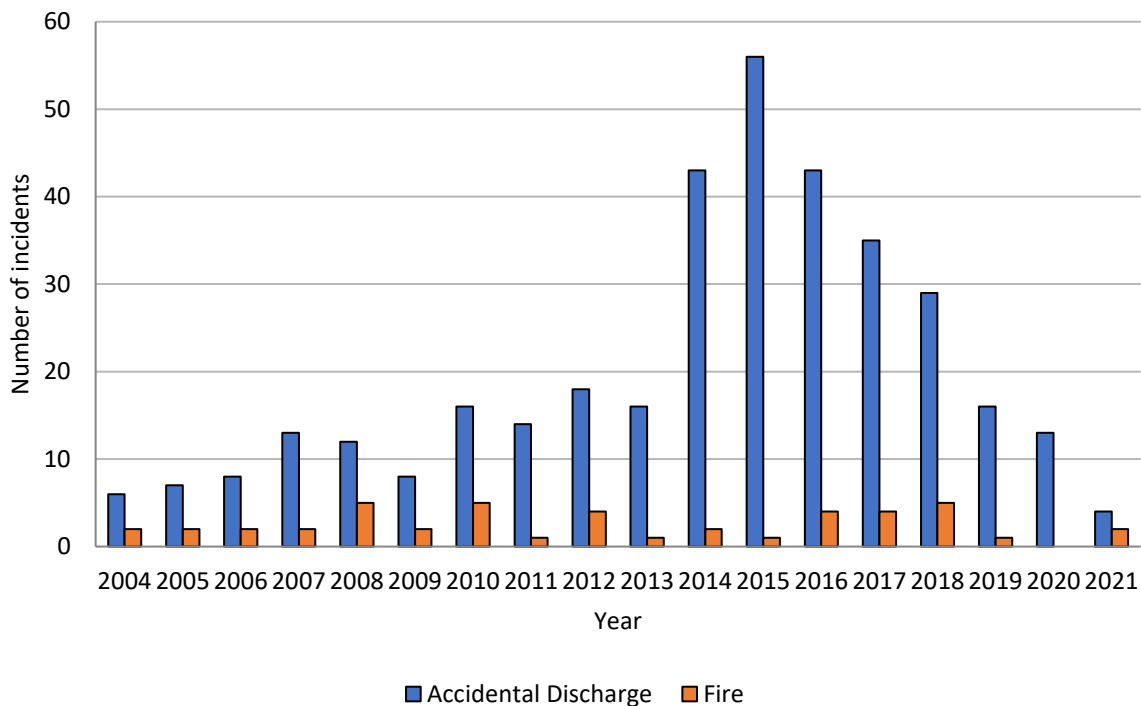


Figure 3-3: Annual Number of Foam Discharges

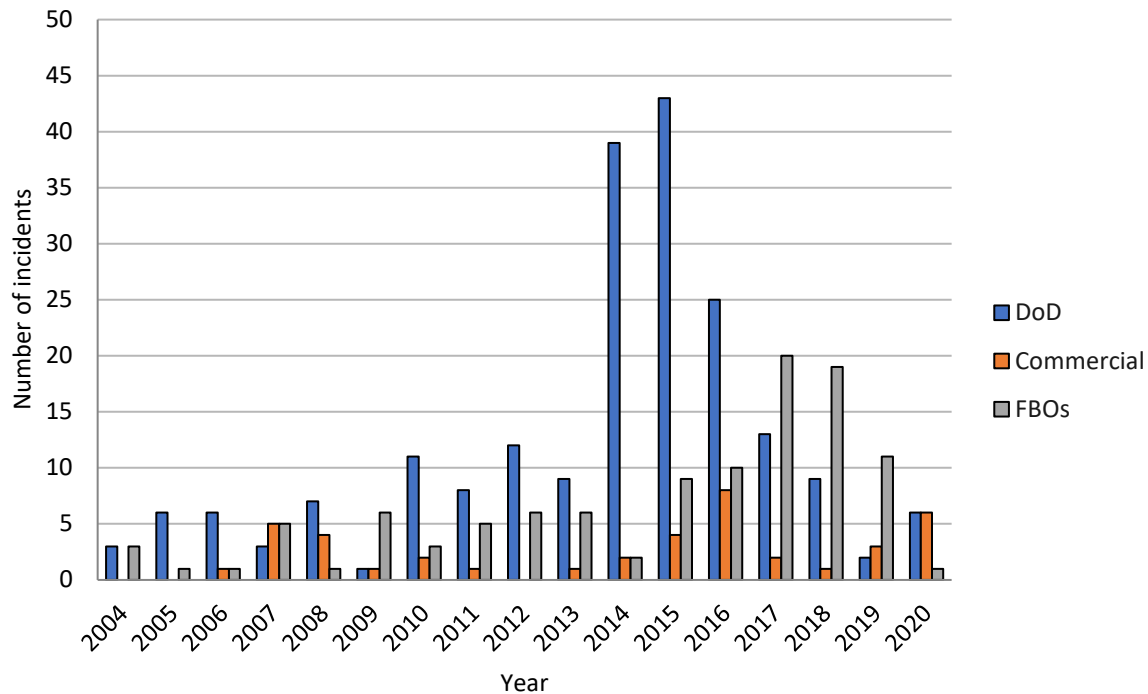


Figure 3-4: Annual Number of Accidental Foam Discharges

The UMD survey collected losses associated with the incidents involving a foam discharge included fatalities, injuries and damage to the building and aircraft. The survey did not acquire data on business interruption, clean-up costs or environmental damage.

There a total of 38 casualties in incidents involving foam discharges over the 17-year period. Six of these casualties were fatal. Of the six fatalities, four of these were in a foam discharge in response to a fire. Half of the non-fatal casualties (16 of 32) were in incidents involving accidental foam discharges, The annual distribution of the casualties is presented in Figure 3-5.

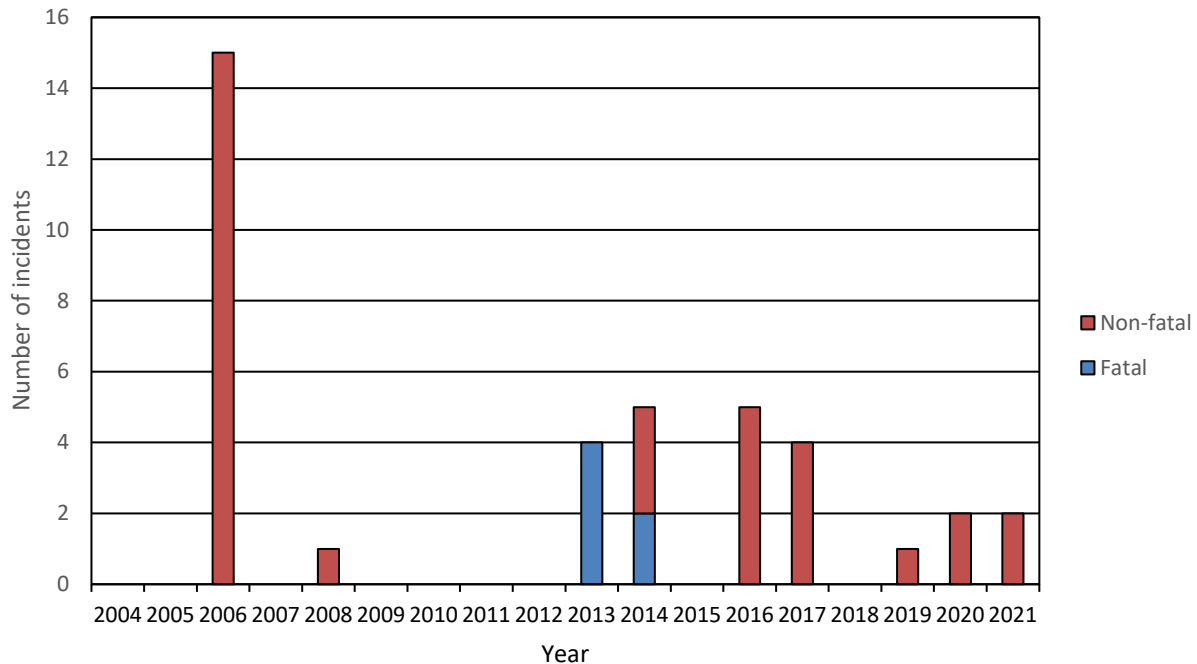


Figure 3-5: Casualties in Incidents involving Foam System Discharges

Of the incidents reported via the surveys, reports from only 209 of the incidents included a monetary damage value. In the initial survey of incidents at hangars managed by FBOs, the damage estimates presented were provided either for damage to the aircraft or damage to the building. In only a limited number of cases was damage reported to both aircraft and building. Therefore, the total cost is expected to be much greater than the presented damage value in this report, given that only a portion of the incurred damage was reported and neither clean-up nor environmental impact were included.

Results of an analysis of the trend in annual total damage (in US \$) from accidental foam discharges is provided in Figure 3-6. The distribution of the cost incurred in each incident with reported damage costs is included in Figure 3-7. The increment with the greatest number of incidents is the 0-0.25-million-dollar category with 137 incidents. The total of all damage estimates for incidents with accidental foam discharges is approximately \$120M, for an average loss of \$336K per incident.

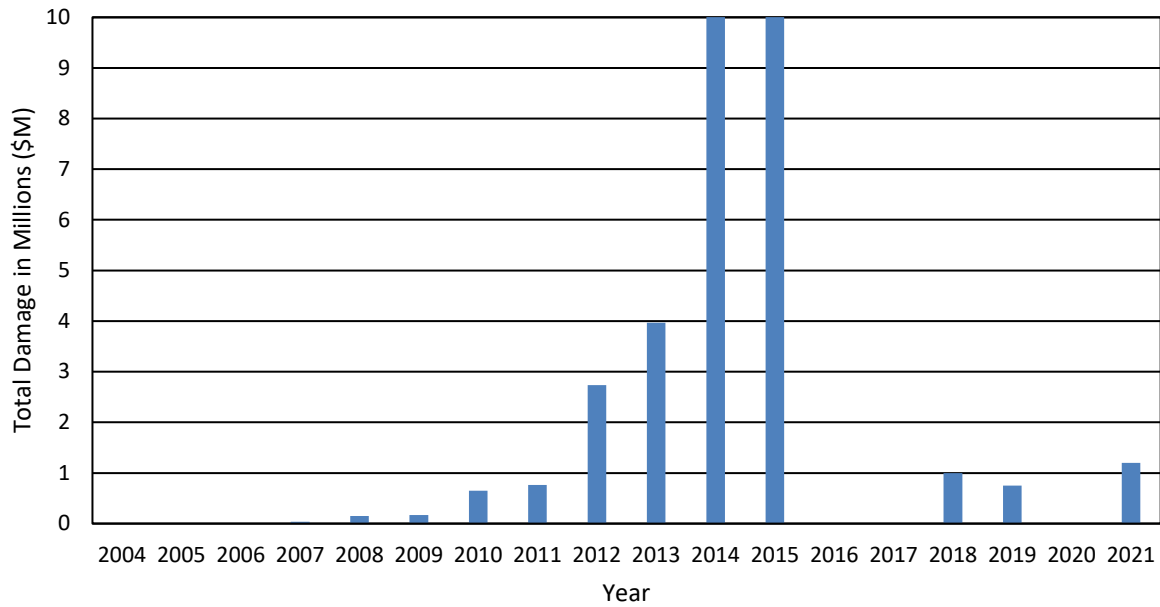


Figure 3-6: Annual Damage Loss in Accidental Discharges (total in 2014 was \$32.3M, in 2015 was 76.6M)

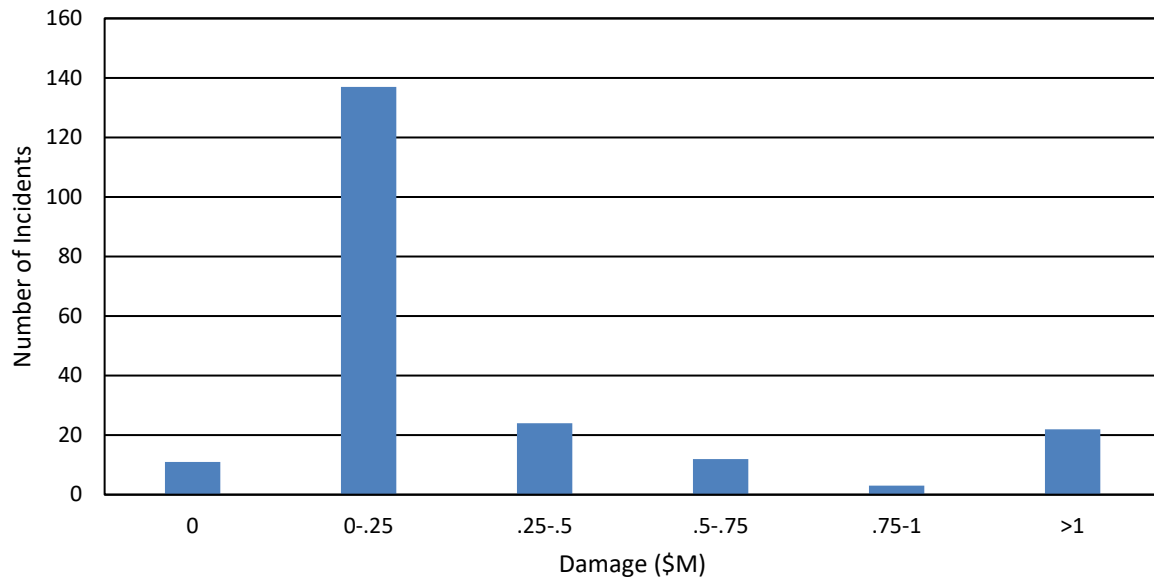


Figure 3-7: Distribution of Damage Costs in Accidental Discharges

The causes of the accidental discharges are presented in Figure 3-8. The most common cause of the accidental discharges, comprising half of all of the incidents, was a failure of the suppression system.

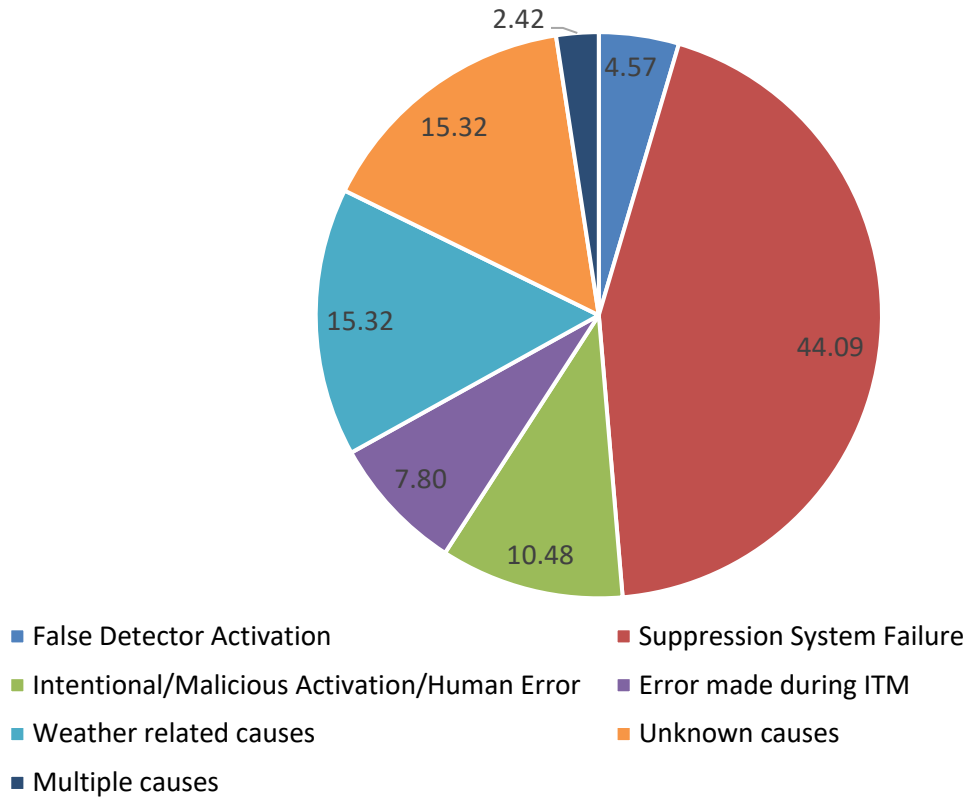


Figure 3-8: Causes of Accidental Foam Discharges

3.4 NATA Survey

For the survey conducted by the National Air Transportation Association (NATA) of its members, they received 72 survey responses. In that survey, a series of questions were asked about the presence of fire suppression systems in hangars and whether such systems had ever discharged, then asked for damage estimates from any such incidents. Out of the 72 responses, foam systems were reported to have discharged on 14 occasions, two of which were in response to a fire. In one of the two fires, the fire involved a pooled fuel spill.

The activities inside hangars reported in the NATA survey are indicated in Figure 3-9. Three of the activities in the figure including fueling and some maintenance, repair and overhaul activities would result in the respective hangars being labelled hazardous operations hangars.¹ The type of suppression system installed in the hangars is indicated in Figure 3-10. While automatic sprinklers are included in almost half of the hangars, approximately 25% of the hangars include some form of foam system, either alone or in combination with sprinklers.

¹ Hazardous operations hangars are considered to include activities such as doping, hot work, such as welding, torch cutting and torch soldering, fuel transfer, fuel tank repair or maintenance not including unfueled tanks, inerted tanks or tanks that have never been fueled and spray finishing operations.² The Secretary referred to in the act is the Secretary of Defense.

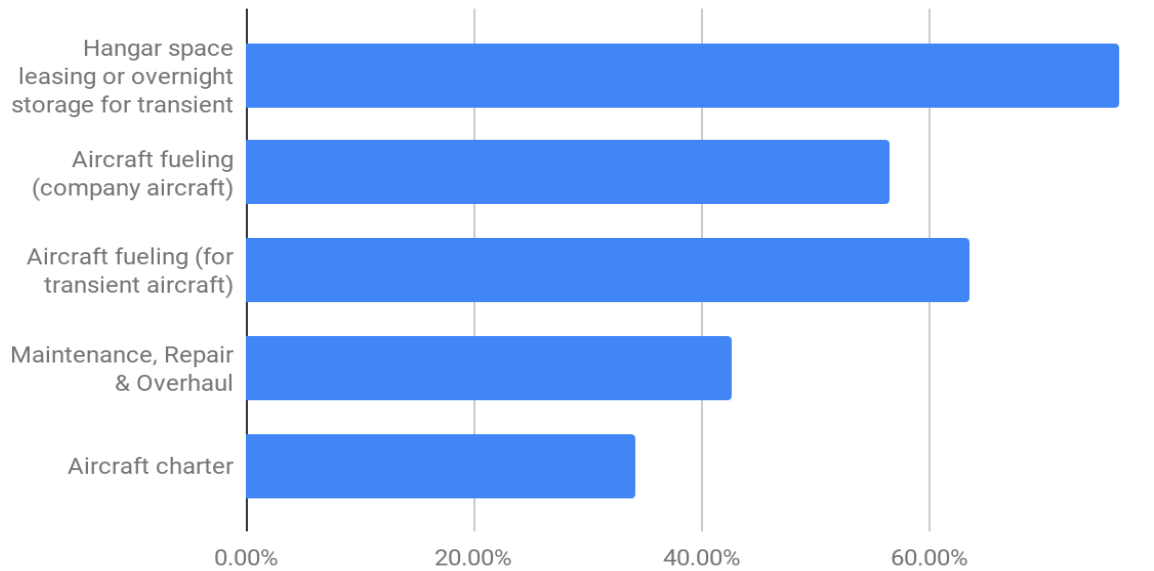


Figure 3-9: Services Provided in Hangars

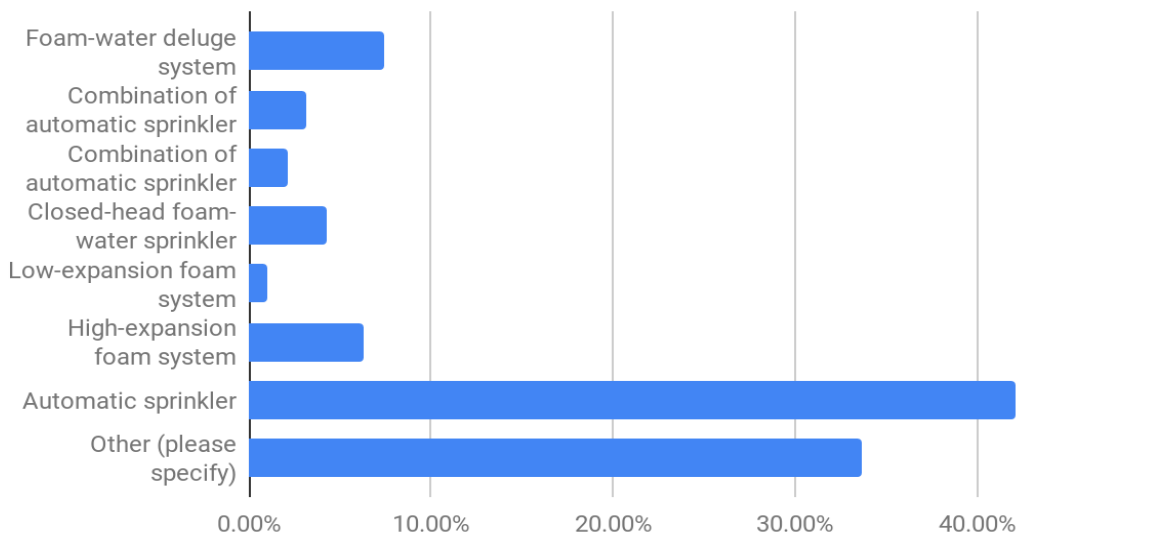


Figure 3-10: Type of Suppression System in Hangar³

The estimated costs of clean-up and damage of aircraft in foam system discharges in accidental foam discharges according to the NATA survey are presented in Figure 3-11 and 3-12. The number of responses varies for these incidents because some respondents either entered “not applicable” or did not answer. As with the University of Maryland survey, the reported damage level to aircraft was \$10M in one incident.

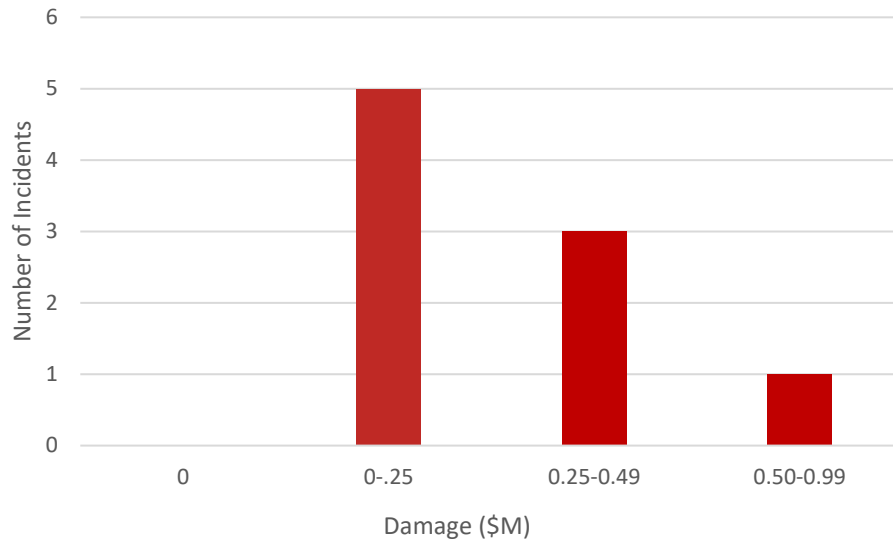


Figure 3-11: Cost of Clean-up for Accidental Foam Discharge (total: 9 incidents)

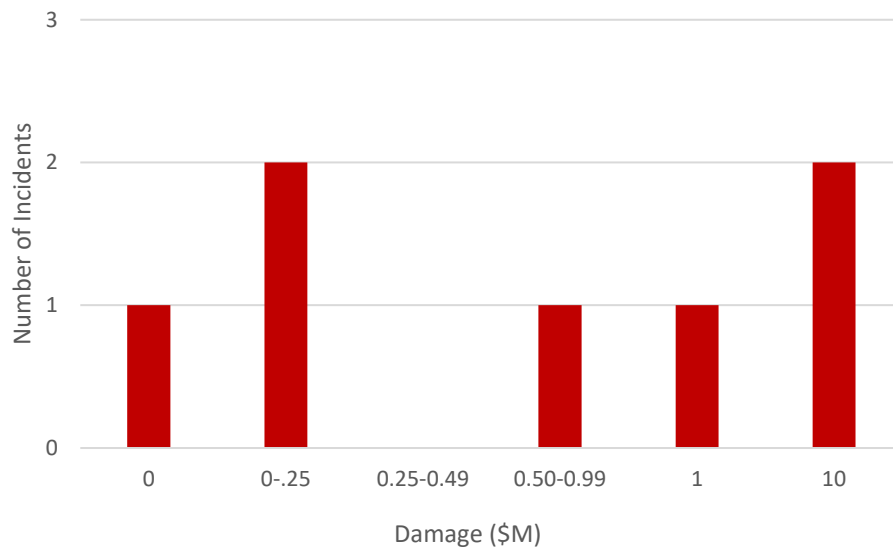


Figure 3-12: Cost of Damage to Aircraft for Accidental Foam Discharge (total: 7 incidents)

4. Fire Protection Alternatives

4.1 Detection

Fire detection equipment is provided in aircraft hangars principally to actuate fire suppression systems. Spot-type heat detectors, linear heat detectors and radiation detectors are the principal types of initiating devices that have been included in hangars.

The performance of spot-type heat detectors was assessed in the research NIST [Gott, et al., 1997]. In that experimental program, the research indicated that the response times for ceiling mounted spot-type heat detectors were relatively similar for spacings up to 12.2 m (40 ft). In that research, rate-compensated detectors with a temperature rating of 79°C (175°F) were shown to be the most effective. A limitation of spot-type heat detectors involves applications where environmental temperature extremes are expected. In such cases, linear heat detection is preferable being reliable over the broad temperature range that may be experienced in a hangar. Linear heat detection may use thermistor technology or use a heat-sensitive polymeric insulation over conductors. There are at least three manufacturers of linear heat detectors and numerous manufacturers of spot-type heat detectors.

The performance of any thermal detector will be influenced by airflows in the hangar, especially if the doors are open on a windy day or the discharge from the Auxiliary Power Unit (APU) of an aircraft. Further, in tall hangars, in the early stages of a fire, the temperature of the smoke layer may be relatively modest (and not sufficient to activate a thermal detector). Also, if the hangar is not drafty, the solar load on the roof of the hangar may heat the air in the upper portion of the hangar which may also cause a delay in the smoke reaching the ceiling (and hence delay the response of thermal detectors).

An alternative to thermal detection is radiation (i.e., flame) detectors. Flame detector technologies have the ability to sense radiation in specific wavelengths, e.g., ultraviolet (UV), infrared (IR), combined ultraviolet and infrared (UV/IR), and multi-spectrum infrared (triple IR). Single band UV or IR detection is not popular in this application due to accidental activations from sunlight, welding, lightning, and artificial lights. In the research by NIST, the response of the combination ultraviolet/infrared detectors provided reasonable response times for fires involved JP-5 and JP-8. [Gott et al., 1997]. The preferred technology is a multi-spectrum IR or triple IR. Three manufacturers provide detectors using this technology.

4.2 Suppression Systems

AFFF has been commonly used in aircraft hangars since the 1960s. In the 1984 Report on Proposals for NFPA 409, the Technical Committee justified requiring foam systems in hangars to provide an effective fire suppression system to meet the challenges posed by fires involving fuel spills. However, the environmental and health hazards posed by per- and polyfluoroalkyl chemicals (PFAS) in AFFF has driven exploration and development of new foam formulations and delivery techniques. In addition, January 3, 2020, Congress passed the William M. (Mac) Thornberry National Defense Authorization Act for Fiscal Year 2021 (NDAA). As part of the NDAA, a phase out of AFFF use by October 2024 by US DoD agencies was required. In response to the NDAA, the Navy no longer includes AFFF in new projects.

Also, Congress requested that a survey be conducted of technologies for Department of Defense application in phasing out the use of fluorinated aqueous film-forming foam” [NDAA, 2020]. The scope of the survey included in the bill are:

“The technologies surveyed under this subsection shall include hangar flooring systems, fire-fighting agent delivery systems, containment systems, and other relevant technologies the Secretary determines appropriate.”²

With concerns about the environmental consequences of discharges of foams containing PFAS chemicals, alternatives to using foam in aircraft hangars (among other installations) has been a topic of recent research [Back and Farley, 2020]. Alternatives being researched include:

- New foam formulations, including fluorine free foams and compressed air foam
- water sprinklers
- water mist
- ignitable liquid drainage (ILD) floor assembly
- clean agents
- wetting and encapsulating agents

Being considered to be used in combination with several of the above alternatives is a grid of floor trenches such as are already in Section 7-11 of the United Facilities Criteria [DoD, 2017]. The trenches have the ability to limit the area covered by a spill and also serve for containment purposes.

4.2.1 New Foam Formulations

In the 2021 version of NFPA 11, Synthetic Fluorine-Free Foams (SFFF) are defined as a foam concentrate based on a mixture of hydrocarbon surface active agents that is not formulated to contain PFAS [NFPA 2021a]. The fluorine free foams (FFFs) mentioned in this report will be referred to as FFFs and are also within the SFFF category. This distinction should be made is important to indicate that not all fluorine containing foams are problematic. The principal environmental concerns are with the fluorinated surfactants with carbon-fluorine bonds.

Numerous studies have recently been conducted and have reported varying success with FFFs, with some studies ongoing [Chauhan, 2022] [Chauhan, 2020] [Rangan, 2019][DoD, 2020]. This research has not included experimental designs that have been associated with a particular application (hangar vs. exterior scenarios).

The majority of these studies demonstrate that some FFFs can perform well with proper testing and design but are not “drop in” replacements for AFFF. There are currently a small number of FFF alternatives available that require equipment to be replaced. The previous studies have indicated that the performance of a FFF varies not only with the type of foam but also the type of fuel the foam is applied to. This makes generalizations of the performance of FFF difficult.

² The Secretary referred to in the act is the Secretary of Defense.

The DoD's Environmental Security Technology Certification Program (ESTCP) funded a project led by Chauhan that tested six commercially available FFFs against the DoD's military specification (Mil-Spec) for AFFF, MIL-F-24385F [Chauhan, 2020] [Chauhan, 2022].³ While none of the FFFs met the required extinguishment time of 30 seconds, most met the required burn back time of 360 seconds. Moreover, the foams tested had a higher aquatic toxicity and were less biodegradable than AFFF, falling short of the Mil-Spec requirements. Also, this study highlighted that FFFs tend to be more viscous, thereby posing challenges related to equipment compatibility and ease of use. Although none of the FFFs tested met the Mil-Spec, revisions to the Mil-Spec are ongoing. Proposed revisions include an improved ability to demonstrate the performance of FFFs under actual operating conditions and altering the requirement that any foam agent include a fluorosurfactant.

Back and Farley conducted a comprehensive study that included tests of eleven FFFs and three fluorine free wetting agents using real scale and approval scale fire tests [Back, 2019]. Under the approval scale tests, AFFF performed the best, followed by the FFFs, and then the wetting agents as shown in Table 4-1. The tests demonstrated that the FFFs, when applied at their optimal application rate, performed well despite taking about 1.5 times longer than AFFF. Similarly, in the real scale tests the FFFs took about 1.5 to 2 times longer than AFFF to achieve extinguishment (Table 4-2). The increased application rate and increased duration of application results in more foam being required to extinguish the fire.

Table 4-1: Approval scale test results [Back, 2019]

Foam/ Agent	Agent Type	Gasoline		Jet A	
		2 gpm (.07 gpm/ft ²)	3 gpm (.11 gpm/ft ²)	2 gpm (.07 gpm/ft ²)	3 gpm (.11 gpm/ft ²)
		Ext (sec)	Ext (sec)	Ext (sec)	Ext (sec)
AFFF	AFFF	30	24	16	12
FFF1	Foam	49-58	37-52	19-33	15-22
FFF2	Foam				
FFF3	Foam				
FFF4	Foam				
FFF5	Foam	77-82	55-67	22-27	15-21
FFF6	Foam				
FFF7	Foam				
FFF8	Foam	126-No	71-No	22-No	16 -114
FFF9	Foam				
FFF10	Foam				
FFF11	Foam	No	104-124	29-32	20-27
WA1	Wetting				
WA2	Wetting				
WA3	Wetting	No	No	No	95

Good

OK

Not so good

SERDP & ESTCP Webinar Series (#121)

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The differences in extinguishment times between the nozzles is noteworthy because this demonstrates the dependency of FFFs on the characteristics of the foam blanket produced and the associated discharge devices. When the foam tube was utilized, extinguishment times were reduced by 30 to 45%. This study produced promising results for current, commercially available

³ The ESTCP has provided a series of webinars on the development of alternatives to PFAS containing foam agents.

FFF when applied within listed parameters and hardware and suggests that FFFs need to be listed for application for specific fuels (gasoline, Jet A, etc.) [Back and Farley, 2020].

Table 4-2: Real scale test results [Back, 2019]

Foam/Agent	Fuel	STD Nozzle (.07 gpm/ft ²)		Foam Tube (.07 gpm/ft ²)	
		Cont (sec)	Ext (sec)	Cont (sec)	Ext (sec)
AFFF	Jet A	25	45	15	25
FFF1-5 (AVG)	Jet A	45	58	25	44
WA3	Jet A	60	No	60	102
AFFF	gasoline	30	50	30	45
FFF1-5 (AVG)	gasoline	100	135	60	105

Alternatives to the fluorocarbon surfactants in AFFF have been developed in new foam formulations. These foams include hydrocarbon and silicone surfactants that don't form a film on the fuel similar to that provided by AFFF [Sheng, et al. 2020]. However, other surfactants are under development that may be able to operate with the same mechanisms as AFFF. Under the DoD's Strategic Environmental Research and Development Program (SERDP), Materials Modification Inc. designed and tested new siloxane formulations for their suitability as film-forming ingredients in AFFF [Rangan, 2019]. The siloxane surfactants successfully formed a water film on top of the fuel and required 59 seconds to extinguish a 28 ft² heptane pool fire compared to AFFF which took 31 seconds. The study demonstrated the potential for siloxane and other surfactants to be drop-in replacements for AFFF with further optimization of additive formulations.

Because most FFFs operate by employing a foam blanket, the technique of creating and applying the foam directly affects FFF performance. Application of foam can be manipulated with nozzles like a foam tube, compressed air foam (CAF), ultra-high pressure (UHP), and functional additives that could improve FFF performance.

The Mil-Spec nozzle is an air aspirating nozzle where foam is created by drawing air in via a Venturi nozzle as depicted in Figure 4-1. In contrast, compressed air foam operates by injecting compressed air at 100-200 psi into the line upstream the nozzle, producing a foam with more uniform, micro bubbles than aspirated foam [Chauhan, 2020]. The foam tube discussed earlier creates foam with a consistency similar to shaving-cream [Back, 2019]. In Chauhan's research, the FFFs had an average reduction of 47% in extinguishment time and an average increase of 34% in burn back time when the CAF nozzle was used [Chauhan, 2020]. This demonstrates the possibility of using lower performance foams that may have been discarded from consideration by utilizing the CAF approach to improve their abilities. Similarly, UHP pressure systems have shown some initial promise in improving the performance of some FFFs [Chauhan, 2022]. However, the CAF systems have shown improved performance, especially relative to burnback resistance as compared to UHP systems. The use of additives is also being explored by Chauhan.

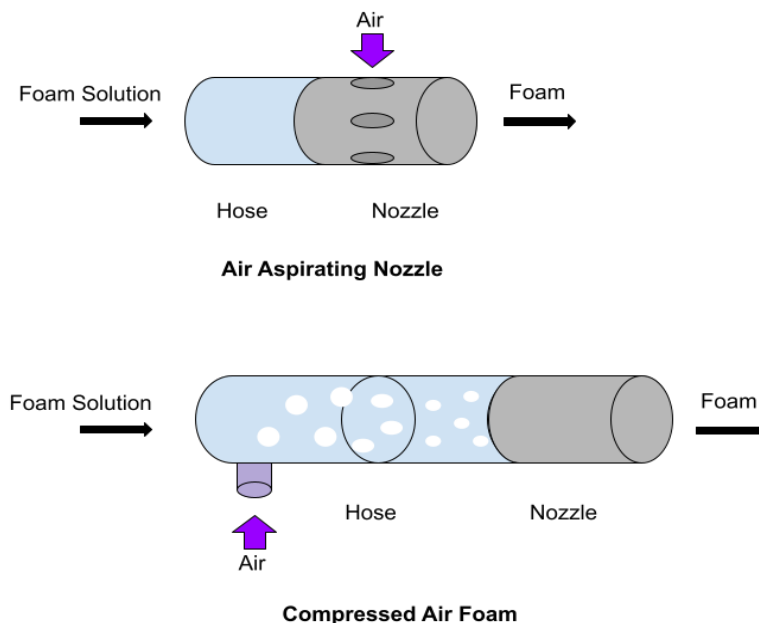


Figure 4-1: Air Aspirating vs CAF

There are several commercially available FFFs in the US today. These options meet the requirements included in UL 162 [1992], which is used to approve foam considering both the proportioning and discharge system together. Consequently, any listed foam agent would need to be implemented along with the system components included in the listing. UL 162 is currently in development to address shortfalls in performance criteria, but the currently UL listed foams can meet NFPA requirements. These foams have been slow to spread through industry in part because incident data that includes the use of these foams is sparse.

The current literature and selection of FFFs indicate that FFFs can produce comparable performance with AFFF if discharge devices and proportioning systems are implemented correctly. The US is in a transitional phase where research is being done to establish FFFs in the US and develop the criteria for the FFF performance. There is concern for the cost of replacing AFFF and associated equipment and a concern that new foam formulations could include ingredients that replace one legacy chemical with another. When evaluating FFF products, consideration of numerous factors including fire performance, equipment compatibility, ease of use, environmental impact, cost, and availability is necessary.

4.2.2 Sprinklers

As outlined in Section 1 of this report, sprinklers are already approved for many applications, such as for hangars with unfueled aircraft. Sprinklers are approved for some applications with fueled aircraft include foam systems supplementing the sprinkler system, apparently due to concerns for potential fires involving fuel spills. Given that fuel spill fires are highly uncommon and that virtually all of the fires involve ordinary combustibles, the use of sprinklers should receive greater consideration.

One limiting factor with sprinklers installed at ceiling level could be that many hangars also have high ceilings. An assessment of the response of closed-head sprinkler systems in aircraft hangars was examined by Gott, et al. [1997]. Four design parameters were investigated to determine their impact on the activation time in hangars with ceiling heights of 15 m (49 ft) and 22 m (72 ft): temperature setting, response time, link design, and dry vs wet installation. The results indicated that the temperature setting is the most important characteristic, followed by the RTI. The 79°C (175°F), quick response sprinklers were identified as the preferred sprinkler. There was no significant difference in response time between wet-pipe and dry-pipe systems for a variety of fire sizes, however any dry-pipe system will have an additional time delay delivering water from the dry-pipe valve.

The response time of the first sprinkler to activate as well as how many sprinklers will activate, is affected by fire size. In the 15 m (49 ft) hangar, no automatic sprinklers activated for fires smaller than 2.8 MW [Gott et al., 1997]. The smallest test fire to activate any automatic sprinkler was a 2.0 m (6.6 ft) diameter pan fire with a heat release rate of about 6 MW. The 141°C (286°F) sprinklers did not activate in any of the tests in the 15 m (49 ft) hangar. The smallest fire to activate automatic sprinklers in the 22 m (72 ft) hangar was 7.9 MW. The smallest fire to activate the 93°C (200°F) sprinklers was 13.3 MW and the smallest fire to activate the 141°C (286°F) sprinklers was 15.1 MW.

With draft curtains in place, more sprinklers operated with shorter response times. As a result of limiting heated smoke to the curtained area, increased response time were observed for sprinklers outside of the curtained area was increased. Without draft curtains, sprinklers were not able to activate within a reasonable time as the hot gas layer was not able to develop to a sufficient temperature.

A principal advantage of sprinklers is that the agent is water, which will not be shown in later years to be environmentally damaging. In urban areas, water is readily available, hence the agent is relatively inexpensive. One disadvantage of sprinklers is if the water supply is not relatively available such that a storage capability is needed. Another disadvantage is if the fire is from a fuel spill (which is shown to be highly uncommon), the water may not provide adequate extinguishment and the runoff of a fuel along with discharged sprinkler water may need to be captured.

Hill, et al. [1999] conducted experiments to assess the performance of water sprinklers in controlling a fire involving a JP-8 fuel spill. The area of the fuel spill in the tests at the time of sprinkler activation ranged from 30 to 32 m². Sprinkler system designs included closed head sprinklers and deluge sprinklers. Design sprinkler densities ranged from 6.9-10.2 Lpm/m² (0.17 to 0.25 gpm/ft²). Draft curtains were not installed in these tests. Operation of either sprinkler design was not able to reduce the flame spread rate or heat flux to targets in the experiments. However, the sprinklers were able to limit temperature rise in the steel beams supporting the roof of the hangar.

Subsequent work by Scheffey et al. [2000] resulted in recommendations for sprinklers that included quick response sprinklers, a design density of 6.9 Lpm/m² (0.17 gpm/ft²) over a design

area of 1,400 m² (15,000 ft²) and draft curtains (with a curtained area not to exceed 700 m² (7,500 ft²).

If due to the operations or activities performed in the hangar on the aircraft create a significant risk or potential for a fuel spill then sprinkler protection as the ceiling with water only, may not be the preferred method of protection, unless floor slope or additional drainage is provided to capture and unwanted fuel spills.

This could be evaluated as part of the now permitted risk assessment or performance-based design approach as referenced in the new 2022 edition of NFPA 409, see Chapter 4 and 5.

4.2.3 Water Mist

A relatively recent technology that poses as a potential fire suppression alternative for aircraft hangars is a water mist fire suppression system. Using only water, the water mist systems utilize the same suppression agent as sprinkler systems, albeit with much smaller droplets.

While water mist systems are considered to be a recent development, substantive research on water mist was conducted by Braidech, Neale, and Matson [1955]. This research involved exploring extinguishment mechanisms of “finely divided water.” and its applications in fire protection. Shortly thereafter, Rasbash, Rogowski, and Stack [1960] conducted experiments to assess the ability of water sprays to extinguish liquid pool fires. Research on water mist was not actively pursued again until the 1990’s, being motivated principally by the need to identify an alternative to Halon 1301. Since that time, other applications for water mist have been studied, including applications involving large spaces.

Over the past two decades, water mist has become a popular alternative due to its suppression mechanisms, efficient water use, and environmental impact. Water mist utilizes cooling effects, radiation attenuation, and oxygen displacement through the rapid evaporation of small water particles. Because the water is used more efficiently in water mist systems, less water is needed to combat a fire than sprinklers.

There are three categories of water mist systems, as identified by NFPA 750 [NFPA, 2019]:

- Low pressure systems, with an operating pressure that does not exceed 1.2 MPa (175 psi)
- Intermediate pressure systems with having an operating pressure of between 1.2 MPa (175 psi) and 3.4 MPa (500 psi)
- High-pressure systems with an operating pressure of greater than 3.4 MPa (500 psi).

An advantage of water mist systems is associated with the reduced water flow rates associated with these systems. Should a water mist system be actuated, the amount of contaminated runoff of water and spilled fuel would be much less than that from sprinklers. A negative aspect of a water mist system is the increased cost (as compared to sprinkler systems), especially for the intermediate and high-pressure systems due to increased costs for piping and pressure development.

Use of a high-pressure water mist system was explored experimentally by the US Air Force [1994]. The experiments involved 2-D and 3-D fires involving JP-4. While the water mist did

not extinguish the fire in five of six tests (in the sixth, re-ignition occurred), the water mist system did cool targets and structural components to prevent damage.

A review of previous research assessing the performance of water mist systems in large open spaces (including some research for hangars) was recently compiled by Steranka [2021]. Tests for this application date back to the 1990's resulting in the approval of nozzles supplied by at least 15 manufacturers by, such as FM Global, the International Maritime Organization (IMO) or other third-party testing laboratories.

Several manufacturers have tested low- and high-pressure water mist system designs in aircraft hangars [Steranka, 2021]. Tests have been conducted with water mist nozzles installed in spaces up to ceiling heights of 15 m (50 ft). For hangars with taller ceiling heights, tests have been conducted with nozzles installed at floor level. The nozzles at floor level are recessed into hangar flooring. In addition to the tall ceiling application, floor nozzles could also be useful to provide underwing protection in applications requiring such coverage.

The performance criteria varied somewhat depending on the test protocol adopted for the experiments. Some of the experiments were conducted for military applications (in several countries). In the review conducted by Steranka, she considered approvals of systems resulting from tests such as those conducted in accordance with FM 5560. Others were conducted for a particular sponsor (usually military-related) and were principally concerned with extinguishment).

Following the literature review, Steranka conducted numerical simulations of water mist systems designs in hangars. She considered low- and high-pressure water mist systems using ceiling and or floor nozzles. The performance criteria considered reduction of the heat release rate of the fire, limiting radiant heat flux to an aircraft and limiting temperature of the structural members supporting the roof of the hangar. These simulations were conducted to assist in the development of an experimental plan to conduct subsequent full-scale experiments of candidate water mist system designs.

4.2.4 Ignitable Liquid Drainage Floor Assemblies (ILD)

In May 2017, FM Approvals released an Approval Standard for Ignitable Liquid Drainage Floor Assemblies under Class Number 6090. FM 6090 specifies that an ignitable liquid drainage (ILD) floor assembly is only one part of an entire ILD system. An ILD system is defined as:

“the complete assembly of devices and components which in their entirety, make up the system that detects and transports the ignitable liquids to the remote holding area. The system may be comprised of, but not limited to a floor assembly, liquid detection devices, pumps for removing the liquid, piping for conveying the pumped liquid, control valves and control station” [FM Global, 2017].

In the FM approval standard, an ILD floor assembly is defined as:

“the part of the drainage system that consists of a specially designed noncombustible structure or platform serving as the base of a room on which one walks, drives or uses as a storage surface. The floor assembly consists of all components required to provide initial containment of a spilled liquid including manifolds, seals, and gaskets” [FM, 2017].

FM Class Number 6090 also lists requirements that an ILD floor assembly must meet in order to attain approval. An ILD floor assembly must function properly independent of whether or not the liquid is ignited. Per section 3.2.1 of FM 6090:

“all ignitable liquid drainage floor assemblies shall meet the following criteria:

- be of non-combustible construction;
- be of sufficient strength to carry the anticipated live and dead loads to which the floor assembly shall be subjected;
- have the capability of cleaning or removing spills or ponding of ignitable liquid in non-fire situations without having to disassemble the flooring assembly. This can be achieved through the use of an internal flushing system” [FM, 2017].

In addition to these requirements, according to Chapter 4 of FM 6090, an ILD floor assembly seeking approval must undergo a Drainage Flow Rate Test, a Survivability Test, and Structural Analysis. The Drainage Flow Rate Test determines the maximum flow rate the floor assembly can collect and transfer successfully. The Survivability Test assesses if the ILD floor assembly is able to “withstand a simulated ignitable liquid fire” [FM, 2017]. This test involves two separate tests where heptane is the fuel source at flow rates of 7.6 lpm (2.0 gpm) and 151 lpm (40 gpm). Both the Drainage Flow Rate Test and the Survivability Test are considered successful if the test is completed without any liquid running over the edge or perimeter of the floor. The third test is the Structural Analysis, which requires “that the assembly will not fail when subject to a total dead load + live load = 125 lbs/in²” [FM 2017]. This can be shown with a set of hand calculations.

As an example, an ILD floor assembly may consist of extruded aluminum profiles that are approximately 9.1 m (30 ft) long, 150 mm (6 in.) wide and 50 mm (2 in.) in height. Within each profile, there are three distinct channels that run the length of the profile. The top of each channel is perforated with drainage holes to allow for spilled liquid on top of the floor to drain into the channels. A stainless-steel foreign object debris screen is installed just under the drainage holes to help prevent loss of small parts or tools that may fall onto the floor.

The floor assembly has a slight slope (e.g., 0.5 percent) to facilitate the flow of liquid down the channels. On the low end of the slope, there is a trench drain that runs along the width of the installed profiles. This trench drain leads to a sump where once liquid is detected, a centrifugal pump transports any collected liquid into a containment tank. On the high end of the profiles, a manifold flushes water through each channel to assist liquid flow towards the trench drain at the bottom of the profiles. The flushing manifold activates only if liquid is detected in the corresponding trench. A modest water flow rate is provided in the flushing manifold (e.g., 1.0 L/min (0.25 gpm) per channel.

An ILD floor assembly can be installed in three different configurations:

- recessed into the hangar floor so that the top of the flooring assembly is flush with the hangar slab and the system drains into sub-grade trenches
- positioned on top of the hangar slab with ramps installed on the sides of the flooring system to allow aircraft and other machinery to move on and off the floor. This option requires the use of new or pre-existing subgrade trenches.
- positioned on top of a T-beam frame with ramps on all sides.

An ILD floor assembly can cover 25% to 100% of the hangar floor area, providing coverage for the area that could be a potential spill zone based on the type of aircraft to be stored in the hangar.

Test results from one manufacturer are presented in this section. Each test was conducted with the same testing floor design setup that is presented in Figure 4-2. The test floor was 6 m long and 6 m wide with a 6 m long (20 ft x 20 ft x 20 ft) trench drain positioned along one end of the floor and a flushing manifold along the opposite side. The floor had a 0.5 percent slope to encourage flow from the flushing manifold side towards the trench drain. The flooring profiles were the same as those described in the previous section.

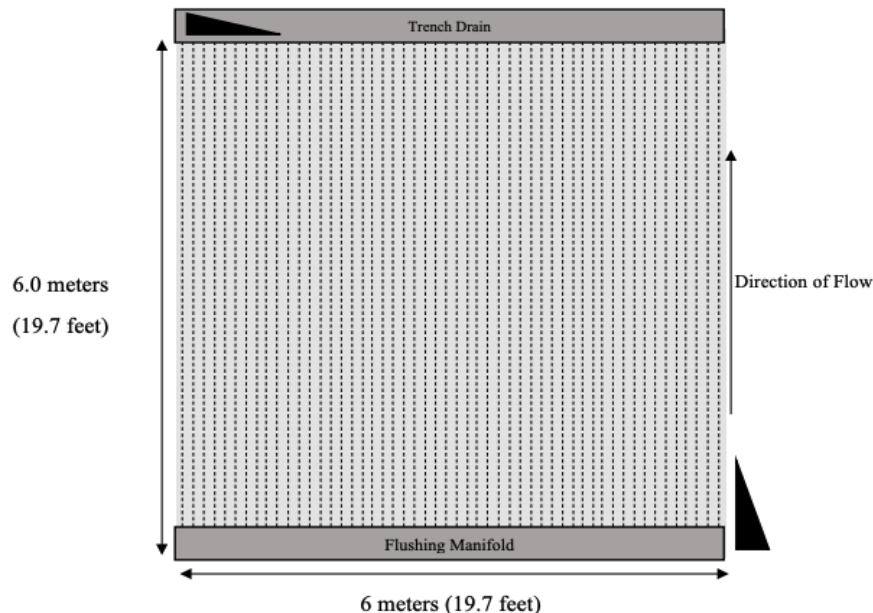


Figure 4-2: ILD Test Floor Dimensions [Giubbini, 2019]

The tests involved evaluation of the conditions maximum splash distance and spill size with no fire and additional tests to assess fire extinguishment and temperatures throughout the test room. Splash distance related to the point where the spill hits the floor to the furthest point where water droplets were observed. Spill size was measured using two different methods considering the “fully wetted” area of the test floor (the area where flowing liquid was observed on the top surface of the floor assembly) and the “95% spill area” (the floor area that absorbed 95% of the spill) [4]. The 95% spill area metric is useful to account for significant splashes that occur

during the spills from 1.8 m (6 ft) and 4.6 m (15 ft) elevations, but it does not include the small number of water droplets that land near the maximum splash distance.⁴

The fire tests included a series of wing tank drop fire tests based on a US Air Force test protocol and a cascading fire test such as those conducted by the Naval Research Laboratory. For the wing drop tests, each of the tests were conducted using a JP-4 equivalent fuel mixture of one-part gasoline and two parts kerosene [Giubbini, 2020]. In all three sets of tests, 625 liters (165 gallons) of the fuel mixture was put into a 757-liter (200 gallons) trash hopper and dropped using a winch and pulley.

The cascading fire test was conducted by pumping kerosene into an experimental apparatus depicted in Figure 4-3 at a flow rate of 70 Lpm (18.5 gpm), then cascaded through the apparatus as it was heated to a temperature of 93°C (200°F) and finally spilled onto the floor assembly at a flow rate of approximately 57 Lpm (15 gpm). After the fuel flowed for about 3.5 minutes, fuel flow was stopped, and the kerosene continued to burn for an additional 90 seconds at which point the fire was contained to the fire apparatus and no fire was burning on the floor assembly.

Detailed test protocols and results test are included in [Giubbini, 2019], [Giubbini, 2020], [Giubbini and Poole, 2021].

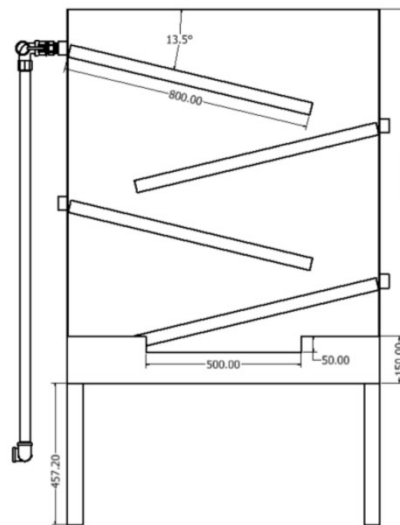


Figure 4-3: Experimental Apparatus for Kerosene Cascade Test [Giubbini, 2019]

4.2.5 Clean Agents

Clean agents are defined as agents that do not leave a residue and are electrically nonconductive, leading to their use in special applications [NFPA, 2022c]. While these agents have traditionally been used to in smaller, enclosed spaces, clean agents could be applicable to protecting aircraft

⁴ The 6-foot spill height was meant to simulate a spill from a wing tank of an F-16 Fighting Falcon and the 15-foot spill height was meant to simulate the wing height of a C-130J Super Hercules.

hangars. Clean agents can be applied either for total flooding or local application. One agent has been tested for use in portable extinguishers that can be utilized for manual suppression of a fire.

A principal benefit of clean agents is that they do not leave a residue, unlike most other fire suppression agents. The nonconductivity property also is a benefit of clean agents given the costly and sensitive electronic equipment in aircraft. Because these systems do not involve water, the water supply arrangements associated with water-based suppression systems can be omitted. While adequate water supplies are likely available at large airports in urban and suburban areas, such may not be the case at rural airfields.

A significant challenge of utilizing clean agents in a total flooding application in the large volume associated with a hangar and the associated large quantity of clean agent that would be required. Even a fixed, local application design would be challenged by the openness of a hangar, exacerbated by the possibility of the large doors being open, especially on a windy day. Due to the weight of these large doors, they do not close quickly, often requiring at least one minute to completely close these doors. With such a delay in closure of the doors, either the agent discharge would need to be delayed or the design would need to account for dissipation of some of the agent while the doors are open.

Similar to the need for water or other fire suppression agents to be stored in these spaces, storage of the clean agent would be necessary. Currently, most clean agents exist in the gaseous phase such that the storage of an adequate quantity of the agent for protecting a hangar would require an appreciable amount of area. However, for an agent stored in the liquid phase at standard atmospheric temperature and pressure, the storage requirements require less space, if the same amount of agent is needed as the gaseous agents.

While the utilization of the clean agent described here is limited currently to portable extinguishers, monitor nozzles may be a means to apply this agent in an automatic system.

One limitation of some clean agents may be the generation of acid gases as a result of the interaction of the agent with flames. Recent research has indicated that the use of one clean agent on a small fire of Jet A (2 liters) resulted in creation of a local atmosphere with 250 ppm of hydrogen fluoride gas [Owens, 2022].

4.2.6 Wetting and Encapsulating Agents

Wetting and encapsulating agents are added to water to reduce the surface tension of the water to better penetrate a fire, absorb more heat and cover a large surface area. Several products are available that act as wetting and encapsulating agents. At least some of these products are fluorine free, do not contain any mutagenic or carcinogenic substances or persistent organic pollutants, and are not bio-accumulating.

Applications involved wetting and encapsulating agents are addressed in NFPA 18 [NFPA, 2021b]. These agents may be utilized where fires involving Class A or Class B fires are anticipated. Any agent utilized requires that it be listed by UL for the fuel type included in the design fire. The UL test results would include the application density required.

For fixed systems utilizing a wetting and encapsulating agent, the design details are provided in NFPA 13, 14 or 15 and also requires an “engineering analysis acceptable to the authority having jurisdiction” [NFPA 2021b, Section 8.3].

5. Fire Risk Assessment

In the 2022 edition of NFPA 409, design for aircraft hangars may be developed using a fire risk-based (Chapter 4) or a performance-based design approach (Chapter 5) [NFPA 2022a]. Using a fire risk-based approach or a performance-based design approach should incorporate a fire risk assessment.

A fire risk assessment is a defined process for the estimation and evaluation of fire risk that addresses fire scenarios and fire scenario clusters with associated probabilities and consequences using one or more applicability thresholds. Furthermore, a fire risk assessment seeks to assess the likelihood and severity of consequences from potential fires. A risk assessment should be conducted in a structured manner in order to be inclusive of all fire scenarios that could impact a facility and consider all consequences of interest. In general, a risk assessment should identify all fire hazards that could become realized in potential fire scenarios, identify what is at risk (people, property, environment, mission continuity or other) identify threshold damage levels for any entity at risk and conduct an analysis of the likelihood and consequence of potential fires.

As indicated in NFPA 551[2022], a variety of risk assessment methods are available. The principal difference in the methods is whether a method is principally qualitative or includes quantitative aspects. A quantitative risk assessment would either involve conducting numerical simulations or conducting large-scale experiments to assess the adequacy of a particular design solution. As indicated in NFPA 551, the validity of the results of a risk assessment does not depend on whether a qualitative or quantitative analysis is conducted.

For any type of risk assessment, a series of steps should be followed, such as those described in The SFPE Engineering Guide to Fire Risk Assessment [SFPE, 2022]. The steps to be followed in a risk assessment are depicted in Figure 5-1. The process identified in the flow chart from the SFPE Engineering Guide to Fire Risk Assessment [SFPE, 2022] is intended to provide structure to a risk analysis effort. An overview of each of the steps is included in this section.

5.1 Define Project Scope and Goals:

The process begins by defining the project scope, e.g., fire protection for an aircraft hangar. It is conceivable that a limited-scope fire risk assessment be performed to specifically evaluate the risk of a major fire or a fire resulting from a fuel spill with or without special hazard fire protection systems. The definition should also include an overview of the hangar, including characteristics such as:

- Hangar dimensions, size of doors
- Description of use of spaces within hangar
- Construction type
- Occupant load
- Identification of sleeping facilities
- Potential for any occupants with disabilities
- Number, type and value of aircraft to be present in the building
- Proposed hangar operations, with description of processes/activities to occur within the hangar
- Proximity of hangar to other adjacent structures
- Available water supply
- Proximity of nearest fire department
- Design weather conditions

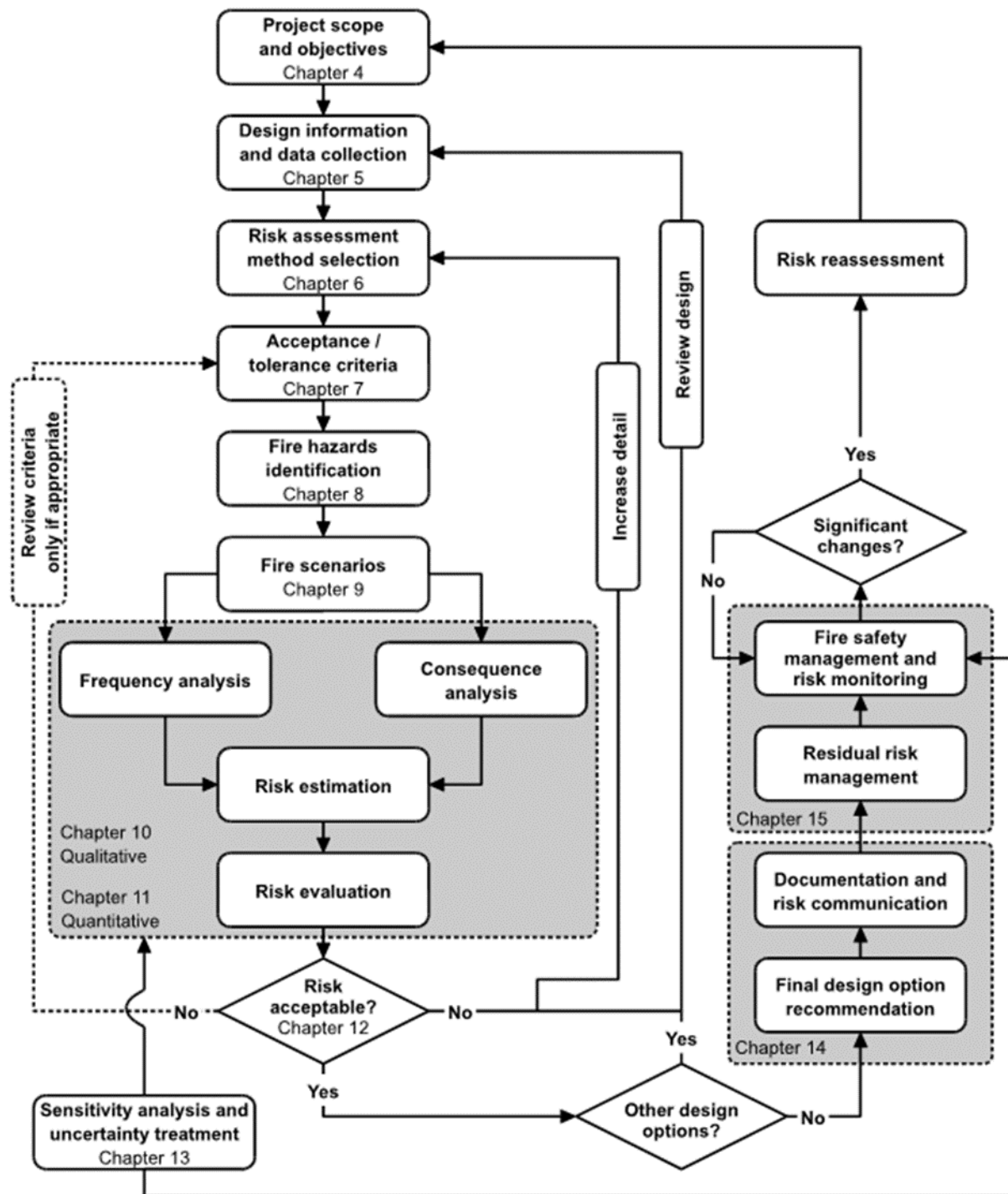


Figure 5-1: Fire Risk Assessment Flow Chart
(Provided by SFPE with Permission)

The fire protection design needs to consider the goals established by the stakeholders [Boucher, 2008]. Project goals may include one or more of the following:

- Conforming to code or insurance requirements for acceptable level of risk or components of risk (severity or probability)
- Life safety, including reducing or avoiding human fatalities and injuries
- Property protection
- Mission continuity
- Minimizing business interruption
- Environmental protection or damage
- Improving cost effectiveness of risk prevention
- Other goals
 - Owner or tenant may want to maximize design flexibility, form, or function
 - Building engineers: installed systems are easy to maintain
 - Preserve cultural heritage

If multiple goals are identified, these need not be weighted equally. For example, in a hangar, the occupant load is often minimal such that life safety might not be highest priority goal. The value of some aircraft housed in a hangar (especially military aircraft) will often exceed the value of the hangar. Similarly, aircraft with unique capabilities may need to be especially protected for reasons of mission continuity. The hangar itself may be of substantial value, either because of its historic designation [Datta and Morrison, 2019] or because of the modest-cost of aircraft housed in the hangar.

The literature includes case studies of fire protection analyses for aircraft hangars [Datta and Morrison, 2019] [Tanis, 2018]. Datta and Morrison review the case of an historic hangar at a Naval Air Station. Tanis' analysis was of a Group I military hangar with goals of life safety and protection of aircraft.

5.2 Define Objectives, Metrics, and Thresholds

Objectives are engineering statements of the goal statements. Fire safety objectives provide more detail than fire safety goals regarding who or what is to be protected from what type or mechanism of harm. These may be spatial or other limitations, or distinctions based on ownership or operational procedures. Objectives serve as the basis for establishing performance criteria which then serve as the benchmarks for evaluating the acceptability of a proposed design. Examples of statements of objectives include:

- Limit the fire to the area of origin
- Minimize smoke spread in paths of egress
- Limit fire size to prevent damage to aircraft or equipment

Performance criteria consists of quantitative metrics to evaluate a design. The metrics selected should relate to damage thresholds. Damage thresholds may include measures such as:

- *Maximum allowable smoke layer temperature.* A maximum smoke layer temperature could be based on the potential of inducing damage in a steel-supported ceiling, i.e., 540

°C [Milke, 2016]. The Korean standard on hangars limits the temperature of the structural steel to 538 °C [Lee and Lee, 2017].

- *Maximum allowable heat flux to fire-exposed targets (either contents or people).* For glass-reinforced composites, a minimum of heat flux of 20 kW/m² was observed to cause visual damage in samples after 19 minutes of exposure [Milke and Vizzini, 1992]. For a carbon-reinforced composite (AS4/3501-6), a minimum heat flux of 10 kW/m² caused visual damage in samples [Milke and Vizzini, 1991]. Predicted heat flux thresholds determined by the US Air Force Research Laboratory for three carbon-fiber composite materials used in military aircraft (IM7/977-3, UM7/RM3002 and IM7/AFR-PE-4) are included in Table 5-1 [Bocchieri, et al., 2003]. Heat flux thresholds for people may be selected based on the heat flux necessary to cause a painful burn due to a short exposure. A threshold value for radiant heat exposure is 2.5 kW/m² which relates to the radiant heat emitted by a 200 °C smoke layer [Babrauskas, 1979] [SFPE, 2019].
- *Maximum allowable temperature of fire-exposed targets.* The maximum allowable temperature of fire-exposed aircraft depends on the materials used in the exposed aircraft component. Contemporary aircraft are generally composed of aluminum or an advanced composite with either carbon or glass fibers. For an aircraft composed of a 6061-T6 aircraft degradation is initiated at 150°C, with a 50% reduction in yield strength about 275°C (Langhelle and Amdahl 2001). Temperature limits of 250 °C were recommended to prevent delamination in the following three carbon-fiber composite materials used in military aircraft: IM7/977-3, UM7/RM3002 and IM7/AFR-PE-4 [Bocchieri, et al., 2003].
- *Maximum fire size.* This may be expressed either in terms of floor area occupied by fuel package(s) or by heat release rate. Where an automatic suppression system is present, this would be identified at the time of actuation of the suppression system

Table 5-1: Heat Flux Thresholds for Delamination of Materials Used in Composite Military Aircraft [Bocchieri, et al., 2003]

Composite Material	Time for Delamination (sec)		
	15 kW/m ²	25 kW/m ²	35 kW/m ²
IM7/977-3	272	142	90
IM7/RM3002	129	74	51
IM7/AFR-PE-4	129	72	47

It is important to acknowledge that naturally occurring risk matrices may not fully reflect the values of all stakeholders. The circumstances of loss may be important and may be valued differently by different groups of stakeholders. Also, expected value summary measures of risk may not reflect stakeholder values, particularly risk aversion.

A method of measuring success of the meeting the fire safety objectives can be validated through the use of a “success tree”. NFPA 550, Guide to the Fire Safety Concepts Tree [2022], describes a success tree, the inverse of a fault tree. Fault tree analysis is a graphical network model used as a tool to identify credible ways that a specified undesired event can occur. This approach portrays various parallel and sequential combinations of faults that would result in a predefined

undesired event. These faults may be associated with initiating events, component hardware failures or human errors.

Another approach that can be taken to measure the success of fire safety objectives is to utilize a “WHAT IF” analysis, which is a simplified technique that involves asking what happens if a particular failure or event occurs. As discussed in the SFPE Guide [2022], the answer will be an opinion based on available knowledge of the stakeholders answering the question and the process can be enhanced by brainstorming among multiple stakeholders. Appropriate remedial action is then agreed upon by the what if analysis team which usually includes designers, operators as well as safety or fire protection representatives.

5.3 Identify Hazards

Development of fire scenarios (the subsequent step) begins with an identification of potential hazards. The SFPE Guide [2022] defines “hazard” as “a condition or physical situation with a potential for harm.” Hazards may be associated with ignition of a fire or contribute to the development of a fire after ignition.

Hazard identification is accomplished by recognizing the variety of combustibles⁵ and ignition sources present. As noted in the SFPE Guide [2022], a review of combustibles and ignition sources should include (but not be limited to) a review of past fire incidents in hangars of the type considered in this analysis.

Cataloging combustibles needs to include aircraft fuels as well as the many other combustibles that may be present in a hangar. The properties of aircraft fuels are included in Table 5-2. Of significance are changes in the types of fuels used for aircraft since 1990. As indicated by Wells, et al. [1997]:

“Current aircraft hangars and fire extinguishing systems were designed and built during a period when aviation gasoline (Avgas) and JP-4 were the predominant aircraft propulsion fuels. Avgas is highly volatile, propagating at an explosive rate when ignited. JP-4 is also highly volatile. Compounding this situation, aircraft undergoing maintenance during that earlier period were not completely de-fueled. As a result of these factors, hangar electrical systems were designed to meet Class I, Division II requirements, and fire suppression systems were designed to respond to incipient explosions and rapidly propagating fires. Today, the predominant fuels now in use are Jet-A in commercial aircraft and JP-8 in military aircraft. These fuels are much more difficult to ignite, and when ignited the flames spread at a much slower rate. These factors result in what appears to be a significant reduction in the fire threat.”

As noted in Section 3 of this report, a substantial majority of fires in hangars involve other combustibles. Hence, including class A combustible materials in the list of combustibles in a hangar is important. In developing the list of combustibles, combustibles associated with the

⁵ The term “combustibles” used in this sentence includes any item which could be ignited or become involved in a potential fire. More typically, the term “fuel” is used in this context, though in this report the term “fuel” will be reserved to refer to aircraft fuels.

planned everyday uses of the hangar need to be considered as well as those associated with any special activities or events that might be proposed for the hangar.

Table 5-2: Properties of Aircraft Fuels

Aircraft	Fuel	Flashpoint	Boiling Point	Classification
Propeller driven (piston-engine)	AvGas	-35°F	75°F	FL IA
Jets, turboprops	Jet A	100°F	176°F	CL II
Military	JP-4 (< 1990)	0°F	>120°F	FL IB
	JP-8 (≥ 1990)	112°F	>325°F	CL II
Other fuels (for comparison)	Gasoline	-36°F	100°F	FL IB
	Kerosene	100°F	>300°F	CL II
	Diesel	149°F	>350°F	CL II

Note: “CL” indicates Combustible Liquid, “FL” indicates Flammable Liquid. Classifications noted are per NFPA 30 [2021].

Potential ignition sources also need to be cataloged. These should include potential failures of equipment contained in the hangar as well as processes conducted in the hangar. A list of potential ignition sources included in Section 6.5.1.1 of the SFPE Guide [2006] are:

- “Cigarettes or other smoking materials (e.g., lighters, matches)
- Torch, hot work, or other open flame devices
- Heating, refrigeration, and air conditioning equipment
- Cooking equipment
- Tools and appliances
- Process or service equipment, including separate motors or internal combustion engines
- Electrical distribution equipment (e.g., wiring, switches, outlets, cords and plugs, light fixtures, transformers)
- Hot objects, most of which also fall into one of the above categories, such as a light bulb or the heating surface of heating equipment
- Vulnerability to lightning or static electricity
- Chemicals capable of spontaneous heating
- Wildfire or other exterior exposure fire”

Experiments conducted by Wells et al. [1997] on JP-4 and JP-8 and found that they had similar ignition properties when a drop of the respective fuel was placed on a hot surface. For ignition, the surface temperature of the object needed to be at least 435 °C for JP-8 and 474 °C for JP-4. Additional tests by Wells et al. were conducted to assess the potential for ignition of JP-4 and JP-8 due to the following ignition sources:

- Acetylene cutting
- Arc welding
- Disc grinder
- 10 kV arc, 0.025 m above a spill.
- 10 kV arc, 0.076 m above a spill.

Spills of both JP-4 and JP-8 ignited when exposed to acetylene cutting or arc welding. Only JP-4 ignited to the Disc Grinder and in two of three tests with the 10 kV arc 0,0245 m above the spill. Neither fuel ignited for the 10 kV arc located 0.076 m above the spill.

These potential ignition sources may be realized via a set of conditions such as those noted in Section 6.5.1.2 of the SFPE Guide [2006]:

- “Physically damaged equipment or other heat source
- Improperly designed equipment or other heat source (e.g., cigarette with heightened ignition strength)
- Improperly installed equipment or other heat source
- Improperly used or applied equipment or other heat source (e.g., overloaded equipment, use of extension cords as permanent extensions to wiring, use of equipment not rated for application)
- Equipment or other heat source that shows signs of overheating in normal use (e.g., by touch, smell, or sight such as smoking)”

5.4 Identify Fire Scenarios

A specification of a fire scenario encompasses characteristics of a fire, the building and its occupants. A comprehensive list of characteristics to consider in a fire scenario are included in Table 5-3 [SFPE, 2007].

Table 5-3: Specification of Fire Scenarios

Building Characteristics	Occupant Characteristics	Fire Characteristics
Architectural Features	Quantity	Location of the initially ignited fuel package, including proximity to heat sources
Structural Components	Responsiveness	Growth rate of the fire (including that within the initially ignited fuel package and potential for spread to other items)
Fire Protection Systems	Physical Capabilities	Peak heat release rate
Building Services/Processes	Mental Capabilities	Fuel load
Operational Characteristics	Distribution	Fuel composition, orientation, surface/mass ratio
Fire Department Response	Alertness/Focal Point	Duration
Environmental Factors	Commitment	Extinction/decay stage characteristics
	Familiarity with the building	Ventilation
	Social Affiliation	Possible interventions
	Training	Yield of combustion products (gas species, soot)
	Level of assistance available	Presence of fire-resistant barriers, flame retardant treatments

Specifications of fire scenarios may be developed in part by considering past incidents that have occurred in similar hangars. As an alternative, engineering analysis such as “what if”, event trees, failure mode and effects analysis and similar methods may also be used to identify fire [NFPA 2022d]. Consideration of external events such as earthquakes, extreme weather events, etc. should be included for hangars in locations prone to such events.

In lieu of quantitative descriptions of the fire severity, fire scenarios may be described qualitatively [ICC Performance Code, 2018]. In this case, labels or terms are used to describe the fire scenario.

- Small - limited to first materials or objects burning
- Medium - limited room or area of origin
- Large - limited to floor, compartment or fire area of origin
- Very large - Extending beyond floor, compartment or fire area of origin

5.5 Specify Scenario Clusters

Because the effort to identify potential fire scenarios may result in a long list of scenarios, reducing the number of scenarios to a manageable number for analysis is useful. As such, scenarios clusters may be utilized to reduce the number of scenarios requiring analysis. A scenario cluster consists of a group of scenarios which have many characteristics in common. Using scenario clusters may also be helpful so as not to get mired into the details of a specific scenario and instead be able to maintain a “big picture” perspective by considering a cluster of related scenarios. In assessing the risk associated with a scenario cluster, a representative fire scenario should be considered which retains the essential characteristics of the scenarios included within that cluster. As part of this step, scenarios may be excluded which are highly unlikely or have trivial consequences.

5.6 Conduct Frequency Analysis

A frequency analysis should consider the likelihood of a fire being ignited and progressing to a specified severity and the performance of the proposed fire protection solution. The frequency analysis will benefit from having data from previous incidents in hangars and reliability data on the performance of the proposed fire protection solutions.

The lack of a property use code for aircraft hangars in NFIRS poses a challenge to acquiring data on fires in aircraft hangars. The information reported in Section 3 of this report provides some insight into the fire incident rate and cause of fires in hangars. Hangar operators may maintain their own database for hangars under their purview and hence should be consulted for information regarding past fire incidents.

A database of 186 fire incidents that occurred in 1968 to 1977 in hangars operated by the US Air Force was compiled by Kennedy and Thomas [1978]. Of the 186 incidents, 53.2% of the incidents involved electric devices, electric conveyors or fluorescent lights. Flammable liquids or gases were the “cause” in 8.1 percent of the incidents (smoking materials were the second most likely cause for 9.7% of the incidents and incendiarism was tied with flammable liquids/gases).

5.7 Conduct Consequence Analysis

The consequences considered in a risk assessment should be consistent with the fire safety goals for the project. For example, where property damage is of concern, the losses considered should relate to damage levels incurred by aircraft, the building or other equipment in the specified fire scenarios.

As with the frequency analysis described in the previous section, historic data can be useful to estimate the consequences associated with a fire in similar hangars. Alternatively, computations may be conducted using computational methods from the discipline of fire protection engineering may be utilized to predict the severity of conditions produced by a fire and compare those to performance criteria associated with damage thresholds (see Section 5.2)

In the database compiled by Kennedy and Thomas [1978], total losses in fire incidents caused by flammable liquids/gases, the total loss in the 15 incidents was \$1610. Total losses incurred in all 186 fire incidents was \$12.1M.

5.8 Risk Estimation

Risk estimation will involve the combination of frequency and consequence for a particular set of scenarios identified in the previous steps. Where the risk is calculated as the product of the frequency and consequence, such a risk estimate requires quantitative values for the frequency and consequence of the scenarios. However, often quantitative measures of frequency and consequence are not able to be obtained because of the lack of data or inability to conduct the necessary computations (see Section 6, Gap Analysis).

Where data is lacking, risk estimation may be provided qualitatively. In this case, the frequency or consequence may be placed into categories such as “low”, “moderate”, “high”, etc. with definitions provided to distinguish between these categories. As an example of such an approach, Table 5-4 presents the labels of consequences from the IBC Performance Based Code for damage to the structure and life safety. Similar measures could be proposed for damage to aircraft, environmental damage, loss of mission continuity or other loss parameters of interest.

Table 5-4: Consequence Categories [ICC, 2018]

Level of Damage	Mild	Moderate	High	Severe
Structure	none	moderate, repairable	significant, repairable	substantial, though significant components remain functional, repair may not be feasible
Casualties	minimal number or severity of injuries	moderate number and nature of injuries, though perhaps with locally significant effects	moderate number and nature of injuries, perhaps with locally significant effects; moderate probability of single fatality, low probability of multiple fatalities	injuries may be high in number and significant in nature; high probability of single fatality, moderate probability of multiple fatalities

In the cases where the risk assessment is done qualitatively, a risk matrix such as that presented in Table 5-5 can be used to summarize the results. In Table 5-5, the least risk would be one with a very rare frequency and mild consequence, thereby residing in the upper right corner of the matrix. A fire scenario with the greatest risk would have a frequent frequency and severe consequence and reside in the bottom left portion of the matrix.

Table 5-5: Risk Assessment Matrix

Risk Assessment Matrix				Probability				
				Frequency of Occurrence Over Time				
				A Frequent	B Likely	C Occasional	D Seldom	E Unlikely
CONSEQUENCE	Effect of Hazard	Catastrophic (Death, Loss of Asset, Mission Capability or Aircraft Readiness)	I	1	23	6	10	15
		Critical (Severe Injury or Damage, Significantly Degraded Mission Capability or Aircraft Readiness)	II	2	5	9	14	19
		Major (Significant Injury or Damage, Degraded Mission Capability or Aircraft Readiness)	III	4	8	13	18	22
		Minor (Minimal Injury or Damage, Little or No Mission Capability or Aircraft Readiness)	IV	7	12	17	21	24
		Negligible (No or Limited Injury or Damage, Little or No Mission Capability or Aircraft Readiness)		11	16	20	23	25
				25 Risk Levels				
				1-25 (high risk = low numbers) (low risk = high numbers)				

Using the risk matrix type of approach presented in Table 5-5 then enables the development of acceptable levels of risk for selected facilities such as that included in the IBC Performance Based Code and included as Table 5.6. Such a table could be adapted for aircraft hangars and incorporated into NFPA 409 [2022a].

Table 5-6: Levels of Building Performance [ICC 2018]

Frequency	Maximum Level of Damage to be Tolerated				
		Severe	High	Moderate	Mild
	Very rare	II	III	IV	>IV
	Rare	I	II	III	IV
	Infrequent	NP	I	II	III
	Frequent	NP	NP	I	II

The categories included in Table 5-6 are defined as:

NP = not permitted

I - Minimum design performance level with which all structures posing a low risk to human life must comply, should the structure fail

II - All structures not in PGs I, III or IV

III - Structures having “increased level of societal benefit or importance”

IV - Structures representing “an unusually high risk or which are deemed essential facilities”

For the categories included in the ICC Performance Code for Buildings, a category IV building is not very risk tolerant, while a category I building is risk tolerant. These categories are based on seven characteristics of the facility:

- Nature of the hazard
- Number of occupants
- Length of occupancy
- Sleeping characteristics
- Familiarity
- Vulnerability
- Relationships

The risk categories are dominated by life safety considerations which may not be relevant for a hangar. As such, a new set of risk categories could be developed for hangars, based on factors such as the number, dollar value, importance (either strategic/mission related or historic) and vulnerability of aircraft housed and the length of time an aircraft is stored in the hangar.

5.9 Examples of Risk Assessment for Hangars

5.9.1 Example of Historic Hangar

An example of the application for a risk assessment of a hangar is provided by Datta and Morrison (2019). In this case, preservation of the hangar was a principal goal due to the hangar being designated as being in an historic district, with buildings in a Naval Air Station having been constructed in the 1930's. The purpose of the risk assessment was to identify initiating events of a fire and assess the performance of fire protection options.

They used event trees to identify possible sequences of events proceeding from a hypothesized ignition scenario leading to a final consequence. As part of each event tree, they identified whether the fire would be detected locally, and fire suppression efforts would be effective. The results of the assessments conducted using the event tree were imported into a risk matrix, similar to what is presented as Table 5-5.

5.9.2. Example of Hypothetical Hangar

This section illustrates the process of developing a fire risk assessment for an existing hangar that is currently protected with an overhead preaction sprinkler system and a low-level low expansion AFFF foam system. Discharge of water from the overhead preaction sprinkler system is initiated by both the single flame detector and enough heat at the ceiling level to activate the fusible element of the sprinklers. The low level, low expansion AFFF foam system is initiated by a manual release station or any two flame detectors.

The hangar for this case study is a Group II hangar operated by an FBO. The hangar is used principally for storage of up to four aircraft (privately owned jets), all containing varying quantities of fuel from full to nearly empty. Only light maintenance is conducted inside the hangar. Very few people are present in the hangar open bay, though are located in adjacent spaces (which are separated from the hangar bay via fire resistant barriers). The construction type of the hangar is noncombustible, but not fire rated, Type II (000).

Step 1. Define Project Scope and Goals

The project scope involves selection of a fire protection solution for the hangar bay. In this situation, the stakeholders identify that protection of the aircraft is the principal goal. Protection of the hangar and limiting environmental impact are secondary goals.

Step 2. Define Objectives, Metrics and Thresholds

Stated fire protection objectives are:

- Limit fire size to prevent thermally induced damage to the aircraft components.
- Limit fire size to prevent thermally induced damage to the hangar structural members.
- Limit fuel spills or discharge of chemicals to the environment or storm or sewage drainage systems.

If a quantitative risk assessment is to be conducted, performance criteria would need to be established. The performance criteria should be selected based on the damage thresholds for the aircraft and the structural steel. In such a case, the structural steel cannot exceed 500 °C. Damage levels for the aircraft depend on the composition of the aircraft and can be based on temperature limits (of the surface of the aircraft component) or incident heat fluxes.

The aircraft maintenance and repair activities being performed in the hangar will also have to be evaluated to determine the risk of a fuel spill or an unwanted discharge of other chemicals, including special hazard fire suppression systems such as foam.

Step 3. Identify Hazards

Reviewing the combustibles and ignition sources in the hangar, the identified combustibles principally include Class A combustibles, and the flammable or combustible liquids present in the fuel system and cells of the aircraft. A small amount of flammable and combustible liquids are present but are stored appropriately in cabinets. The owner and operator of the hangar is not aware of any fires that have occurred in the hangar or any other hangars they own or operate.

Ignition sources include electronic equipment in the area. No hot work activities are performed in the hangar bay, such as welding, cutting or grinding. All necessary hot work activities are performed in a shop adjacent to the hangar bay which is separated by a fire rated barrier.

Step 4. Identify Fire Scenarios

Hypothesized fire scenarios include:

1. electric equipment or appliances with the hangar bay overheating causing an electrical fire of the equipment or appliance,
2. electric equipment or appliances with the hangar bay shorting out causing an electrical fire of the equipment or appliance,
3. electrical distribution or service equipment overheating or excessive resistance heating causing fire of the equipment,
4. overheating of the electrical motors or other equipment causing ignition of the equipment,

5. puncture or damage to a fuel cell or the fuel system causing a large quantity of the fuel onboard the aircraft to be discharge on the floor, then ignition of the fuel from some heating source,
6. spill of a flammable liquid from maintenance or repair activities being ignited from a static spark or other heated element,
7. spill of a combustible liquid onto a hot or heated component during maintenance or repair activities causing ignition of the combustible liquid,
8. ignition of a flammable aerosol used for cleaning of components or parts from a static spark or a heated component during maintenance or repair activities,
9. ignition of class A combustibles in in a trash receptacle or a combustible component from a cigarette or other incendiary or heated source,
10. ignition of a small quantity of combination of different chemicals or single chemical that might spontaneously ignite causing a fire of the chemicals, and
11. lightning strike of the facility causing ignition of combustible materials.

Step 5. Specify Scenario Clusters

Down selecting the scenarios from Step 4 involves a review of the incidents to determine those which have similarities as well as to exclude those which are highly unlikely or have trivial consequences.

All of the electrical equipment or appliance fires can be clustered together as the likely hood and severity, or consequence of these vents are low.

Step 6. Conduct Frequency Analysis

The relative frequency of the remaining scenarios is outlined below. Given the lack of data on fire incidents in hangars, the frequencies are identified via engineering judgement.

The frequency of any one of the fire events #1 through #4 identified in Step 4 above is considered to have an unlikely to occasional probability of occurrence.

Below is the frequency analysis based for the other identified fire scenarios:

- #5 - puncture or damage to a fuel cell or the fuel system causing a large quantity of the fuel onboard the aircraft to be discharge on the floor, then ignition of the fuel from some heating source – the frequency of this event is classified as unlikely because the type of maintenance and repair activities performed on the aircraft is “light maintenance”; therefore, perform work on the fuel system or the fuel cells is not permitted and the other light maintenance activities being performed is not expected to damage or puncture a fuel cell. Furthermore, having an ignition source to ignite that fuel spill (combustible liquid) is also unlikely.
- #6 - spill of a small quantity of flammable liquid from maintenance or repair activities being ignited from a static spark or other heated element – the frequency of a small spill of flammable liquid is considered occasional or likely, but the probability of a static spark or other ignition source igniting the liquid is unlikely.

- #7 - spill of a combustible liquid onto a hot or heated component during maintenance or repair activities causing ignition of the combustible liquid – working with combustible liquids around or near hot or heated components is not permitted per the maintenance standard operating procedures, and if it is accidentally performed the quantity of the combustible liquid is expected to be small; therefore, the frequency of this even is expected to be unlikely or seldom.
- #8 - ignition of a flammable aerosol used for cleaning of components or parts from a static spark or a heated component during maintenance or repair activities – using flammable aerosols to clean aircraft parts or equipment is common; however, bonding and grounding of these components is required as part of the standard operating procedures; therefore, the frequency of this even is considered to be unlikely or seldom.
- #9 - ignition of class A combustibles in a trash receptacle or a combustible component from a cigarette or other incendiary or heated source – smoking, hot work and use of heated or hot components are prohibited in the hangar bay; however, if it was to happen the quantity of class A combustible is generally minimized and controlled to housekeeping procedures; therefore the frequency of this even is considered unlikely to seldom.
- #10 - ignition of a small quantity of combination of different chemicals or single chemical that might spontaneously ignite causing a fire of the chemicals – the use of chemicals that spontaneously ignite or reactive chemical being used together causing a fire is closely controlled through the safety and health procedures, the frequency of this event is considered unlikely to seldom.
- #11 - lightning strike of the facility causing ignition of combustible materials – even though this hangar is located in an area of the United States prone to lightning strikes, the building is provided with a lightning protection system as outlined in NFPA 780; therefore, the frequency of a fire from a lightning strike is considered unlikely.

Step 7. Conduct Consequence Analysis

The relative potential consequence of the remaining scenarios is outlined below. As with the frequency assessment, the cluster of electrical fire scenarios (scenarios #1 through #4) will be considered as a single scenario.

The consequence analysis for fire scenarios #1 through #4 is considered minor to major as depending on the proximity of the equipment to the aircraft may cause fire or heat damage to the aircraft. Furthermore, if the fire is large enough and detectable by two or more flame detectors, it will cause activation of the low level, low expansion foam system, which then may cause discharge of the AFFF solution into the environment or storm or sewage drainage systems.

Below is the consequence analysis based for the other identified fire scenarios:

- #5 - puncture or damage to a fuel cell or the fuel system causing a large quantity of the fuel onboard the aircraft to be discharge on the floor, then ignition of the fuel from some heating source – the consequence of this event is classified as critical to catastrophic because large fuel spill fire is expected to cause loss or significant damage to the aircraft

or the structure. Furthermore, this may cause discharge of the fuel or the AFFF solution into the environment or storm or sewage drainage systems.

- #6 - spill of a small quantity of flammable liquid from maintenance or repair activities being ignited from a static spark or other heated element – the consequence of a small spill of flammable liquid with a static spark fire is considered minor. However, if the fire is large enough and detectable by two or more flame detectors, it will cause activation of the low level, low expansion foam system, which then may cause discharge of the AFFF solution into the environment or storm or sewage drainage systems.
- #7 - spill of a combustible liquid onto a hot or heated component during maintenance or repair activities causing ignition of the combustible liquid – working with combustible liquids around or near hot or heated components is not permitted per the maintenance standard operating procedures, and if it is accidentally performed the quantity of the combustible liquid is expect to be small; therefore, the consequence of a fire is minor to major. However, if the fire is large enough and detectable by two or more flame detectors, it will cause activation of the low level, low expansion foam system, which then may cause discharge of the AFFF solution into the environment or storm or sewage drainage systems.
- #8 - ignition of a flammable aerosol used for cleaning of components or parts from a static spark or a heated component during maintenance or repair activities – using flammable aerosols to clean aircraft parts or equipment is common; however, bonding and grounding of of these components is required as part of the standard operating procedures; therefore the consequence of this fire is considered minor or major depending on the proximity of the fire to the aircraft. However, if the fire is large enough and detectable by two or more flame detectors, it will cause activation of the low level, low expansion foam system, which then may cause discharge of the AFFF solution into the environment or storm or sewage drainage systems.
- #9 - ignition of class A combustibles in in a trash receptacle or a combustible component from a cigarette or other incendiary or heated source – smoking, hot work and use of heated or hot components are prohibited in the hangar bay; however, it it was to happen the quantity of class A combustible is generally minimized and controlled to housekeeping procedures; therefore the consequence of this fire is considered minor or major depending on the proximity of the fire to the aircraft. However, if the fire is large enough and detectable by two or more flame detectors, it will cause activation of the low level, low expansion foam system, which then may cause discharge of the AFFF solution into the environment or storm or sewage drainage systems.
- #10 - ignition of a small quantity of combination of different chemicals or single chemical that might spontaneously ignite causing a fire of the chemicals – the use of chemicals that spontaneously ignite or reactive chemical being used together causing a fire is closely controlled through the safety and health procedures; therefore, the consequence of this fire is considered minor depending on the proximity of the fire to the aircraft. However, if the fire is large enough and detectable by two or more flame detectors, it will cause activation of the low level, low expansion foam system, which

then may cause discharge of the AFFF solution into the environment or storm or sewage drainage systems.

- #11 - lightning strike of the facility causing ignition of combustible materials – even though this hangar is located in an area of the United States prone to lightning strikes, the building is provided with a lightning protection system as outlined in NFPA 780; therefore, the consequence of this fire is considered negligible or minor depending on the proximity of the fire to the aircraft. However, if the fire is large enough and detectable by two or more flame detectors, it will cause activation of the low level, low expansion foam system, which then may cause discharge of the AFFF solution into the environment or storm or sewage drainage systems.

Step 8. Risk Estimation

The scenarios identified in Steps 6 and 7 can be placed in the risk matrix to determine which fire protection solutions are, and whether or not the AFFF fire suppression system can be eliminated.

Below is the fire risk assessment matrix for which the above fire scenarios will be estimated.

The corresponding risk level number identified will have been established based upon the corresponding number in the cell for the combined frequency and consequence of each individual scenario. Based on the graphical display of the Risk Assessment Matrix below, any fire scenarios in the red (Risk Levels 1 – 6) clearly should be provided with a AFFF fire suppression system and any fire scenario in the green (Risk Levels 16 – 25) clearly do not need an AFFF fire suppression system. The fire scenarios in the yellow (Risk Levels 7 – 15) should be further analyzed to confirm if the fire is from a flammable or combustible fire then an AFFF fire suppression system may be justified if the risk of a fire out-weighs the risk of an unwanted discharge of the flammable liquid or the AFFF solution from being discharged to the environment or the storm or sewage drainage system.

Table 5-7: Case Study Risk Matrix

Risk Assessment Matrix				Probability				
				Frequency of Occurrence Over Time				
				A Frequent	B Likely	C Occasional	D Seldom	E Unlikely
CONSEQUENCE	Effect of Hazard	Catastrophic (Death, Loss of Asset, Mission Capability or Aircraft Readiness)	I	1	23	6	10	15
		Critical (Severe Injury or Damage, Significantly Degraded Mission Capability or Aircraft Readiness)	II	2	5	9	14	19
		Major (Significant Injury or Damage, Degraded Mission Capability or Aircraft Readiness)	III	4	8	13	18	22
		Minor (Minimal Injury or Damage, Little or No Mission Capability or Aircraft Readiness)	IV	7	12	17	21	24
		Negligible (No or Limited Injury or Damage, Little or No Mission Capability or Aircraft Readiness)		11	16	20	23	25
				25 Risk Levels				
				1-25 (high risk = low numbers) (low risk = high numbers)				

Fire Scenario #1 through #4: Frequency = Occasional, Consequence = Major; and Risk Level = 13. The activation of the AFFF fire suppression system is not needed for this type of fire; therefore, the potential impact and risk of the AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

Fire Scenario #5: Frequency = Unlikely, Consequence = Catastrophic; and Risk Level = 15. The activation of the AFFF fire suppression system is warranted for a large fuel spill fire; however, if satisfactory mitigation measures can be put in place to limit or reduce the risk of a fuel spill, the impact and risk of the potential for the fuel and AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

Fire Scenario #6: Frequency = Occasional, Consequence = Minor; and Risk Level = 17. The activation of the AFFF fire suppression system is not justified for a small flammable liquid fire; therefore, if satisfactory mitigation measures can be put in place to limit or reduce the risk of a fire, the impact and risk of the potential for the flammable liquid or the AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

Fire Scenario #7: Frequency = Seldom, Consequence = Major; and Risk Level = 18. The activation of the AFFF fire suppression system is not justified for a small combustible liquid fire; therefore, if satisfactory mitigation measures can be put in place to limit or reduce the risk of a fire, the impact and risk of the potential for the combustible liquid or the AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

Fire Scenario #8: Frequency = Seldom, Consequence = Major; and Risk Level = 18. The activation of the AFFF fire suppression system is not needed for this aerosol fire; therefore, the potential impact and risk of the AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

Fire Scenario #9: Frequency = Seldom, Consequence = Major; and Risk Level = 18. The activation of the AFFF fire suppression system is not needed for this type of class A fire; therefore, the potential impact and risk of the AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

Fire Scenario #10: Frequency = Seldom, Consequence = Minor; and Risk Level = 21. The activation of the AFFF fire suppression system is generally not needed for this type of small chemical fire; therefore, the potential impact and risk of the AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

Fire Scenario #11: Frequency = Unlikely, Consequence = Minor; and Risk Level = 24. The activation of the AFFF fire suppression system is not needed for this type of fire; therefore, the potential impact and risk of the AFFF being discharge to the environment or to the storm or sewage drainage system out-weighs the risk of needing an AFFF system for this fire scenario.

In summary Fire Scenario #5 can result in the most catastrophic loss event; however, the frequency of that event is considered unlikely resulting in a Risk Level of 15. Fire Scenarios #1 through #4 resulted in the lowest Risk Level, which was 13. Since the fire scenarios are electrical in nature, the use of an AFFF fire suppression system is not needed for this type of fire; therefore, the potential impact and risk of the AFFF being discharge to the environment or to the storm or sewage drainage system from an unwanted AFFF discharge out-weighs the risk of needing an AFFF system for this fire scenario.

In conclusion, the AFFF fire suppression system is not justified based on the frequency and consequences of the postulated fire scenarios as compared to the risk of an unwanted discharge of AFFF solution to the environment of the storm or sewage drainage systems.

6. Gap Analysis

The gap analysis is organized by the set of steps associated with a risk assessment which were outlined in Section 5 of this report.

Step 1. Define Project Scope and Goals

Currently, there is no guidance on possible goals for the fire protection system or for a list of considerations on setting relative priorities of the goals. As is, setting goals is at the discretion of the stakeholders. While that approach could be acceptable, the NFPA committee of Airport Facilities could consider providing some structure to this issue.

Step 2. Define objectives, metrics and thresholds

Performance metrics, i.e., damage thresholds, are essential to conducting a quantitative risk assessment. But, even for qualitative risk assessments, having an understanding of the damage thresholds for key components in a hangar, including structural members, pieces of equipment or aircraft components, would be very useful to identify the item of value that would be sensitive to damage. As such, compiling a list of temperature or heat flux limits for typical materials in a hangar such as those presented in Section 5 of this report, would be very useful.

Step 3. Identify Hazards

Hazard identification trends need to be monitored. Fuels or aircraft may change that would necessitate being informed as to the differences in hazards associated with those changes. For example, with the continuing development of electric-powered aircraft, energy storage systems pose a different set of hazards than those seen with current aviation fuels.

Step 4. Identify Fire Scenarios

A principal method of identifying fire scenarios is via a search of previous incidents in hangars. With no systematic collection of fire incident data in hangars, this step cannot be accomplished via a review of historic data.

A review of NFIRS data and four surveys have been conducted to collect information on fire incidents which have occurred in hangars. Even so, all of the collected information provides only a partial glimpse of fire experiences in hangars. Having an understanding of historic fires in hangars is essential to be able to appreciate the frequency and severity of fires that have occurred. As noted in Section 2.1, fire protection solutions included in NFPA 409 were predicated on the opinion that fires involving fuel spills were the predominant scenario of concern. However, the USCG database on spills and the surveys suggest that fuel spills in hangars are uncommon and fires involving fuel spills are even less frequent.

Providing a risk-based fire protection solution requires data to construct fire scenarios of concern and appreciate in-the-field performance of fire protection systems in this application. As noted in Section 3.1, without a property use code for aircraft hangars, it's challenging to identify fire incidents that occurred in hangars in the database. The research team also reached out to the Aircraft Rescue and Firefighting working group; a network of chief fire officers associated with fire departments at airports. The contact was made with the intention that such a group might maintain their own database of fire incidents. However, that contact did not yield any information.

Steps 5-6. Specify Scenario Clusters, Conduct Frequency Analysis

The gap associated with these steps is the same as that identified for the previous step. If data is available of the frequency of scenarios, this enables the type of in-depth study conducted by Lee and Lee [2017] to assess the impact of a particular fire protection solution on the frequency of the particular consequence. They relied on data from incidents in Korean military hangars and utilized a fault tree to conduct their analysis. While such an analysis is very insightful, it requires data from fire incidents (which is lacking).

Step 7. Conduct Consequence Analysis

Consequence analyses may be conducted qualitatively, as in the example presented in Section 5.9.2 or quantitatively. Qualitative consequence analyses can be sufficient in many cases, especially given that quantitative analyses can require an appreciable amount of time. The time may be worth the investment because of the subjective nature of a qualitative analysis where the results obtained may be subject to substantial debate.

Conducting a consequence analysis either requires a comprehensive database of fire protection system performance in fire incidents (such as that used by Lee and Lee [2017]), test data of fire protection system performance or the ability to conduct numerical simulations. Information on the performance of fire protection solutions in hangars is largely based on listing requirements of the included systems by nationally recognized test laboratories (NRTL's) such as UL or similar entities. In addition to tests conducted by NRTL's, some federal government agencies (including military organizations) and private companies have conducted experiments to explore the performance of fire protection solutions in hangars.

Having information from experimental programs is very common method for selecting fire protection solutions for a wide variety of occupancies, especially where such tests are conducted by a NRTL. However, because the test data associated with tests conducted by a NRTL are often not publically available, such an approach is not conducive to comparing the performance of multiple fire protection options and hence selecting the best system for the application. That approach is also not helpful if the nature of the hazard has changed or is not what was perceived. In addition, in the case of potential fires occurring from fuel spills, the fuels used in aircraft have changed significantly in the last 50 years, with combustible liquids rather than flammable liquids being the fuels in all jets.

As an alternative to relying solely on information from NRTL's, engineering calculations can be utilized in designs based on risk assessments to determine the optimum fire protection solution. However, the ability to conduct engineering calculations to estimate the performance of fire protection solutions in hangars is limited, requiring data associated with the performance of the fire protection system. Such an approach has required design fire scenarios be identified for the analysis, which is constrained by the lack of data on historic fire incidents.

Estimating the response of fire detectors requires information about the sensitivity of the respective detectors. An engineering method to estimate the response of heat and flame detectors is included in NFPA 72 [2022c] and computer models such as CFAST and FDS include routines to provide estimates of response times for heat detectors [Peacock, et al., 2021]

[McGrattan, et al., 2019]. The calculations done by CFAST and FDS require the sensitivity of the heat detector to be known, though the response time index of selected heat detectors is not widely published. While routines to estimate the response of smoke detectors are also included in CFAST and FDS, estimates obtained via those models can include an appreciable amount of error given the operating mechanism for smoke detectors is not represented in the models [Milke, et al., 2008].

Estimating the performance of fire suppression systems via engineering analysis is also limited. Analysis of fire suppression by water sprays, such as those produced by sprinklers and water mist nozzles, is included in CFAST and FDS. However, making use of those models requires a detailed characterization of the respective nozzle via experimentation as well as to capture the physics associated with the spray-fire interaction [Steranka, 2021]. Information on the initial spray patterns for suppression nozzles is limited, with research ongoing in this area.

Calculation methods do not exist to assess the performance of foams, wetting and encapsulating agents, clean agents or ILDs. Hence, for at least the immediate future, the performance of these fire protection options needs to rely on experimental results.

7. Future Research Plan

The previous section identified the two principal areas where gaps exist that inhibit the performance of rigorous risk assessments to determine the appropriate method of fire protection for a hangar.

One of the areas involves the collection of fire incident data to provide a means to estimate the performance of fire protection solutions. As a short-term initiative, continued efforts can be pursued to obtain information from the range of stakeholders of aircraft hangars. Requests for such data could be extended to insurers, airlines, aircraft hangar operators and ARFF.

Longer term, a proposal should be developed and forwarded to the U.S. Administration to add a property use code explicitly for hangars (with 880, 881 and 882 being used for various vehicles storage facilities, and with 883 currently not being used, 883 could be proposed for aircraft hangars). Any data analysis of incidents in NFIRS would need to be delayed by at least a year should this change be implemented to allow the database to be populated with fire incidents using the 883 (or other) code.

The other significant gap indicated in the previous section was conducting research to explore the performance of fire protection solutions in hangars. As a result of restrictions being implemented for PFAS-containing foams, several research efforts have been conducted to explore alternative design solutions, as reviewed in Section 4. Many of the recent efforts have explored the feasibility of the solutions reviewed in Section 4, though much research is still needed to explore limitations of the solutions and identify design optimizations.

Conducting quantitative consequence analyses require improved analytical capabilities. As identified in Section 6, improvements are needed relative to developing simulations which can address the application of foam and wetting and encapsulating agents. The application of existing numerical simulations to assess the performance of sprinkler and water mist systems require input data that addresses the characteristics of the initial water spray.

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Appendix A: UMD Survey Form



Department of Fire Protection Engineering

Data Collection Form, Foam Suppression System Discharge Analysis

Date of incident _____ Location (city, state) _____

Size hangar (note group or area/door height)

Group (per NFPA 409) _____

Area _____, Door height _____

Consequences

Injuries

Fatal _____ Nonfatal _____

Damage to building, building systems (\$) _____

Damage to aircraft (\$) _____

Damage to other building contents (\$) _____

Other damage

Business interruption (\$ or describe) _____

Environmental (\$ or describe) _____

Cause for activation (place 'X') (feel free to include brief commentary on incident)

Fire

Fire from fuel spill _____ Fire from other _____ Non-fire _____

Intentional/malicious activation _____

Suppression system failure _____

Detection false alarm _____

Improper maintenance _____

Error during testing/maintenance _____

Unknown _____

Note: date and location is requested to check for duplicate reports of same incident. Such information will not be conveyed in any reporting.

Appendix B: FPRF Survey Form

Questionnaire on Fire Incidents in Aircraft Hangars and Suppression System Performance

You are invited to participate in a research study conducted the Fire Protection Research Foundation, NFPA's research affiliate, where the objective is to establish an evaluation method that can be used to assess the performance of fire protection systems for aircraft hangars. The project summary for the "Performance Criteria for Aircraft Hangar Fire Protection Systems" study is available [here](#).

This questionnaire has been created as part of this study to collect information on fire incidents and suppression system activations in aircraft hangars to ensure that design fires and the corresponding performance criteria for suppression systems is reflective of incidents in aircraft hangars today. The questions below seek your responses specific to fire incidents in aircraft hangars. If you have multiple incidents to report, we request that you retake this questionnaire by clicking the same URL to report additional incidents.

Your participation in this research questionnaire is voluntary. You may skip any question that you are not able to answer. The information you provide through this survey will be anonymous. This means that your name or organization will not be collected or linked to the data in any way. The anonymized and compiled results of this survey will be used in the final documentation of this study, but your identity will not be disclosed.

We thank you for your time and participation. The survey deadline is September 10, 2021.

If you have any questions regarding this questionnaire, please contact Victoria Hutchison, Fire Protection Research Foundation, at vhutchison@nfpf.org or Jim Milke, at University of Maryland at milke@umd.edu.

Baseline Incident Information

1. On what date did the incident occur?

Date:

2. Where was the incident located (state, country)? This information will not be shared, but will only be used to ensure incidents are not duplicated in the data.

3. According to the Hangar Classification Groups identified in NFPA 409, what hangar group did this incident occur in?

- ☐ Group I
- ☐ Group II
- ☐ Group III
- ☐ Group IV
- ☐ Unknown

4. What was the approximate size of the hangar (area)?

- ☐ 5,001 - 8,000 ft²
- ☐ 8,001 - 12,000 ft²
- ☐ 12,001 - 15,000 ft²
- ☐ 15,001 - 20,000 ft²
- ☐ 20,001 - 30,000 ft²
- ☐ 30,001 - 40,000 ft²
- ☐ Unknown
- ☐ Other (please specify)

5. What was the height of the hangar door?

- ☐ Less than or equal to 28 ft
- ☐ Greater than 28 ft
- ☐ Unknown
- ☐ Other (please specify)

6. Was a fire suppression system installed in the hangar?

- ☐ Yes
- ☐ No

7. What type of suppression system was installed?

- ☐ Sprinkler
- ☐ Hi-expansion foam
- ☐ AFFF
- ☐ Low-level, low-expansion foam
- ☐ Low expansion foam at ceiling
- ☐ Foam, unknown type
- ☐ Foam-water deluge
- ☐ Other (please specify)

- ☐ Not applicable

8. Did the installed suppression system activate? If the system activated, but not as intended, please explain the reasoning, if known, in the comment field.

- ☐ Yes

☐ No

☐ Not Applicable

If the system activated, but not as intended, please explain the reasoning here, if known.

9. If the suppression system did not activate, please explain the reason for the lack of activation.

10. Did this incident result in any injuries?

☐ Yes

☐ No

11. How many people were injured in this incident?

12. Did this incident result in any fatalities?

☐ Yes

☐ No

13. How many fatalities were there, directly related to this incident?

Please indicate any damage or financial loss as a result of the incident, to the categories listed below:

	Damage?	Financial Loss?
Building/Building Systems	☐	☐
Aircraft	☐	☐
Business Interruption	☐	☐
Environmental	☐	☐

Please provide additional relevant information here.

Cause for Activation of Suppression System

15. If the suppression system activated, was it in response to a fire?

☐ Yes

☐ No

16. If the system activated in response to fire, what was the contributing factor for the fire incident?

☐ Fuel Spill

☐ Other (please specify)

17. If the cause of the fire was a fuel spill, please provide the following information:

Size of fuel spill
(ft² or m²)

Cause of fuel spill

Type of
containment
measures used

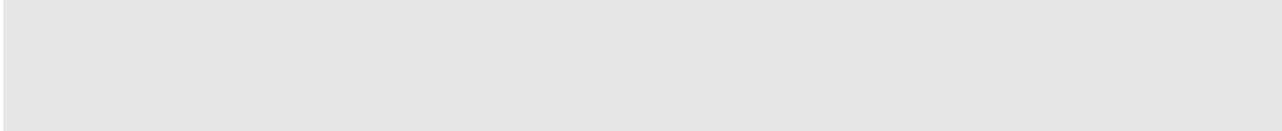
18. If the suppression system activated as a result of fire, what was the cause of ignition?

- ☐ Operating Equipment (e.g., spark, ember, flame, radiated or conducted heat, electrical failure, electrical arcing, or heat from operating equipment)
- ☐ Hot or Smoldering Object (e.g., hot work operations, sparks from friction, hot metal fragments, etc.)
- ☐ Explosives, Fireworks
- ☐ Other Open Flame or Smoking Materials (e.g., cigarette, pipe or cigar, match, lighter, candle, fuse, flare, backfire from internal combustion engine, open flame, etc.)
- ☐ Chemical, Natural Heat Sources (spontaneous combustion, chemical reaction, lightning, static electricity discharge, etc.)
- ☐ Heat Spread From Another Fire (e.g., heat from direct flame, radiated from another fire, flying brands, embers, sparks, etc.). Excludes operating equipment.
- ☐ Other Heat Sources
- ☐ Unknown
- ☐ Other (please specify)

19. If the fire suppression system activated, without the presence of fire, please indicate the cause of activation:

- ☐ Intentional/malicious activation
- ☐ Suppression system failure
- ☐ Detection False Alarm
- ☐ Improper maintenance
- ☐ Error during testing/maintenance
- ☐ Unknown
- ☐ None of the above

In further detail, please explain the cause of the accidental discharge.



Thank you for your participation in this questionnaire. Please click "done" to submit your responses. If you have another incident to report, please re-click the survey link and follow the same process. Thank you.

Appendix C: Summary of Results from FPRF Survey

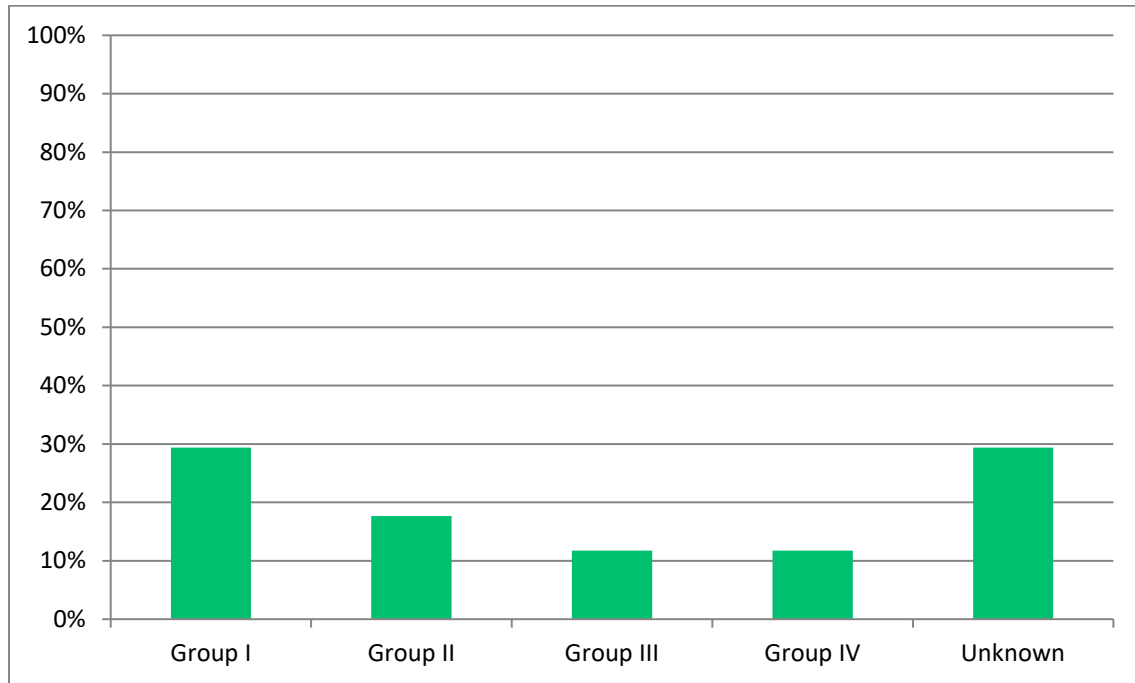


Figure C-1: Question 3: According to the Hangar Classification Groups identified in NFPA 409, what hangar group did this incident occur in?

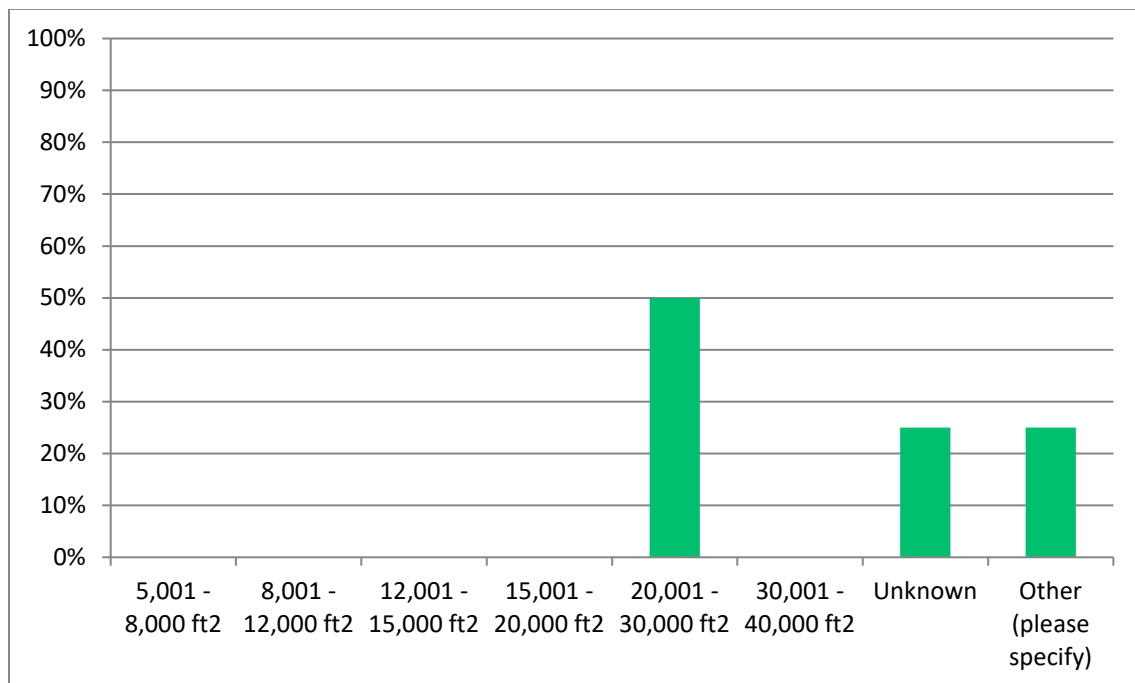


Figure C-2: Question 4: What was the approximate size of the hangar (area)?

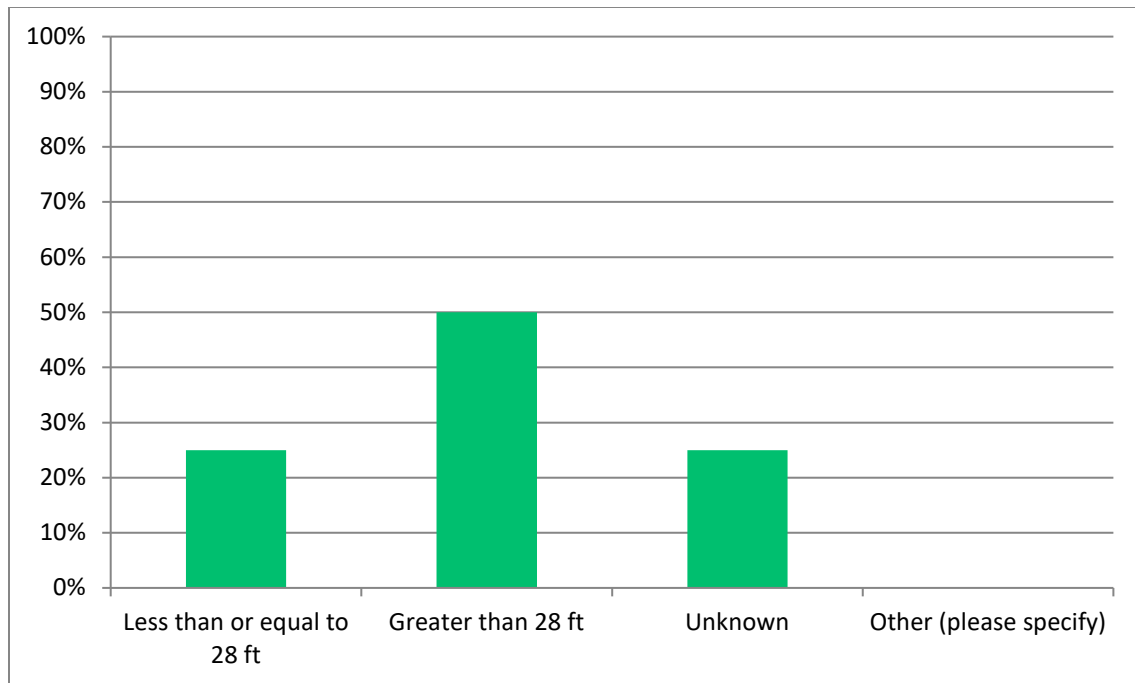


Figure C-3: Question 5: What was the height of the hangar door?

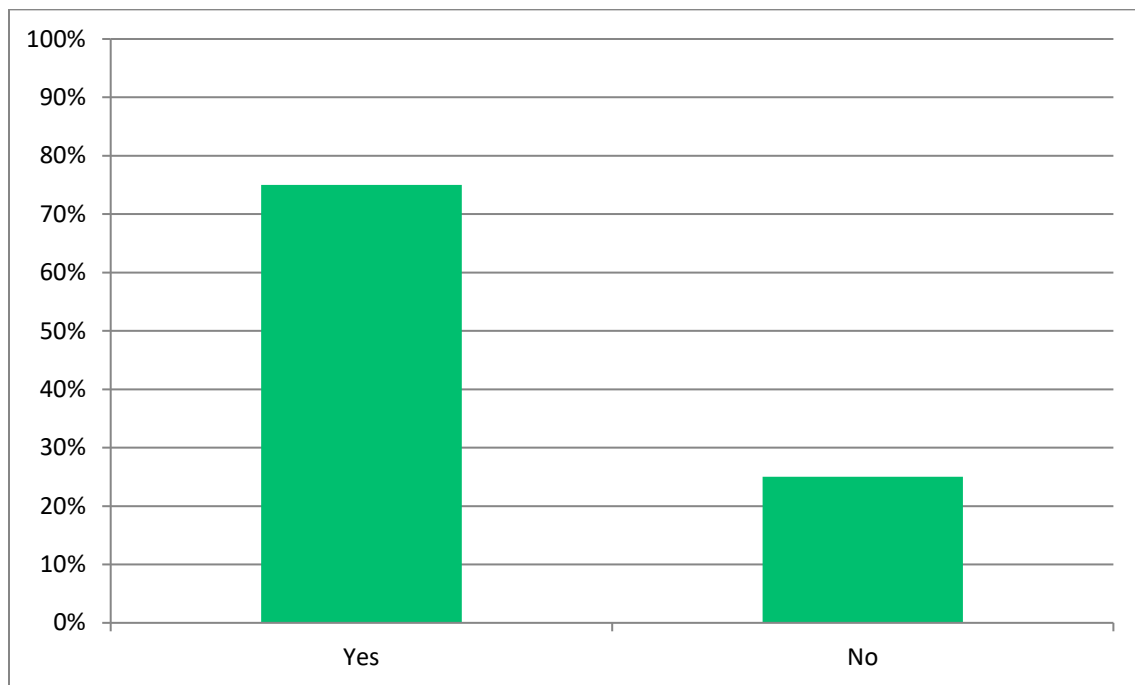


Figure C-4: Question 6: Was a fire suppression system installed in the hangar?

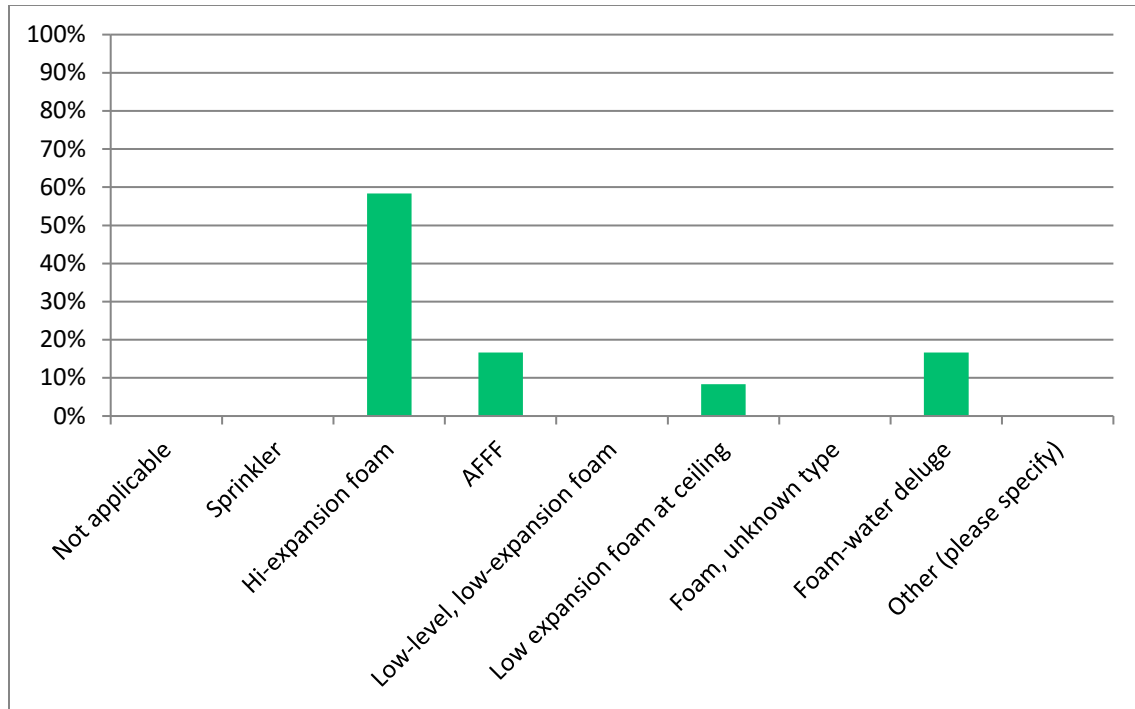


Figure C-5: Question 7: What type of suppression system was installed?

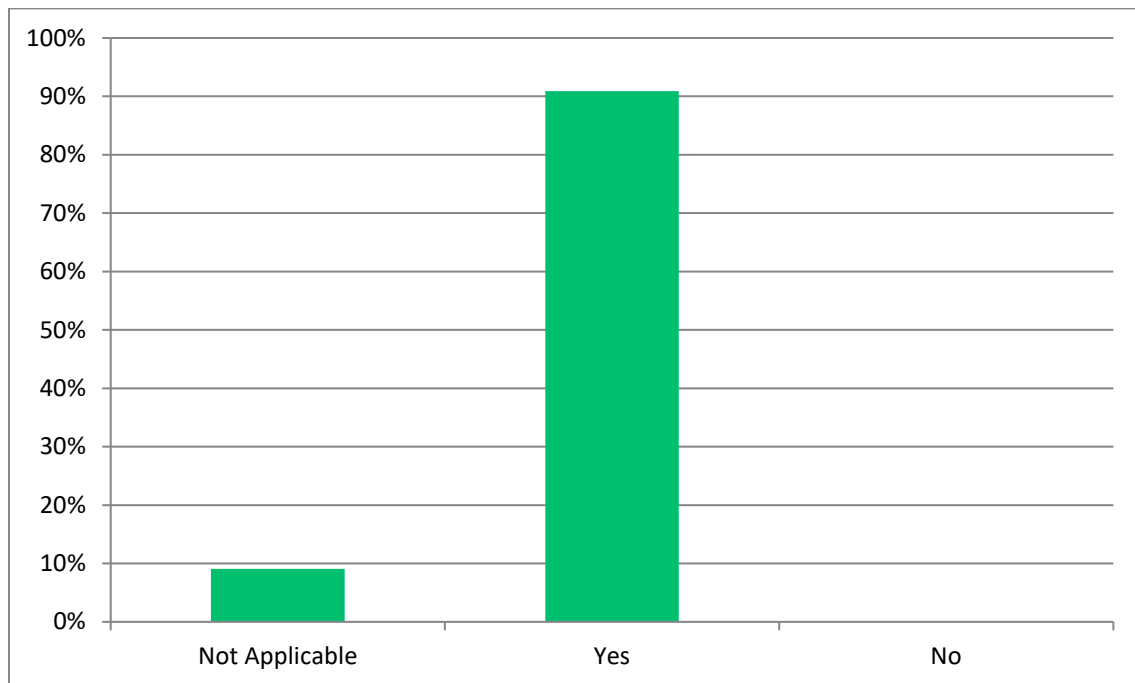


Figure C-6: Question 8: Did the installed suppression system activate?

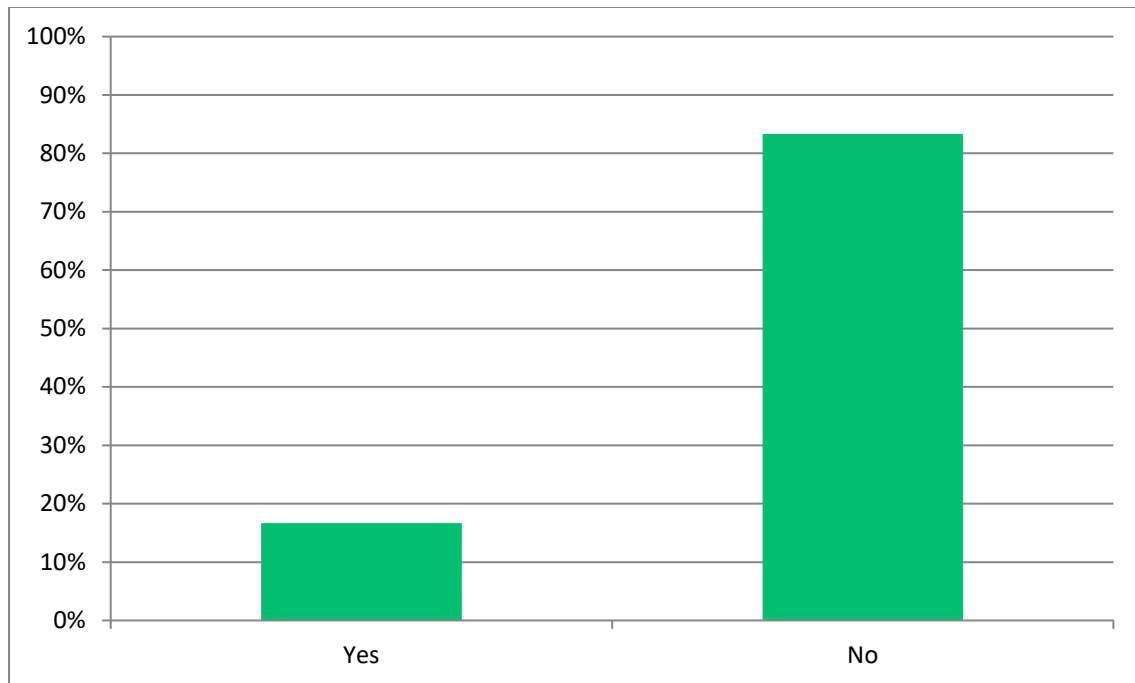


Figure C-7: Question 10: Did this incident result in any injuries?

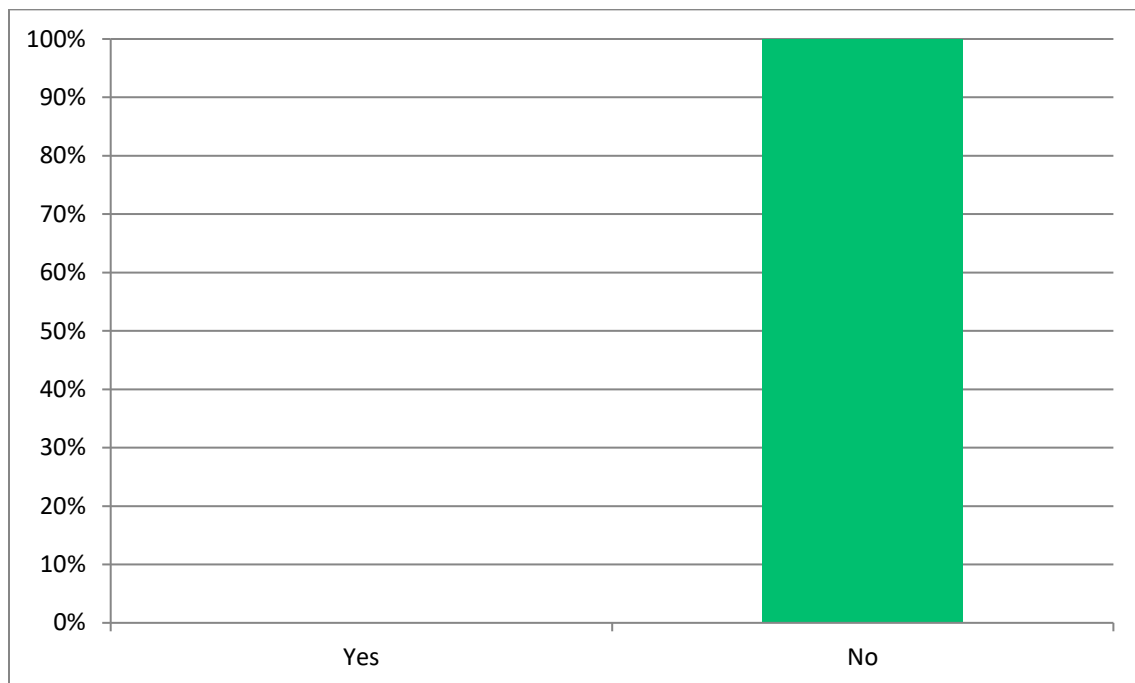


Figure C-8: Question 12: Did this incident result in any fatalities?

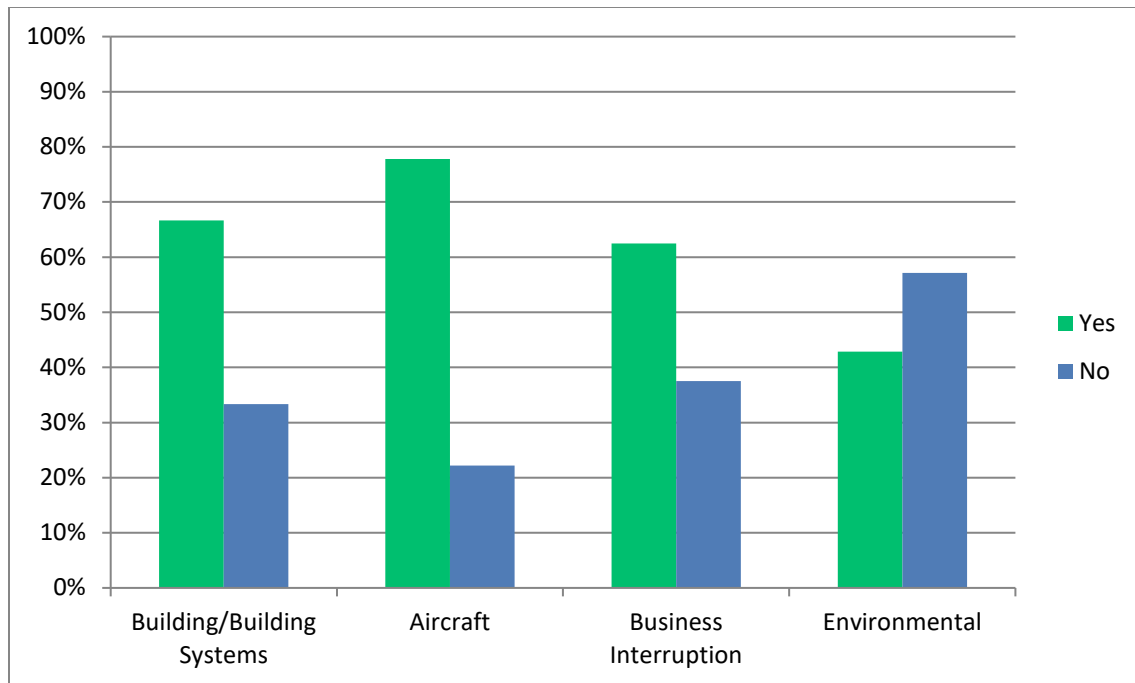


Figure C-9: Question 12: Facility Type?

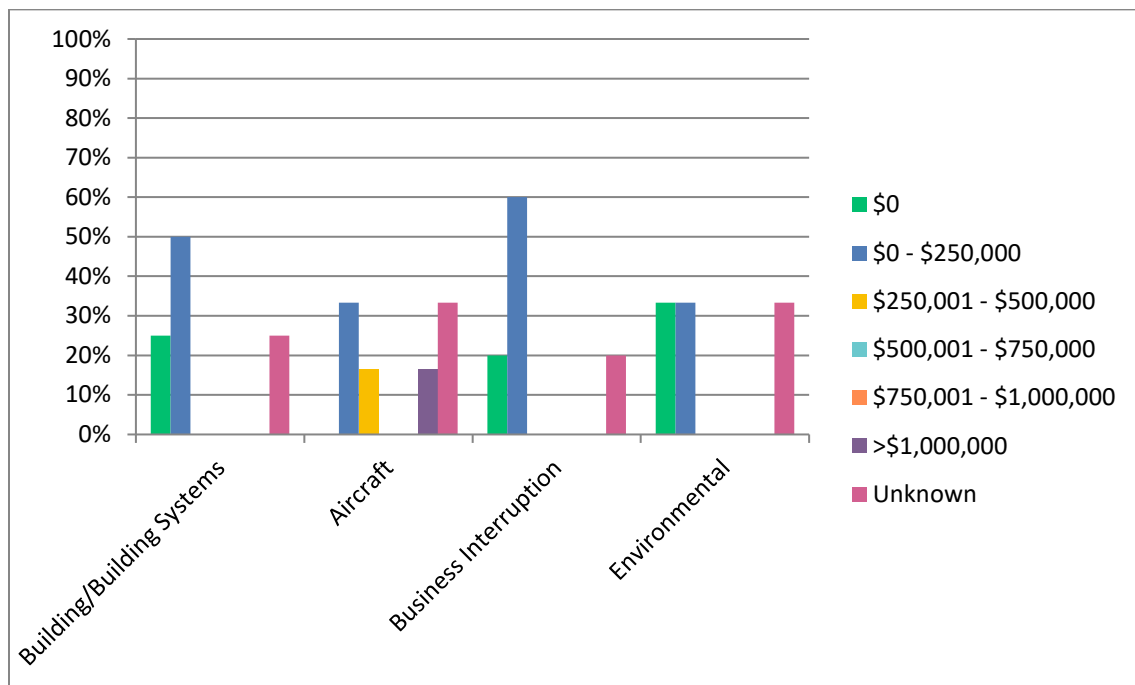


Figure C-10: Question 14: Please indicate any damage or financial loss as a result of the incident?

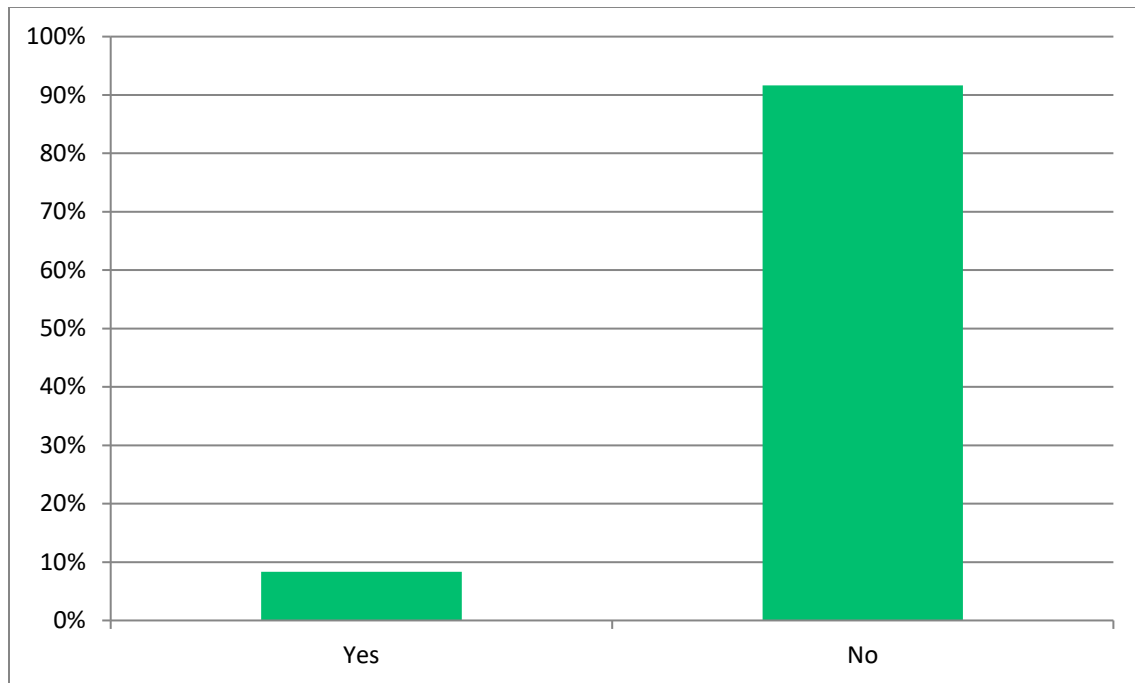


Figure C-11: Question 15: If the suppression system activated, was it in response to a fire?

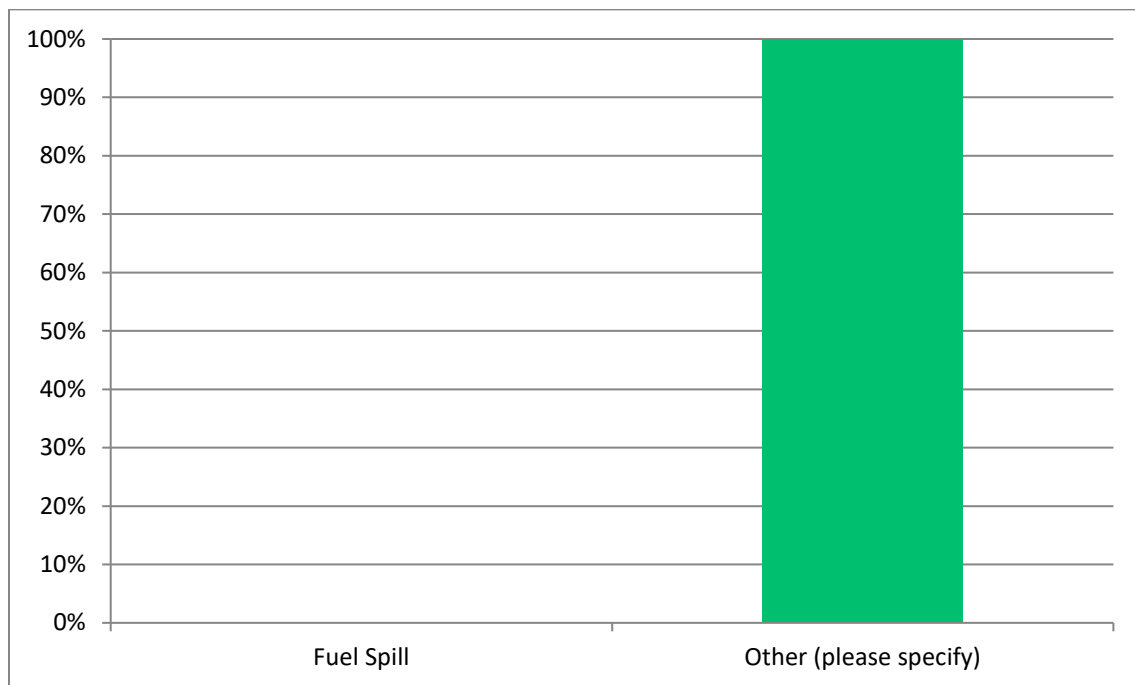


Figure C-12: Question 16: If the system activated in response to fire, what was the contributing factor for the fire incident?

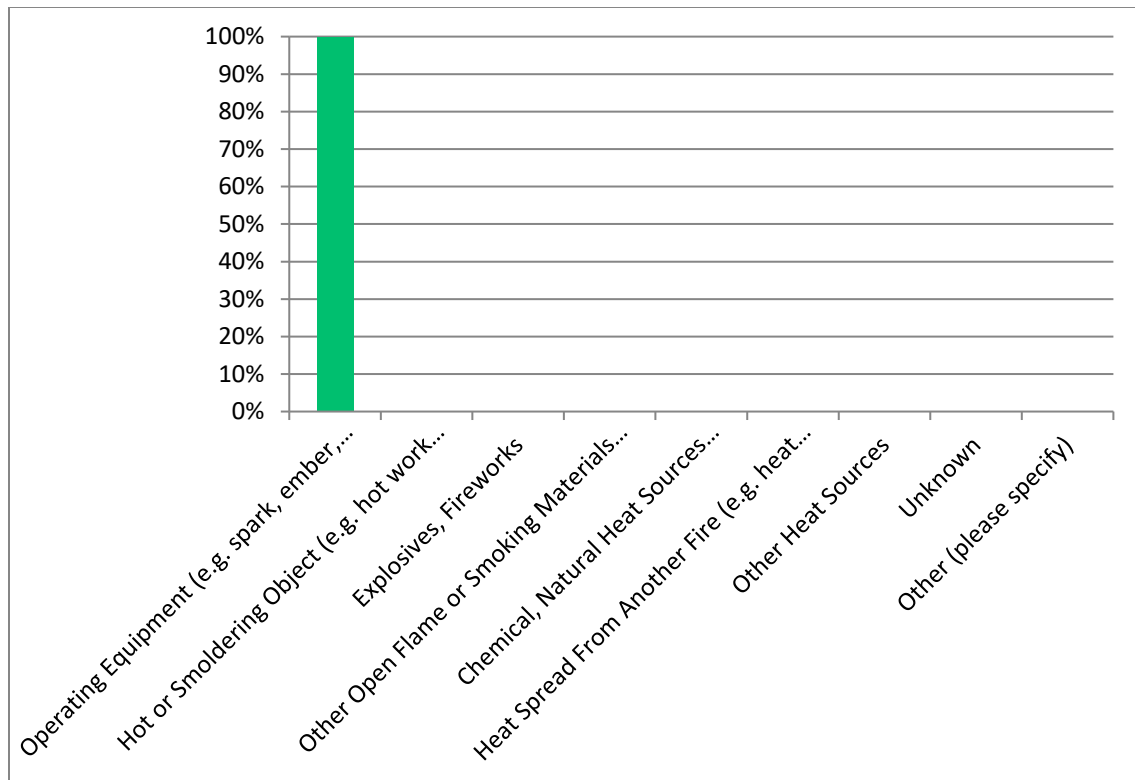


Figure C-13: Question 18: If the suppression system activated as a result of fire, what was the cause of ignition?

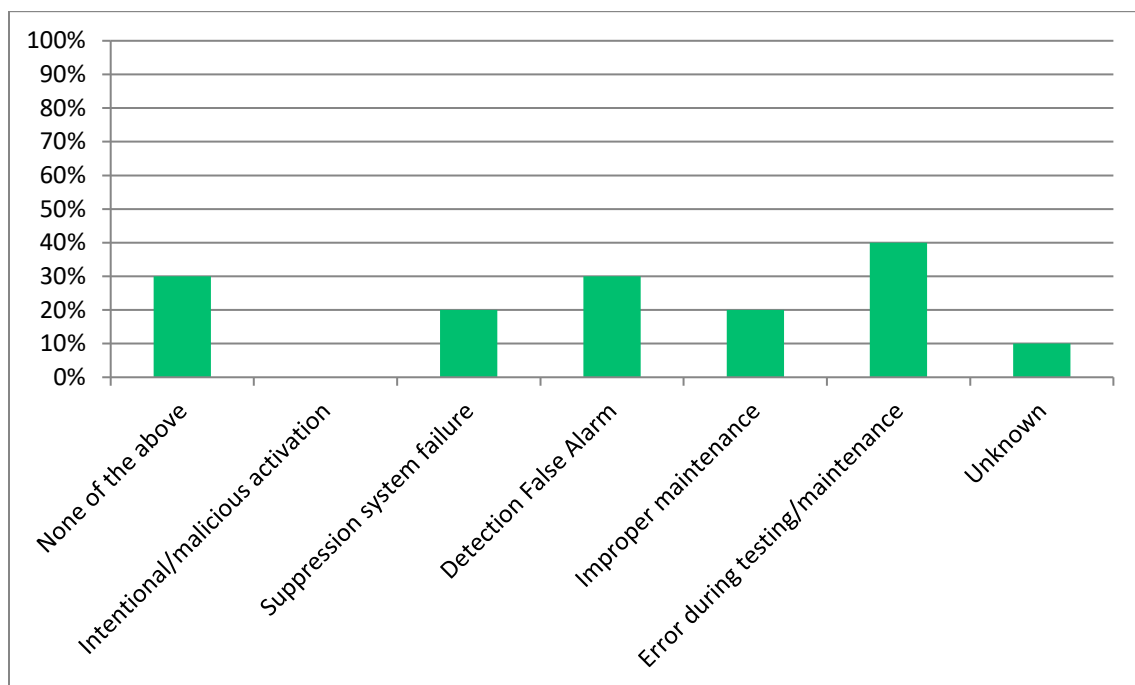


Figure C-14: Question 19: If the fire suppression system activated, without the presence of fire, please indicate the cause of activation?