Fire Suppression Systems in Aircraft

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All work in this thesis is original, except where stated

Abstract

Halons have been used for suppression on aircraft for decades. However, halons cause damage to the ozone layer during their production and decomposition. Consequently, recent legislation requires alternatives to halon suppression to be available for use on aircraft in the near future. This thesis reviews and discusses the progress made in developing new suppression systems for aircraft; the overall aim is to determine how suppression systems on aircraft can be improved upon and whether progress in developing new systems is adequate.

It was found that using halon as a benchmark for suppression was inappropriate. A more performance-based approach should be used for developing suppression. Additionally, substances under consideration as replacements still produce the same environmental damage as halons. Review material demonstrates that efforts to develop suppression are split into four sections: the cabin, the engine and APU, the lavatory trash receptacle, and the cargo bay. Improvements can be made and are suggested for all four areas -- particularly the cabin, where there are multiple flaws in the development process. With the exception of the cabin, progress in developing suppression is satisfactory, and replacements will likely be available before halon is banned. Testing methods are suggested in this thesis to assist in development.

Moreover, new fire risks -- such as composites used on aircraft, and lithium batteries -- are assessed to determine how they affect suppression requirements. It is concluded that these risks can be mitigated without suppression, and provide some benefits for overall fire-safety.

Acknowledgements

I would like to thank all those who have helped me along the way with my thesis and, as this is my last piece of university work, all those who have helped me with my degree. Firstly I'd like to thank Dr. Ricky Carvel for being a brilliant thesis supervisor who was always on hand to answer my questions and discuss my progress. And I'd like to thank Dr. Stephen Welch for providing valuable feedback and suggestions in the first weeks of my thesis. I'd also like to thank my excellent proof reader Jen Blyth for having the patience to read my work and put up with my stressing throughout my degree. Additionally I'd like to thank my parents for supporting me through my degree, my fellow students for making the years memorable, and Edinburgh University for employing outstanding engineering lecturers.

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1 Introduction

Replacement suppression systems for aircraft need to be developed due to an EU ban on ozone depleting substances (ODS). The ban includes halons used for suppression on aircraft. This thesis details and discusses the development of those systems.

The ban on the production of ODS came into enforcement in the 1990's. An exception was made for aircraft and they were allowed to continue using recycled ODS due to the unique challenges of fire on an aircraft. However, more recent EU legislation of 2010 states that aircraft suppression may no longer use ODS.
This thesis includes:

- Background information of the challenges of fire on aircraft
- Details of the ban on halon
- New fire challenges on aircraft
- Review of suppression on aircraft and systems being developed
- A critical discussion of the progress made, detailing the problems of suggested safety strategies and potential improvements
- Testing methods which could be used to prove the effectiveness of suppression

The main aim of the thesis is to determine if adequate progress has been made in developing new systems in time for the ban on halon, and suggest improvements for the fire safety strategy.

2 Background

Understanding the background of fire safety on aircraft is vital in determining what is required of suppression.

2.1 History and Problems of fire on aircraft

This details how fire on aircraft has occurred in the past and how it has been dealt with. It also includes the specific challenges of fire on an aircraft.

2.1.1History

Halons 1211 and 1301 have been the main suppression agents on aircraft for 50 years. They have been extremely effective at suppression for multiple reasons:

- High flooding capacity
- Low-toxicity
- Non-conductive
- Light weight
- Non-corrosive
- Easy to clean
- Strong suppressant

When fire occurs in aircraft, systems are modified and improved to prevent the same fire occurring again. This learning-from-disaster approach has produced an effective safety strategy which means that fatal fires on aircraft are rare.

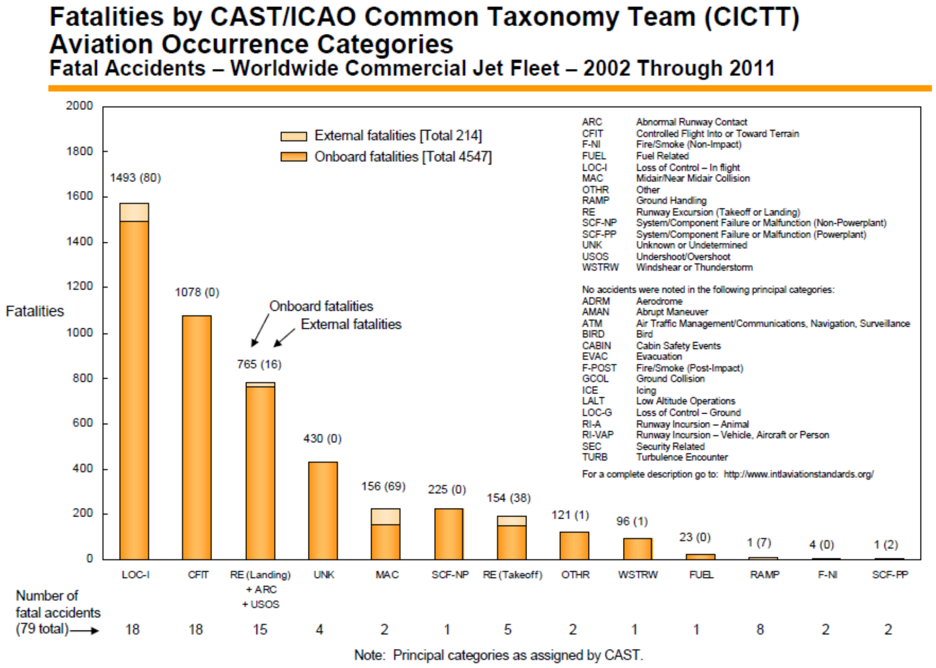


Figure 1 – Fatal Accident occurrence for Boeing aircraft [1]

Figure 1 may not accurately reflect deaths due to fire on an aircraft. For example, loss of control can be caused by fire.

2.1.2 Specific dangers of fire on an aircraft

Several factors make fire on aircraft specifically dangerous:

1) Lack of egress or fire department
   If there is a fire in a building, occupants are alerted and evacuated and fire services respond within 10 minutes. In an aircraft, however, it can take in excess of 200 minutes [2] before egress can start. In this time, smoke can lead to asphyxiation; radiation could fatally burn; and damage could cause loss of control. Egress will also be slow on the ground due to limited exits.

2) Recycled air supply
   Toxic fumes cannot escape: any suppressant or smoke produced in the aircraft will stay. Breathing apparatus is provided to prevent asphyxiation but harmful gases can still cause extreme discomfort to eyes and skin.

3) Vulnerable electronics and flammable material
   Potentially large fire loads are present on aircraft, including:

- mechanical components
- electronics
- fuel
- cargo

Efforts are taken to reduce this fire load [3] though this does not prevent the potential for fire. If fire occurs in the mechanics or electronics, it can lead to loss of control. A spark or fire in the fuel tank can cause an explosion, ultimately destroying the aircraft. A fire in the cargo bay, however, produces smoke and radiation, and can degrade the structure to cause decompression.

4) False alarms
A false alarm of fire on aircraft can be dangerous. If an alarm is activated, the aircraft must land at the nearest available site. If the landing site was not designed for the aircraft, it can be a dangerous landing. If the alarm activates in a hidden compartment -- e.g. the cargo bay or the auxiliary power unit -- then fire cannot be confirmed unless a camera is present.

2.1.3 Specific suppression challenges

Several factors make suppression on aircraft specifically challenging:

1) Inaccessible and hidden areas
Some areas cannot be accessed or seen by occupants, such as:

- Wall cavities
- Cargo bays
- Engine nacelles
- Auxiliary power units
- Landing gear
- Avionics bay
- Fuel tank and dry bay
- Lavatory trash receptacle

This makes suppression difficult, as occupants cannot manually suppress it. They may not know where the fire is, how large it is, or what damage it is causing.

2) Weight restriction
Halons are ideal for suppression on aircraft due to their lightness as they don’t significantly increase the fuel required. Most other suppression systems are heavier than halons.

3) System must not harm occupants or aircraft
   Suppression used must be non-conductive, non-corrosive and non-toxic; it also must not physically damage the aircraft due to strong release force.

4) Environmental restrictions
   Under legislation, aircraft suppression systems must not have a global warming potential or be an ozone-depleting substance, due to its decomposition in fire or its production.

5) Detection issues
   Determining where a fire is can be a problem and has led to disaster before. As stated in section 2.1.2, false alarms can be hazardous.

6) Multiple states of the aircraft
   Suppression must be effective in all conditions of the aircraft. This includes:

   - In-air
   - on the ground
   - unoccupied
   - post-crash

   In-air is the main threat to life safety; it is the most common state and most dangerous. If the suppression system can work in the air, it will work on the ground. An unoccupied aircraft is not a threat to life but is a threat to the aircraft. Post-crash, however, is a difficult challenge for suppression as there is no guarantee suppression systems will be working, or that any trained occupants will be conscious to use them.

2.1.4 Different types of aircraft

There are different types of aircraft which need to be considered for fire safety. They each have different scenarios and objectives for fire safety:

1) Passenger Jet
   Passenger jets have the most occupants; when fire does occur, the number of people at risk is greater than on other forms of aircraft. Occupants are mostly untrained in fire safety and may accidently carry hazardous materials or start a fire.

2) Cargo Plane
   Providing fire safety on a cargo plane is a challenge. Cargo containers have unknown fuel and there are many inaccessible and hidden areas. Furthermore, the crew is limited: there are fewer personnel available to fight the fire.

3) Light aeroplane
   If fire safety can be provided on a passenger jet, then it can be provided on a light aeroplane. This is assuming that the crew are trained and aware of the risk, and that the aircraft is properly equipped and maintained.

4) Military Jet
   Defence departments often undertake their own research and provide their own devices for fire safety on military equipment. Military equipment is not used as regularly as other forms of aircraft but there is a larger risk of fire due to enemy attacks.

5) Helicopter
   Fire safety strategy for a helicopter can differ greatly from that of other forms of aircraft due to its different form.

2.1.5 Case Studies

It is important to understand how fire has occurred in the past and what damage it has caused in order to know what is required of new suppression systems. These case studies are a selection of the very worst instances of fire on aircraft, focusing on different areas and causes. The details of these studies can be extensive; therefore, only major details are provided along with references, should further information be required.

2.1.5.1 Wall Cavities

1) Concealed electronic fire above ceiling -- 250 passengers. Less than 20 minutes after an unusual odour was detected, the aircraft crashed into the ocean. The aircraft was destroyed with no survivors [4].

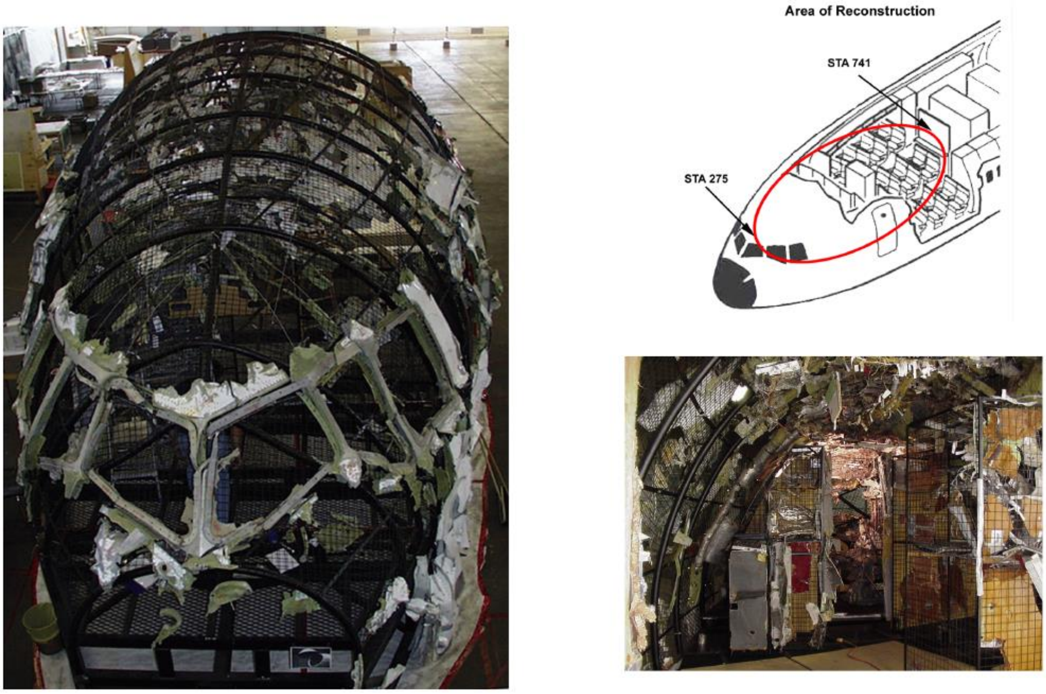


Figure 2 – Reconstruction of case study wall cavities 1 [4]

2) Concealed electronic (suspected) fire behind back wall of lavatory -- 41 passengers. Gas masks were not provided and delays were caused before landing. One minute after the aircraft landed, flashover occurred, 23 fatalities [5]

2.1.5.2 Fuel Fires

1) Fuel tank on left wing punctured during take-off. The fuel ignited and take-off was abandoned. The fire quickly spread to the cabin and the aircraft was destroyed. 55 fatalities [6].

2) Fire caused by fuel leak after in-air refuelling. The fire spread and caused an explosion in-flight and the aircraft was destroyed. No survivors [7].

2.1.5.3 Cargo Container fires

1) Transportation aircraft crew of two. Fire reported in cargo compartment in-flight. No suppression system present. 29 minutes after fire was detected, the aircraft crashed and was destroyed. No survivors [8].

2) Passenger aircraft -- 105 passengers. Fire occurred in Class D cargo bay due to mishandled chemical oxygen generators. No suppression was required in cargo bays of this class; fires were to be controlled through oxygen starvation. As an oxygen generator was fuelling the fire, the aircraft crashed and was destroyed 10 minutes after take-off. No survivors [9].

2.2 Ban on Halon

This section details what a halon is, how it is used, and the exact details of its ban.

2.2.1 Description of Halon

There are three types of halon used on aircraft [10]:

1) Halon 1211 is used in portable extinguishers and is a streaming agent
2) Halon 1301 is used in fixed extinguisher installations and is a total flooding agent.
3) Halon 2402 is used though it is not as common [11]

(From now on, when halon is mentioned it will refer to these three types.)
A halon is an organic compound containing both carbon and a halogenated atom. Halons are classified according to the number of atoms it contains e.g. halon(carbon)(fluorine)(chlorine)(bromine). For example, a halon with 1 carbon, 2 fluorine, 3 chlorine and 4 bromine would be Halon1234 [12]. It is the chlorine and/or bromine which makes halon an ODS [13] when halon is produced or decomposes. It is also these atoms which make halon effective at suppression [11]. Halon is ideal for suppression for multiple reasons:

- High flooding capacity
- Low-toxicity
- Non-conductive
- Light weight
- Non-corrosive
- Easy to clean
- Strong suppressant

2.2.2 Details of EU Ban

The Montreal agreement [14] banned production of ODS in 1994. Their production caused damage to the ozone layer; the ban was an attempt to 'heal' that damage. Usage continued with recycled and leftover material, until EC Regulation 2037/2000 [15] put a ban on the use of all ODS. Exceptions were made for areas where conventional suppression was not an option; this included aircraft. Recent EU legislation from 2010 [16] requires aircraft to cease using ODS by these deadlines.

	Lavatory Trash Receptacle	Fuel Tank	Dry bays	Handheld	Engine and APU	Cargo Bay
New Design	2011	2011	2011	2014	2014	2018
Current Design	2020	2040	2040	2025	2040	2040

Table 1- EU deadlines for halon replacement [11]

New design means alternatives must be available. Current design means halon usage must stop.

The different dates represent the challenges involved -- e.g. receptacle extinguishers are the easiest to replace, whilst cargo bays are the most challenging. The international Civil Aviation Organization differs from EU legislation, stating aircraft should have replacements for receptacle and handheld extinguishers as soon as they become available [17].

3 New Fire Risks

Aircraft designs are constantly evolving. Next generation aircraft have recently been unveiled by Boeing and Airbus. These designs provide new fire risks which must be considered for new suppression systems.

3.1 Composites in aircraft

Composite structures are now replacing aluminium due to their lightness and resilience. Unlike aluminium, however, composites burn -- this is a new fire risk.

3.1.1 Transition to composites

Aluminium has been the main material for aircraft construction for several decades, though there are problems with it:

- Heavy so it needs more fuel
- Expensive
- Hard to maintain

Recent efforts have led to aircraft using lightweight composites in their design. This means aircraft will use less fuel and be more sustainable economically and environmentally. Unlike aluminium, composites can catch fire. This is a new fire hazard for aircraft which must be considered in the design of new suppression systems.

3.1.2 What composites and where

The type of composite used determines the fire load which will be present. The design of composites can differ depending on the location in the aircraft and the preference of the manufacturer. Any composite used will have a high-strength fibre such as carbon or glass [18].

Composites are already used in some aircraft, most notably the Boeing 787, which uses different types of composite material.

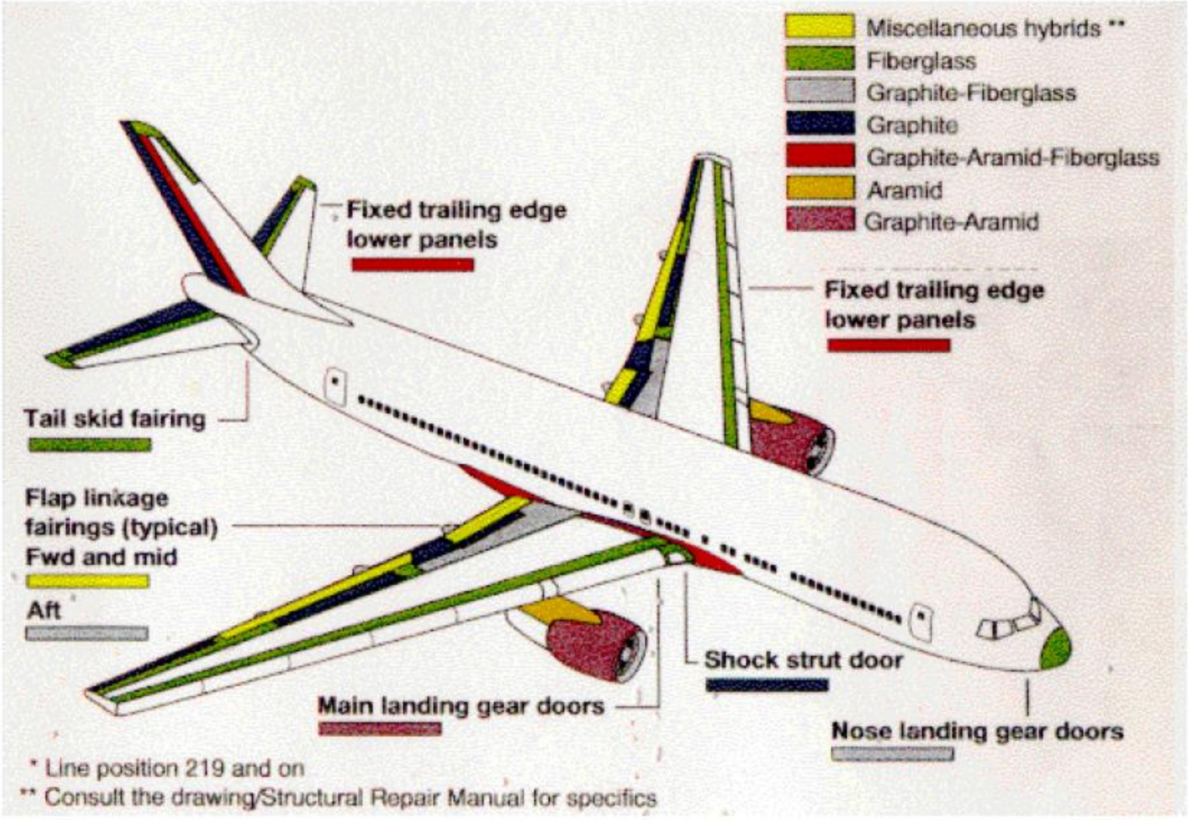


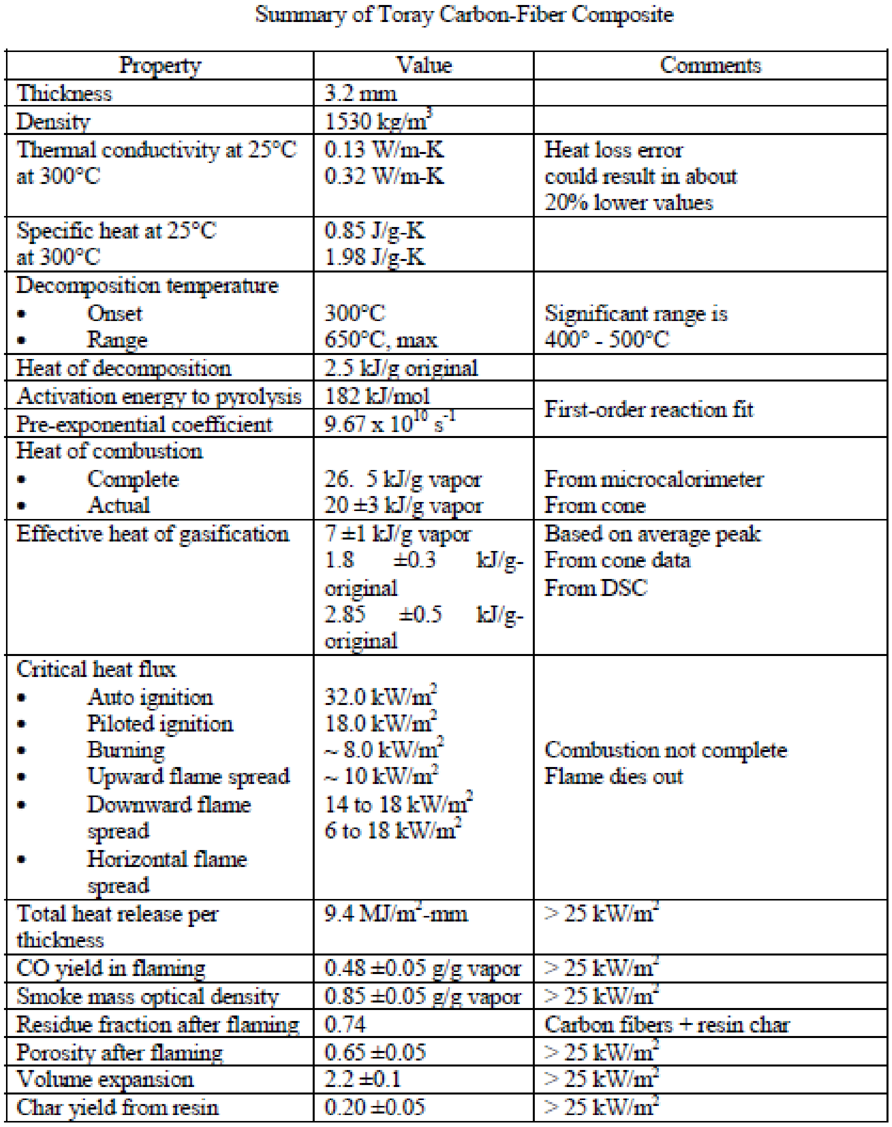
Figure 3 - Composite areas of a Boeing 787 [19]

It is unclear how much of an aircraft will be composed of composite materials in the future; potentially anything non-mechanical could be a composite. Figure 3 indicates that the main fire risks, in the fuselage, are still made of aluminium.

3.1.3 Thermal Properties

Although the types of composite used vary, estimates can be made of their thermal properties. It is important to compare these properties to aluminium to determine the change in fire risk. Tests show aluminium melts at 660 °C [20]; since it has a melting point, structural failure is rapid. Composites degrade and burn between 300-500 °C; [20] they will continue to maintain structural integrity during this process, until it burns through. There is no accurate burn time available due to the variables involved: such as the thickness, and type of composite. But it is expected that composites will maintain structural integrity longer then aluminium would [20].

Table 2 shows the thermal properties of a carbon-fibre composite material. Experimental methods used to find these properties are extensive [20].



Summary of Toray Carbon-Fiber Composite

Property	Value	Comments
Thickness	3.2 mm	
Density	1530 kg/m^3	
Thermal conductivity at 25°C at 300°C	0.13 W/m-K 0.32 W/m-K	Heat loss error could result in about 20% lower values
Specific heat at 25°C at 300°C	0.85 J/g-K 1.98 J/g-K	
Decomposition temperature • Onset • Range	 300°C 650°C, max	 Significant range is 400° - 500°C
Heat of decomposition	2.5 kJ/g original	
Activation energy to pyrolysis	182 kJ/mol	First-order reaction fit
Pre-exponential coefficient	9.67 x 10^{10} s^{-1}	
Heat of combustion • Complete • Actual	 26. 5 kJ/g vapor 20 ±3 kJ/g vapor	 From microcalorimeter From cone
Effective heat of gasification	7 ±1 kJ/g vapor 1.8 ±0.3 kJ/g-original 2.85 ±0.5 kJ/g-original	Based on average peak From cone data From DSC
Critical heat flux • Auto ignition • Piloted ignition • Burning • Upward flame spread • Downward flame spread • Horizontal flame spread	 32.0 kW/m^2 18.0 kW/m^2 ~ 8.0 kW/m^2 ~ 10 kW/m^2 14 to 18 kW/m^2 6 to 18 kW/m^2	 Combustion not complete Flame dies out
Total heat release per thickness	9.4 MJ/m^2-mm	> 25 kW/m^2
CO yield in flaming	0.48 ±0.05 g/g vapor	> 25 kW/m^2
Smoke mass optical density	0.85 ±0.05 g/g vapor	> 25 kW/m^2
Residue fraction after flaming	0.74	Carbon fibers + resin char
Porosity after flaming	0.65 ±0.05	> 25 kW/m^2
Volume expansion	2.2 ±0.1	> 25 kW/m^2
Char yield from resin	0.20 ±0.05	> 25 kW/m^2

Table 2- Summary of Composite thermal properties [20]

Thermal properties will differ depending on the composite; however properties should be similar.

The structural properties of composite will change as it is heated [20] which means they may change rapidly when cooled. This transformation could lead to structural failure during suppression; however, this will depend on the type of composite used.

3.2 Lithium Batteries

Lithium metal batteries are a new development used to power electronics on aircraft. They are preferable to traditional power sources due to their light weight; they may also be stored in the cargo bay or cabin. These batteries have recently been a fire hazard and are difficult to suppress.

3.2.1 Which aircraft use it

Lithium batteries were planned for use on two next-gen aircraft, the Airbus A350 and the Boeing Dreamliner 787. Aircraft also have to be capable of safely carrying lithium batteries in the cargo bay or cabin, although their transportation is restricted [21]. They will also be used on new F-35 military jets [22].

Their use on Boeing has caused several fires due to overheating .This resulted in the Boeing787 being grounded until the battery was considered safe by the FAA [23]. Due to this long and costly redesign, Airbus opted not to use them.

Another use for lithium batteries is in tesla electric cars, which use many small protected cells. This is a safer design as the heat release from one cell is not enough to ignite another [24]. This is in contrast to Boeing’s design which uses 8 large cells.

3.2.2 Where is it used

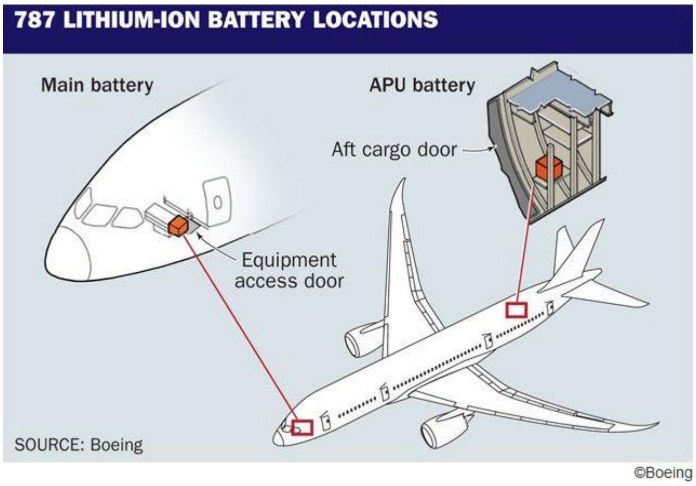


Figure 4 – Location of lithium batteries on a Boeing 787 [24]

Boeing787 has two batteries. One is in the avionics compartment, which powers the controls, entertainment and environmental systems. One at the rear is used with the auxiliary power unit.

They can also be transported in the cabin or cargo bay with the size and power of the battery restricted [25].

3.2.3 Why is it used

Lithium batteries have multiple benefits compared to traditional power sources:

- The battery is half as heavy
- It takes up half the space
- Less fuel and thrust required
- Easier and cheaper to maintain
- Less cabling required

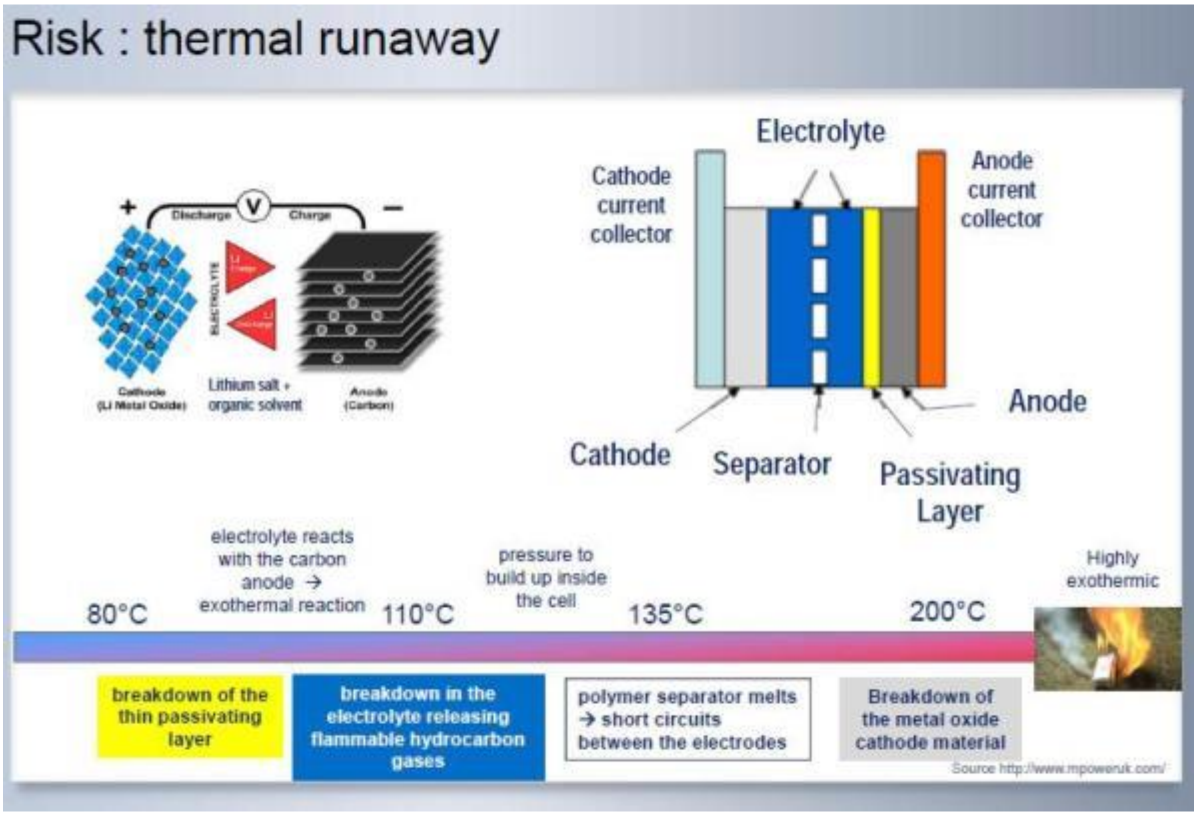
This makes flying more sustainable economically and environmentally. Boeing estimates that it will save 2% on the volume of fuel required [25].

3.2.4 Fire challenges

Lithium battery fires are dangerous for several reasons. In addition to them being highly combustible and potentially providing a high heat release rate, they are difficult to suppress effectively. This is due to thermal runaway and the fact that it produces oxygen as it burns [26]. This makes halon or water suppression ineffective. A suppression system would require halon to extinguish the battery and water to cool it down and prevent adjacent cells undergoing thermal runaway. This would be a streaming agent.

In previous lithium battery fires on aircraft, the fire has usually been extinguished with specialist equipment on the ground, generally a dry chemical extinguisher [26]. This is not ideal for use on aircraft as it can damage nearby electronics.

Smaller lithium battery cells are less of a risk due to less heat release and less chance of causing thermal runaway in adjacent cells. This means smaller batteries are easier to extinguish [24]



Risk : thermal runaway

80°C — electrolyte reacts with the carbon anode → exothermal reaction

110°C — pressure to build up inside the cell

135°C

200°C — Highly exothermic

breakdown of the thin passivating layer

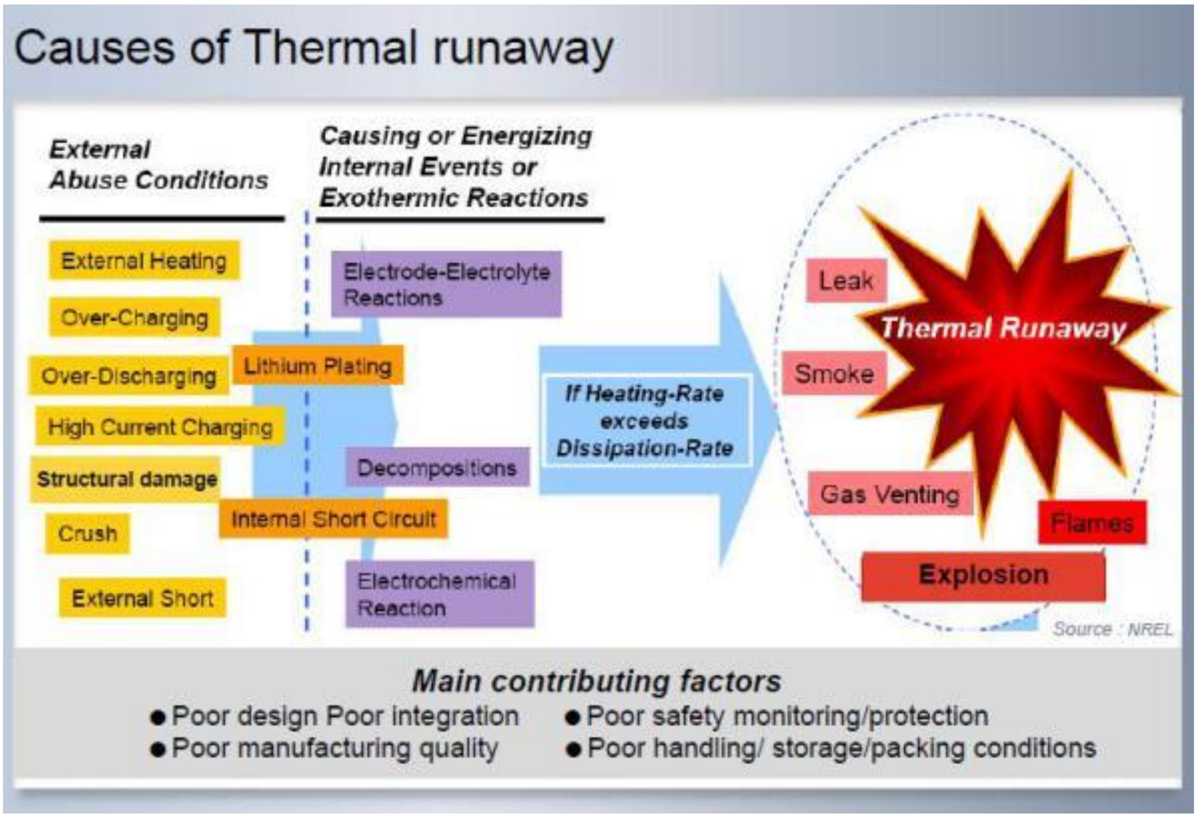
breakdown in the electrolyte releasing flammable hydrocarbon gases

polymer separator melts → short circuits between the electrodes

Breakdown of the metal oxide cathode material

Source http://www.mpoweruk.com/

Figure 5 – Lithium battery thermal runaway risk [26]



Causes of Thermal runaway

External Abuse Conditions

- External Heating
- Over-Charging
- Over-Discharging
- High Current Charging
- Structural damage
- Crush
- External Short

Causing or Energizing Internal Events or Exothermic Reactions

- Electrode-Electrolyte Reactions
- Lithium Plating
- Decompositions
- Internal Short Circuit
- Electrochemical Reaction

If Heating-Rate exceeds Dissipation-Rate

Source : NREL

Main contributing factors

- Poor design Poor integration
- Poor manufacturing quality
- Poor safety monitoring/protection
- Poor handling/ storage/packing conditions

Figure 6 – Lithium battery thermal runaway causes [26]

3.2.5 Fire protection

Size is restricted for batteries transported in the cabin and cargo bay so that suppression is capable of controlling the fire. Tests are being developed by the FAA to determine if these fires can be suppressed by halon replacements [27]. Tests have proven that bulk quantities of lithium batteries were insuppressible. After these tests, lithium metal batteries cannot be transported in bulk on an aircraft [28].

In the avionics compartment and APU, battery cells are too large to be suppressed. Fire protection focuses on preventing fire from occurring, and Boeing recently stated their 'battery redesign eliminates chance of fire' [29].

There are now multiple layers and forms of protection, most notably to prevent overheating:

- Gases which build up in the battery are now released
- Each cell is secured and compartmentalised
- The battery is sealed in a steel box and wrapped in tape; this would prevent a lithium battery fire spreading, and prevent air from getting into the battery so that a fire cannot start

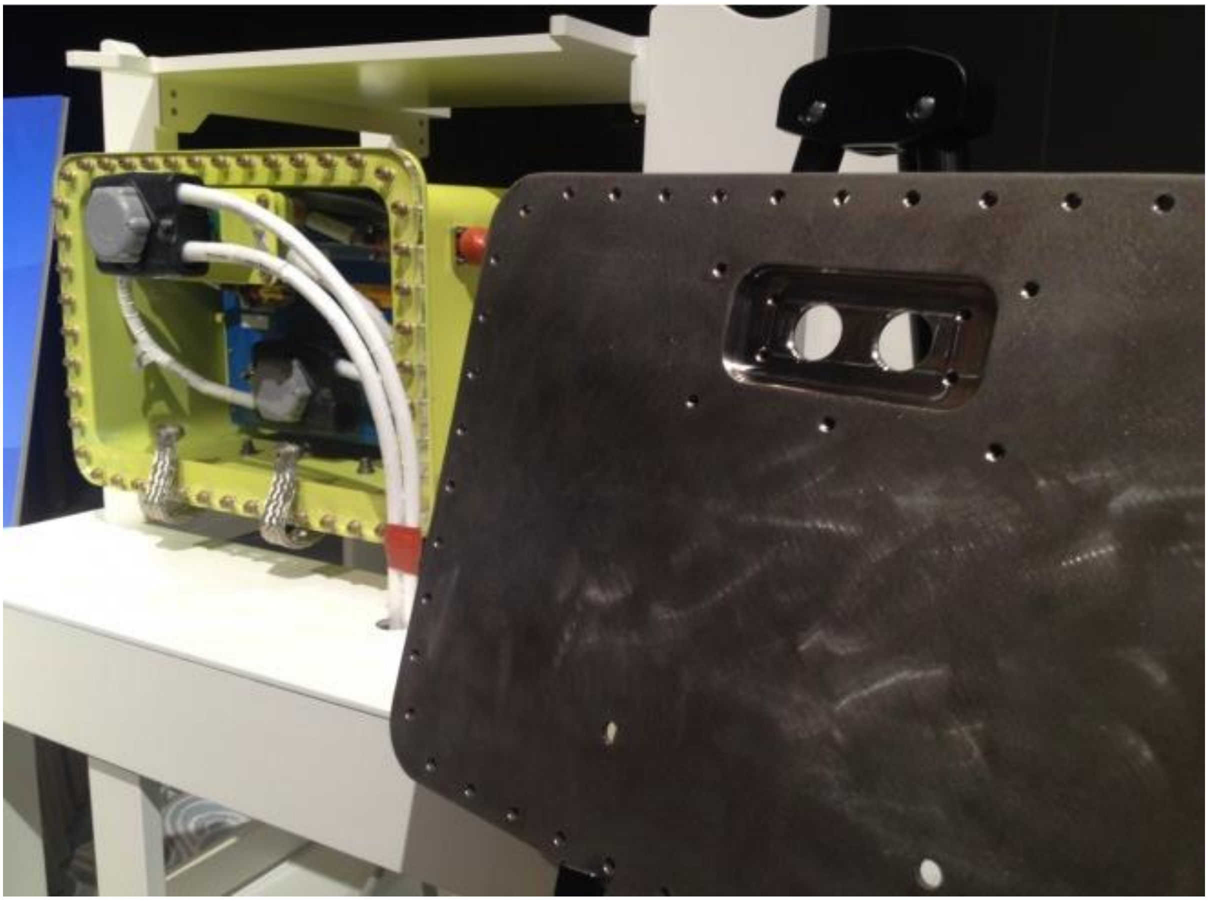


Figure 7 – Lithium battery fire protection [29]

4 Suppression

Suppression is required for the maximum diversion time, which could be in excess of 200 minutes [2]. This section reviews how suppression on aircraft works and how new systems are being developed.

4.1 How to suppress a fire

There are multiple ways to suppress a fire. These methods of suppression are also useful for understanding the development of suppression systems before manufacturing.

4.1.1 Fire triangle

In order for a fire to exist, it needs fuel, heat, and oxygen, which combine to form a chain reaction [30]. If one requirement is removed, the fire is normally suppressed. All methods of suppression focus on removing one or more of these requirements.

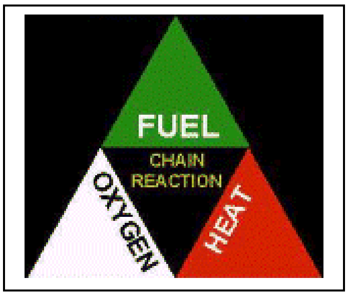


Figure 8 – Fire triangle [31]

4.1.2 Remove heat

Heat energy allows the combustion process in a fire. For example, fires require a spark or a source of energy to start. By cooling the fire and absorbing the heat, the fire loses its energy. Generally, this is accomplished by using water on the fire.

4.1.3 Remove fuel

A fire cannot exist without fuel -- fuel provides the energy for combustion. Removing fuel from fire can be accomplished by covering it with something which cannot catch fire, such as sand. Making potential fuel sources unsuitable is also effective. By removing fuel from the area, damping it, or protecting it, so the fire is isolated.

4.1.4 Remove Oxygen

Combustion requires oxygen for the chain reaction. Starving a fire of oxygen is normally achieved by compartmentalisation or introducing a substance which would displace oxygen, such as carbon dioxide.

4.1.5 Interrupt chain reaction

Fire occurs due to a chemical reaction within the fire, involving O and H atoms and OH radicals reacting with vaporised molecules from the fuel. Chemically active agents suppress fire by adding an atom which reacts with the radicals and slows the fire. This occurs when the chemical agent decomposes in the fire; for example, a halogenated chlorine atom becomes $HCl+H=H_2+Cl$ [32]. Suppression may not completely extinguish the fire, and this works best on fuel and gas fires. Effectiveness is dependent on several variables:

- Specific heat capacity of the chemicals
- Atomic structure of the chemical
- Concentration in the air
- Volume used

All of these are used to predict the effectiveness of suppression before producing the agent.

4.2 Minimum Performance Standards

Minimum Performance Standards (MPS) have been developed by the FAA to provide requirements and benchmarks for replacement options. Standards include:

- Toxicity levels
- Cannot damage the aircraft
- Weight
- Environmental impact
- Effectiveness as determined through testing

Four areas have MPS:

- Engine and APU
- Cargo Bay
- Cabin
- Lavatory trash receptacle

4.2.1 Require non-toxic substances

Since breathing apparatus is provided on aircraft, an exposure time of 5 minutes is allowed, meaning agents released must not harm occupants in 5 minutes or under [11]. Additionally, substances released must not harm through exposure to eyes or skin. Unoccupied compartments can use toxic substances provided they naturally dissipate and pose no threat to occupants [33].

4.2.2 Low weight

Suppression needs a low weight to be commercially viable. The current benchmark is the equivalent, or less, than halon. Halon has an agent mass of 0.331 kg/m^3 of protected volume at 20 $^\circ C$ [11].

4.2.3 Cannot damage aircraft

Suppression used must not damage the structure, electronics, machinery, or require excessive clean-up. Property protection on aircraft leads to life-safety. For example, if suppression is used on a wire, damage to the wire may cause loss of control. Suppression must be stable in storage conditions and not be hazardous due to changes in pressure or temperature.

4.2.4 Non pollutant

Suppression must not use a banned substance by the Environmental Protection Agency, including ODS and substances with significant global warming potential (GWP). It is this that makes currently used halons unsuitable.

4.2.5 Must effectively suppress the fire

In a building, suppression contains the fire so occupants can evacuate; this normally takes 5-10 minutes. In an aircraft, it could take more than 200 minutes [2] before egress can begin. For this reason, simply delaying the fire's growth is not acceptable. Tests to prove effectiveness are detailed later in this chapter.

4.3 Types of suppression

This section details the types of suppression being considered, including their respective advantages and disadvantages [11]. Systems being developed for each type are also listed. A more detailed list can be found in section 4.4.

4.3.1 Halocarbon

Description: There are halocarbons available other than halons, although many of these have their own phase-out schedules due to environmental damage.
Effect: Interrupts the chemical reaction.
Advantages: Non-toxic, light, non-conductive, high flooding capacity, generally easy to clean, non-corrosive
Problems: High GWP, normally an ODS
Areas where these cannot be used: Can be used anywhere
Systems in production: HCFC, HFC, H Galden HFPEs, CF, SF6, Chlorobromo-methane, HBFC-22B1

4.3.2 Foams and wetting agents

Description: Fills an area with foam which often contains a water-based agent.
Effect: Separates the fuel from the air, and provides a cooling effect.
Advantages: Non-toxic, environmentally friendly
Problems: Heavy, conductive, can be difficult to clean, poor flooding capacity
Areas where these cannot be used: Areas with electronics, areas which need flooding
Systems in production: Surfactant Blend, Foam A

4.3.3 Water sprinklers

Description: Most common suppression in use, sprinkles droplets of water on an area.
Effect: Cools the fire and dampens any potential fuel source.
Advantages: Non-toxic, cheap, environmentally friendly
Problems: High weight, conductive, low flooding capacity
Areas where these cannot be used: Areas with electronics, areas which need flooding
Systems in production: Water

4.3.4 Dry chemicals

Description: These are fine powders with an average particle size of 20 – 25 µm.
Effect: Interrupts the chain reaction.
Advantages: Light weight, can be more effective then halons
Problems: Poor flooding capacity, difficult to clean, corrosive
Areas where these cannot be used: Areas with electronics, areas which need flooding
Systems in production: Dry Chemical

4.3.5 Carbon Dioxide

Description: Common greenhouse gas fills the area, displacing oxygen.
Effect: Reduces the amount of oxygen available to fire.
Advantages: Gas at room temp, non-conductive, strong flooding capacity, easy to clean
Problems: Can be an asphyixiant in confined spaces, high GWP, high weight and volume requirement
Areas where these cannot be used: Occupied areas
Systems in production: Carbon Dioxide

4.3.6 Loaded Stream

Description: A loaded steam is water mixed with anti-freeze.
Effect: Cools the fire and dampens any potential fuel source.
Advantages: More effective then water, environmentally friendly, non-toxic
Problems: Conductive, low flooding capacity, difficult to clean
Areas where these cannot be used: Areas with electronics, areas which require flooding capacity
Systems in production: Sodium acetate, water, and ethylene glycol by Kidde

4.3.7 Water misting systems

Description: Small droplets of water flood the area in a mist form.
Effect: Cools the fire and dampens any potential fuel source.
Advantages: Non-toxic, environmentally friendly, easy to clean
Problems: Conductive, high weight, poor penetration of objects
Areas where these cannot be used: Areas with obstacles, areas with electronics
Systems in production: Water Mist Systems

4.3.8 Fine Particulate Aerosols

Description: Micron-sized particles flood the area.
Effect: Interrupts the chemical reaction.
Advantages: Some total flooding capacity, effective
Problems: Obscures vision, potentially corrosive, difficult to clean
Areas where these cannot be used: Potentially areas with electronics
Systems in production: Powdered Aerosol

4.3.9 Solid Propellant Gas generators

Description: Similar to aerosols except it limits particulates and produces a cleaner discharge
Effect: Interrupts the chemical reaction
Advantages: Effective, some total flooding capacity
Problems: Obscures vision, potentially corrosive

Areas where these cannot be used: Potentially areas with electronics, areas which require total flooding
Systems in production: OS-10, N2 Towers System, Aerojet

4.3.10 Inert gases and on-board inert gas generation system

Description: Floods the area with an inert gas to displace oxygen.
Effect: Reduces amount of oxygen available to prevent a fire starting.
Advantages: High flooding capacity, non-conductive, easy to clean
Problems: Weight toxicity and environmental damage depends on the inert gas being used.
Areas where these cannot be used: Potentially occupied areas
Systems in production: IG (Inert gas)

4.3.11 Combination and new foam agents

Description: Mixture of substances generally with water or halocarbons; cooling gelling agents are also used.
Effect: Generally separates the fuel from the air and provide a cooling effect.
Advantages: Dependent on the combination, mixes the advantages of the substances used
Problems: Dependent on the combination, mixes the problems of the substances used
Areas where these cannot be used: Generally areas with electronics
Systems in production: Gelled Halocarbon/Dry Chemical Suspension, Firebane

4.4 Halon Replacement options

This section is a table which lists all known candidates being considered for use on aircraft [11] [34]. Details of where these candidates are to be used can be found in section 4.5 to 4.8.

Substance	Alternates	Trade name	Type
HCFC	123	FE-232	Halocarbon
	124	FE-241	
	Blend B	Halotron 1	
	Blend C	NAF P-III	
	Blend D	Blitz III	
	Blend E	NAF P-IV	
	22		
	23	FE 13	
	135	FE 25	
Gelled Halocarbon/Dry Chemical Suspension	With nothing else	Envirogel	Combination and new foam agents
	With ammonium polyphosphate	Envirogel with ammonium polyphosphate	
	With sodium bicarbonate additive	Envirogel with sodium bicarbonate additive	
	With any additive other than ammonium poly-phosphate or sodium bicarbonate	Envirogel with any additive other than ammonium poly-	

		phosphate or sodium bicarbonate	
Surfactant Blend	A	Cold Fire	Foams and wetting agents
		FlameOut	
		Fire Strike	
Water Mist Systems	Potable		Water misting systems
	Natural sea water		
	Uni-light Advanced Fire Fighting Foam 1% water mist system	Uni-light Advanced Fire Fighting Foam 1% water mist system	
	Nitrogen/Water Mist Vortex System	Victaulic Vortex System	
Carbon Dioxide			Carbon Dioxide
Dry Chemical	Monoammonium Phosphate		Dry chemicals
	Sodium Bicarbonate		
	Potassium Bicarbonate		
	Urea and potassium bicarbonate complex	Monnex	
Water			Water sprinklers
Firebane	1170	Firebane 1170	Combination and new foam agents
	1179	Firebane 1179	
	1175	Firebane 1175	
	All-weather 1175	Firebane All-weather 1175	
HFC	227ea	FM-200	Halocarbon
	236fa	kidde	
		FE-36	
	134a		
	125 with 0.1% d-limonene	NAF S 125	
	227ea with 0.1% d-limonene	NAF S 227	
	Blend B	Halotron II	
	32		
CF	CF_3I		Halocarbon
	C_6F_{14}	PFC-614	
		CEA-614	
	C6-perfluoroketone(1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone)	Novec1230	
	C_3F_8	PFC-218	
		CEA-308	

	C_4F_{10}	PFC-410	
		CEA-410	
	CF_3I		
	CFC-11		
H Galden HFPEs			Halocarbon
Powdered Aerosol	A	SFE	Fine Particulate Aerosols
	Inert Gas/Powdered Aerosol Blend	FS 0140	
	C	PyroGen	
		Soyuz	
	D	Aero K	
		Stat X	
	E	Fire pro	
	F	KSA	
	G	Dry Sprinkler Powdered Aerosol (DSPA) Fixed Generators	
IG (Inert gas)	100	NN100	Inert gases and on-board inert gas generation system
	01	Argotec	
	55	Argonite	
	541	Inergen	
Foam A		Phirex+	Foams and wetting agents
OS-10		ATK OS-10	Solid Propellant Gas generators
N2 Towers System		N2 Towers System	Solid Propellant Gas generators
Aerojet		Aerojet	Solid Propellant Gas generators
SF6			Halocarbon
Chlorobromomethane		Halon 1011	Halocarbon
HBFC-22B1		FM-100	Halocarbon

Table 3 – Halon replacement options

4.5 Engine Nacelle & Auxiliary Power Unit

Although engine nacelles and APU are in separate areas, they are considered together when designing suppression due to their similarities [11].

Figure 9 – Boeing APU [35]

4.5.1 Layout

A standard aircraft has 2-4 engine nacelles located on the wings; the size of these engines depend on the size of the aircraft. Aircraft often have redundancies which allow it to fly if one or two engines fail. Nacelles are adjacent to fuel lines, deceleration flaps and gears.

The APU is in a compartmentalised area beneath the tail of the aircraft. It is used for manoeuvring the aircraft on the ground. The APU is located adjacent to tail rotors, landing gear, gears, fuel lines, and potentially a fuel tank.

4.5.2 Specific fire hazards/problems

Fire in these areas would likely be caused by an electronic malfunction. If fire is not suppressed, it would spread and cause substantial damage, leading to loss of control. These areas are inaccessible whilst the aircraft is in-air. Fire scenario for this area is a Class B fire (aviation fuel, hydraulic fluid, or oil lubricant).

4.5.3 Specific Requirements

Systems used here must not damage machinery or electronics; must be non-conductive and non-corrosive. The agent must be able to flood the area regardless of obstructions and it must be 100% effective. If not, the fire would spread and damage the aircraft, which would cause loss of control. Due to inaccessibility, suppression must be automated or controlled by the pilot. Additionally, a detection system is required to identify the source of fire [11].

4.5.4 System currently used

Fixed system using [11]:

- Halon 1301
- Halon 1211
- Halon 2402

4.5.5 Systems being developed

These substances are undergoing testing [36] [11]:

- HFC-125
- CF3I
- 2-BTP
- FK-5-1-12
- KSA

4.5.6 Testing Methods

Suppression for engines is tested by simulation using a nacelle [37].

Figure 10 – Engine nacelle suppression test [38]

Four tests are conducted -- two using 115% design concentration of the suppression and two using 85%. This proves suppression is effective within these boundaries; it is not to develop more efficient concentrations. Each concentration is tested in a high and low ventilation to ensure effectiveness in different airflows.

A re-ignition time delay is used to measure the effectiveness of the substance. This is the time it takes from the fire being extinguished to it reigniting. It is a measure of the time the suppression substance lingers in the compartment and is part of the design criteria. Re-ignition time of halon is the benchmark.

Another test is performed in a “high fidelity” environment; this simulates the flow patterns that an engine will experience.

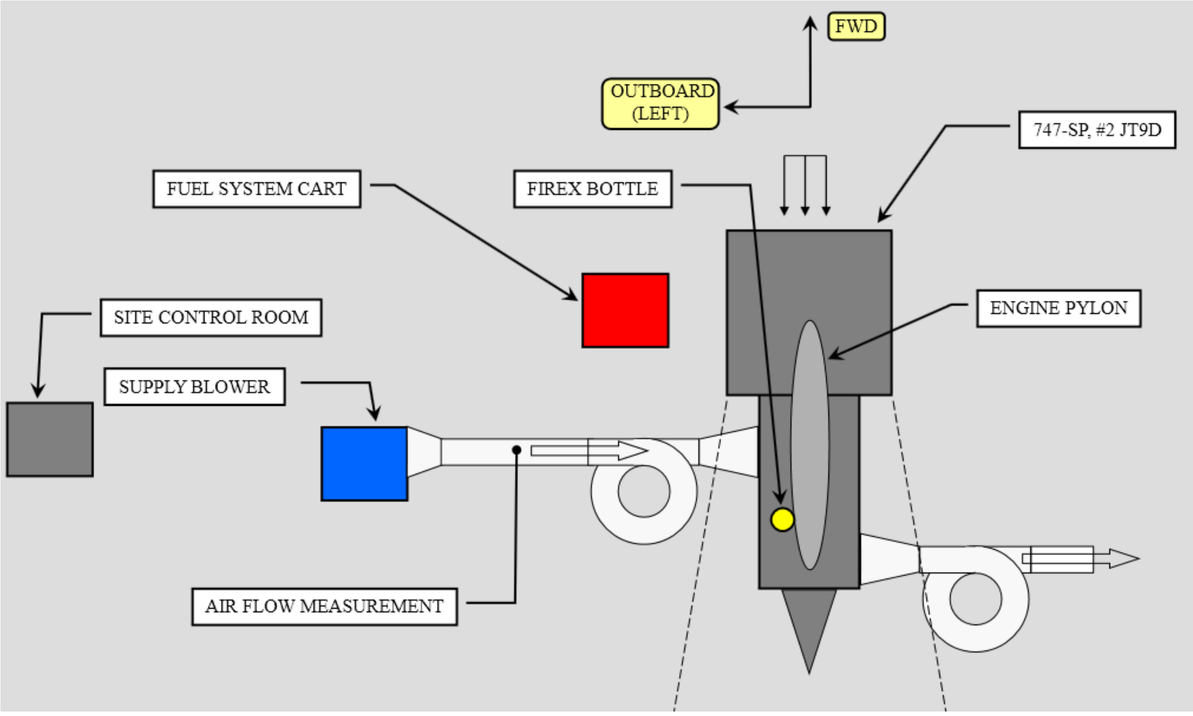


Figure 11 – Layout of engine nacelle simulator [36]

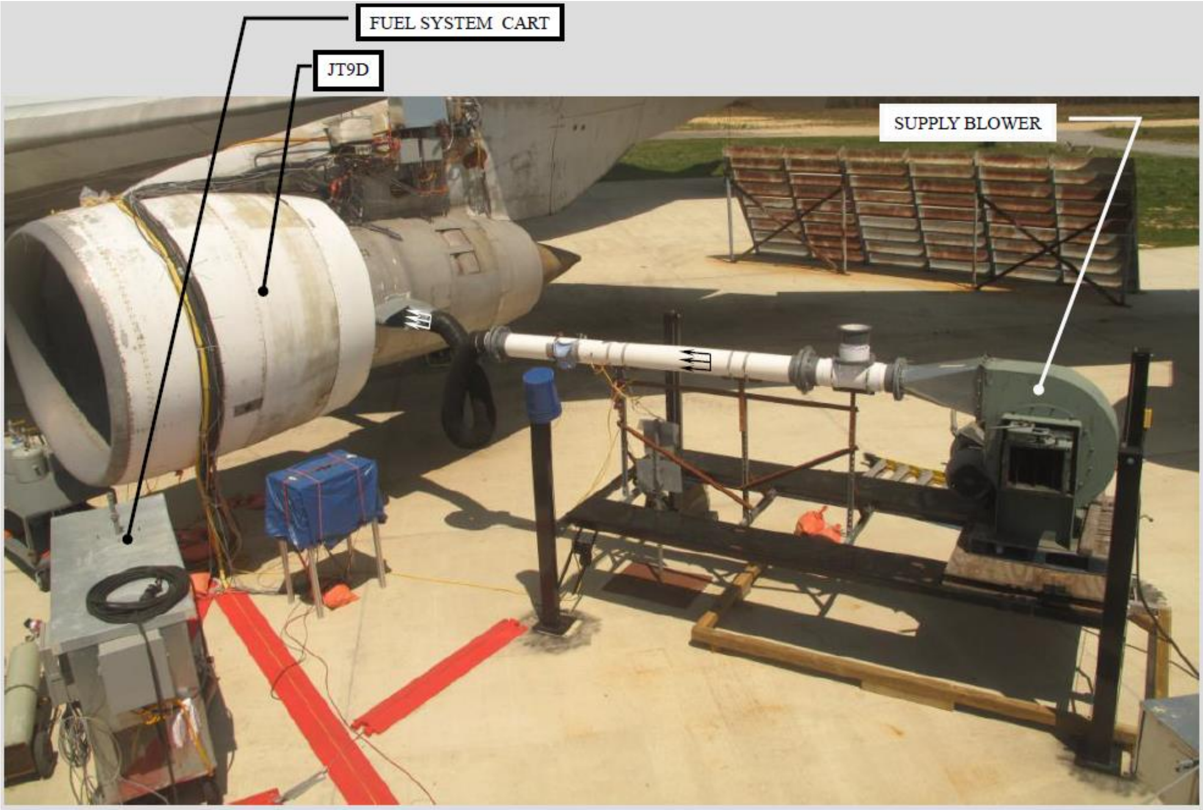


Figure 12 – Nacelle simulator with ventilation [36]

4.6 Cargo bay

The size and configuration of the cargo bay varies between aircraft.

4.6.1Layout

There are four classifications of cargo bay defined in CFR 25.857 [39] [40].

Class	Common aircraft type	Size	Accessible	Suppression	Compartmentalized
A	Light	Tiny	Yes	Handheld	No
B	Light	Small	Yes	Handheld	Yes
C	Passenger	Medium	No	Automated	Yes
E	Cargo	large	No	None	Yes

Table 4 – Cargo bay classes

In 1998 new FA regulations eliminated Class D cargo compartments as it was determined Class D cargo compartments had to meet the fire safety standards of a Class C or Class E compartment [41].

Class E is for cargo planes only -- compartmentalisation is used to contain fire [42] by restricting available oxygen. Fatal fires have recently occurred for this class [40]. Cargo provides obstruction for suppression; there is no internal compartmentalisation. Ventilation keeps the bay above freezing (higher if it is to be occupied), and the bay has a minimum pressure corresponding to an altitude of 8000 feet. Detection systems inside the bay must activate in under 1 minute [11].

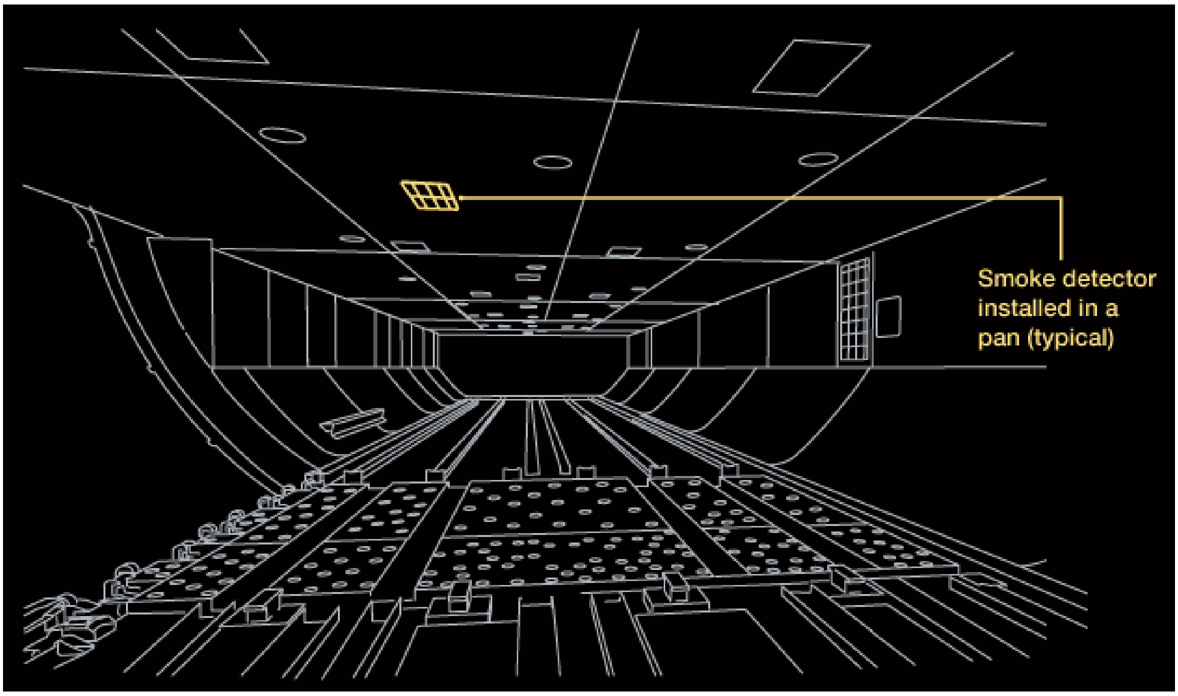


Figure 13 – Empty cargo bay area layout [42]

4.6.2 Specific fire hazards/problems

It is difficult to regulate cargo carried by aircraft. Quantity of cargo is limited by the bay's size, though the composition of that fuel is unknown. Restrictions are placed on high-risk materials such as reducing size, or preventing travel or ensuring appropriate protections are taken [21].

The bay is often inaccessible and concealed. A fire could be started by mishandled cargo, such as a malfunctioning laptop or poorly stored lighter. Unknown fuel means multiple fire scenarios; it could be a Class A, B, or C fire, or it could be an explosion.

4.6.3 Specific Requirements

Due to the bay's size and objects stacked inside it, automated suppression needs a high total flooding capacity and must penetrate behind obstacles [11]. Fire could start behind or underneath other cargo.

Toxicology requirements vary depending on whether the bay is habitable or not (4.2.1). Although passengers and crew may not have access animals may be stored in the cargo bay, therefore non-toxic is normal [11].

Suppression requirements here can be summed up by four points [11]:

- The system must suppress a Class A deep-seated fire (bulk-loaded cargo) for at least 30 minutes.
- The system must suppress a Class A fire inside a cargo container for at least 30 minutes.
- The system must extinguish a Class B fire (Jet-A fuel) within 5 minutes.
- The system must prevent the explosion of an explosive hydrocarbon mixture by either fire control or inerting the cargo compartment.

4.6.4 System currently used

Fixed and handheld systems using [11]:

- Halon 1301
- Halon 1211

4.6.5 Systems being developed

Systems recently tested include [11]:

- HFC-125
- HFC-227ea
- PGA, 2-BTP
- FK-5-1-12
- Water mist
- Powdered aerosol D (most promising results so far, though not yet perfected)

None of these substances have yet to pass all tests

4.6.6 Testing Methods

Currently there are four tests to determine the effectiveness of suppression in cargo bays, each test focuses on one of the requirements in section 4.6.3. All are conducted in a full-scale simulation and focus on Class C bays [43]:

1) Bulk-load fire test
   This test uses a pre-determined volume of paper ignited in the bay. The paper (stored in cardboard boxes) occupies 30% of the volume of the cargo container.

2) Containerised-load fire test
   This is similar to the bulk-load fire test, except that the burning paper is stored in an aluminium container.

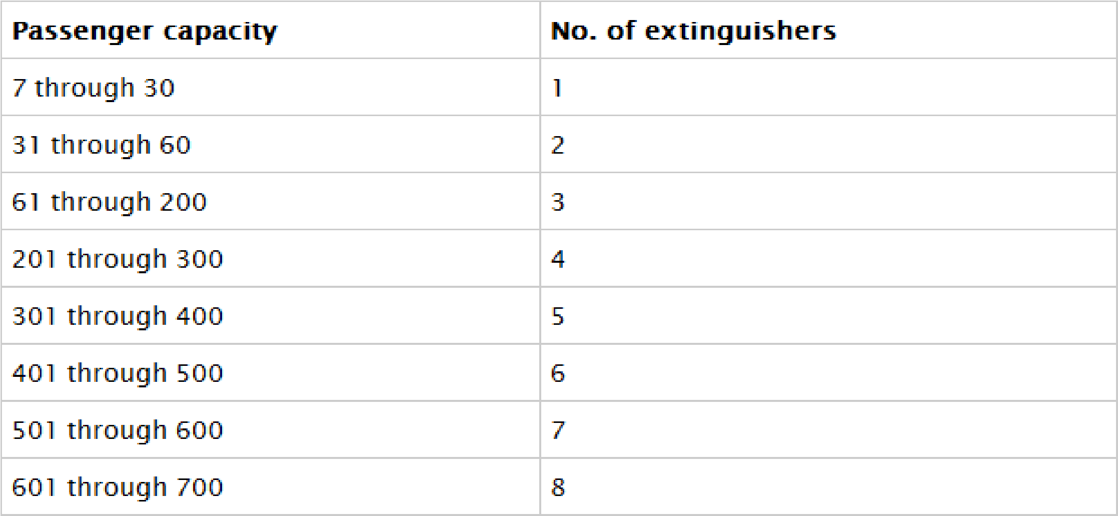
3) Surface-burning fire test
   A pan of fuel is placed in the bay and lit. The pan is placed in the most difficult location for the suppression to act.

4) Aerosol can explosion simulation
   This test simulates an aerosol can explosion; a device to simulate this explosion is used in the cargo compartment. This has proven to be a particularly challenging test; systems have struggled to maintain concentration needed for inerting the compartment [11].

5) Lithium Battery test (still needs developed) [27].
   Recent research plans request a test to be developed to simulate a lithium battery fire in a cargo bay.

4.7 Cabin

The cabin includes occupied areas and uses hand extinguishers. The number of extinguishers required is dependent on the size of the aircraft.



Passenger capacity	No. of extinguishers
7 through 30	1
31 through 60	2
61 through 200	3
201 through 300	4
301 through 400	5
401 through 500	6
501 through 600	7
601 through 700	8

Table 5 – Hand extinguisher numbers required on an aircraft [44]

4.7.1 Layout

Passenger section

This is the most occupied part of the cabin; it is a long section not normally compartmentalised. Breathing apparatus is provided for passengers, and hand luggage can be stored in overhead compartments. This section also includes the lavatory.

Flight Deck

The flight deck is where the aircraft is operated from. It must always have smoke goggles, breathing apparatus and a fire extinguisher present [44]. This area is often compartmentalised from the rest of the aircraft.

Wall cavities

These are concealed spaces above the ceiling (overhead area) and below the floor (cheek area). The cheek area contains wires, electrical components and hydraulic lines. The overhead area contains wiring, breathing apparatus, ventilation and other systems. The heights of these areas could vary from a few inches to over four feet [45].

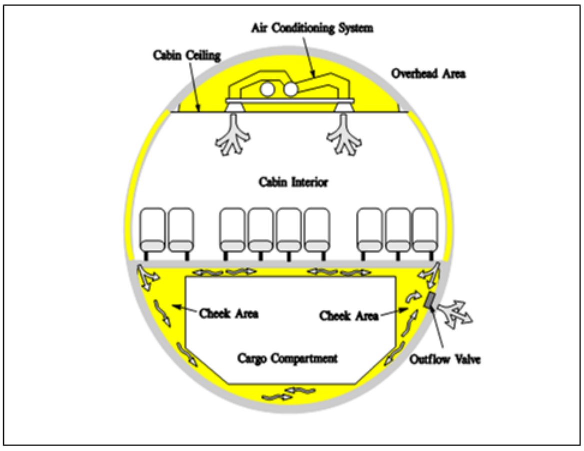


Figure 14 – Layout of cavities in cabin [46]

Figure 15 – Inside of wall cavity [46]

Access to these areas varies [16]:

- Sometimes panels can be easily removed, or forced off
- Some aircraft have speakers which can be detached to make a port for an extinguisher
- The panel can be punctured, though this may damage equipment

Fires here are to be found by feeling for hot spots and determining the origin of smoke.

4.7.2 Specific fire hazards/problems

Passenger section

There are many occupants in this area. Fire hazards include faulty electronics, seat fires, or inappropriate actions from occupants, such as smoking in the lavatory. An uncontrolled fire here would expose occupants to radiation and smoke.

Flight deck

If a fire occurs in this section, it could result in loss of control by damaging equipment. Fire here could occur due to an electrical fault.

Wall cavities

Fire here could start due to faulty electrics. If there is a fire, it would be difficult to access and hidden from occupants. Also smoke and radiation could fill into the passenger section. Damage to electrical systems would result in loss of control.

4.7.3 Specific Requirements

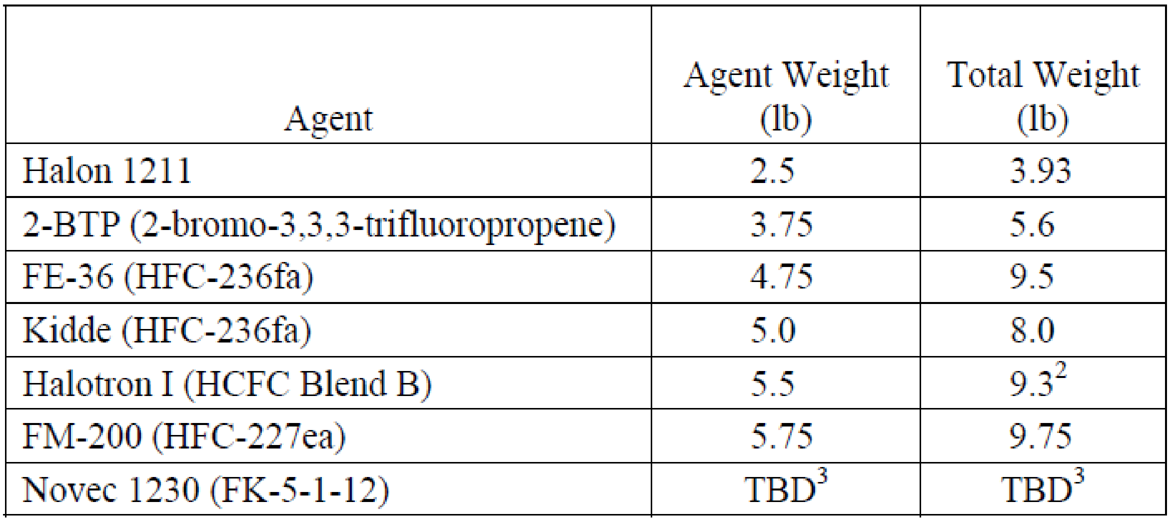
Hand extinguishers used must be appropriate for the passenger section, flight deck, and wall cavities. Occupants cannot identify separate extinguishers during a fire. The system used must be non-toxic [11]. Non-conductive and non-corrosive substances are needed so aircraft controls are not damaged. Suppression must not obscure pilots’ vision. The system must not damage the exterior of the aircraft. Additionally, a high flooding capacity which can penetrate behind objects is needed for the wall cavities to ensure suppression of any area.

4.7.4 System currently used

Handheld systems using [11]:

- Halon 1211
- Halon 1301
- Halon 2402

4.7.5 Systems being developed



Agent	Agent Weight (lb)	Total Weight (lb)
Halon 1211	2.5	3.93
2-BTP (2-bromo-3,3,3-trifluoropropene)	3.75	5.6
FE-36 (HFC-236fa)	4.75	9.5
Kidde (HFC-236fa)	5.0	8.0
Halotron I (HCFC Blend B)	5.5	9.3[2]
FM-200 (HFC-227ea)	5.75	9.75
Novec 1230 (FK-5-1-12)	TBD[3]	TBD[3]

Table 6 – Systems being developed for use in hand extinguishers [11]

- Carbon Dioxide
- Surfactant Blend A
- Loaded Stream
- Gelled Halocarbon/Dry Chemical Suspension

Most of these substances have passed testing, but need improvement to reduce weight and environmental impact

4.7.6 Testing Methods

There are two tests used to prove the effectiveness of hand extinguishers [47]:

1) Chair test

   This examines the toxicity of suppression after decomposition and the extinguishers' effectiveness. In this test, a trained firefighter uses an extinguisher on three seats 30 seconds after they've been ignited.

2) Hidden fire test
   This tests suppression's total flooding capacity. Cup burners are lit in a sealed compartment and are exposed to a predetermined mass of suppression by a hand extinguisher through a port. The substance is determined to pass if it extinguishes more cups then an equivalent mass of halon 1211.

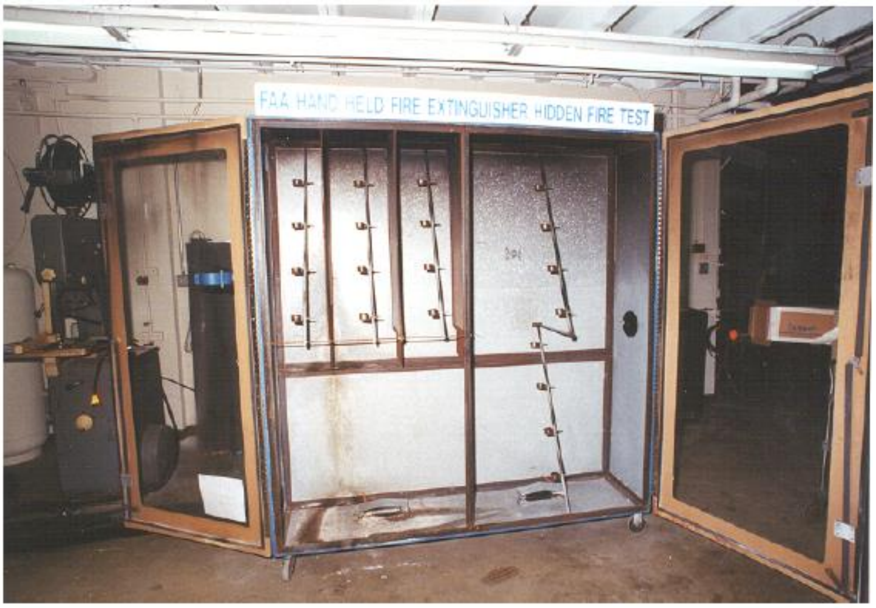


Figure 16 – Hidden fire flooding test [47]

Figure 17 – Hidden fire test extinguisher [47]

A third test is in development to simulate wall cavities on a larger scale with more accurate boundary conditions. It is unclear if this will be part of the MPS; it is also unclear what the parameters and scenario of this test will be.

Figure 18 – Full scale simulation test of ceiling cavity fire [46]

4.8 Lavatory Trash Receptacle

The lavatory trash receptacle requires its own suppression due to the risk of fire in this section [11].

4.8.1 Layout

The trash receptacle is adjacent to the lavatory; it is hidden and inaccessible to occupants. There is no detector present in this area. In the event of a fire, an automatic suppression system is used [11]. The receptacle is not compartmentalised, as a gap is needed to insert rubbish. The material and size of the receptacle varies depending on the aircraft, though it is generally small and made of aluminium or composites.

4.8.2 Specific fire hazards/problems

Fires here are normally Class A, involving paper towels, with the ignition source being a cigarette. This would cause smoke to filter into the cabin. A substantial fire could burn through the receptacle and damage electronics, machinery or the exterior of the hull, causing loss of control.

4.8.3 Specific Requirements

Suppression must be non-toxic as gases will flow to the lavatory and passenger section. Ideally it will not damage the receptacle. In addition, suppression must penetrate rubbish to the source of the fire. The system must also activate automatically in the event of a fire [11].

4.8.4 System currently used

Fixed system using [11]:

- Halon 1301
- Halon 1211
- HFC-236fa
- HFC-227ea

- Water based and combination agents

4.8.5 Systems being developed

Halocarbons are environmentally damaging and water-based agents are heavy; the process is on-going to improve these systems.

4.8.6 Testing Methods

A simulated trash receptacle is used to test this suppression system.

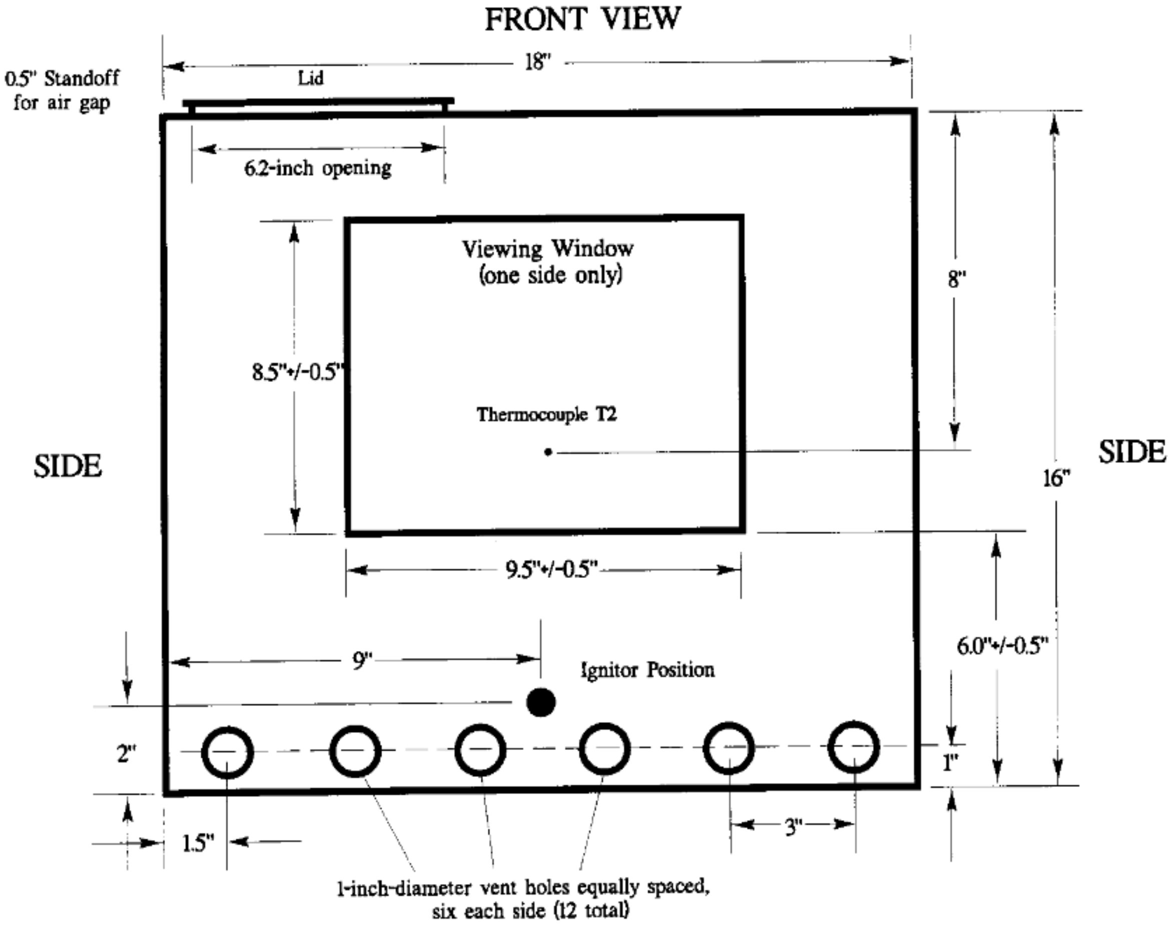
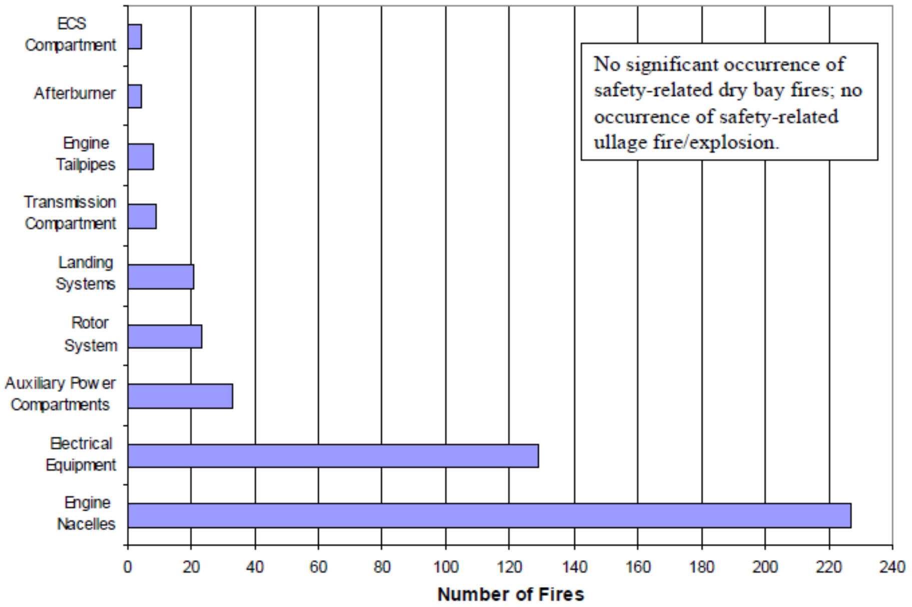


Figure 19 – Lavatory receptacle simulator layout [48]

The simulator is made from steel or aluminium, with a glass window to view the progress of the fire and holes to allow ventilation. Thermocouples measure the temperature of the fire. Paper towels fill the container and are ignited electronically. The suppression system is weighed before and after testing. If visual and temperature observations indicate the fire has been extinguished five minutes after discharge, an access panel is opened. The simulator is left for 2 minutes; if the fire reignites during this time, then the test is a failure. The weight of suppression used and the time to extinction is compared to the results of halon or water [49].

4.9 Other areas

Other areas do not necessarily need a replacement for halon. Suppression used may not require halon, or there is no suppression present.



No significant occurrence of safety-related dry bay fires; no occurrence of safety-related ullage fire/explosion.

USN Fire Mishaps and Incidents by Aircraft Compartment, 1977-1993

Figure 20 – Occurrence of fires on US Navy aircraft, by area [50]

4.9.1 Fuel tank

The fuel tank is mentioned in EU legislation [16] as an area where halon needs to be replaced though no MPS exist for this area. The main fire risk is the ullage, which is a combination of fuel vapour and air inside the tank. If a spark is formed here, it can cause an explosion. An on-board inert gas-generator system reduces the oxygen concentration to 12% to prevent a fire from starting. The inert gas used is generally nitrogen [51]. Suppression is tested in an explosion-proof steel compartment where pressure and temperature are measured before an ignition source is introduced.

4.9.2 Avionics compartments

The avionics compartment is beneath the flight deck and contains electronics and power sources used for flight and environmental control. This area is normally inaccessible [52]. In this section, fire can occur due to faulty equipment; an unsuppressed fire here would cause loss of control. Suppression strategies differ in this section. Parts of the floor can sometimes be removed for hand extinguisher access, potentially with a specialised hand extinguisher. Most aircraft focus on fire prevention and ensure components are working correctly so that no fire occurs.

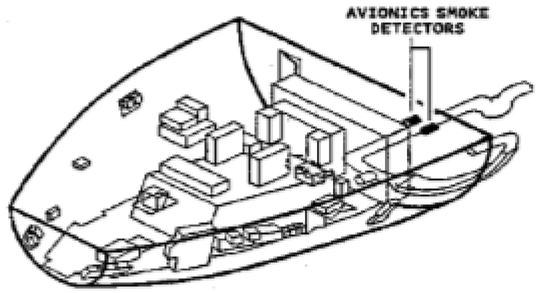


Figure 21 – Avionics bay [52]

There are literature references which mention suppression specifically for this compartment, though precise details of these systems are limited [53] [54] [55]. The only evidence of their existence is easily misinterpreted quotes. A lot of emphasis in this section is put into detection, to minimise false alarms and provide early warnings. If suppression is used then testing is probably conducted in a simulator.

4.9.3 Landing gear

Landing gears can overheat or suffer damage during take-off or landing; this can lead to fire [56]. Fire protection here focuses on prevention and detection. A fire in this area can damage hull, electrics, or even heat the fuel tank to the point of ignition [57]. Like the avionics bay, there are references to suppression being used but no details or evidence of those systems [53]. Suppression for this area could be achieved by a cabin hand extinguisher as it is for wall cavities.

4.9.4 Dry Bays

The dry bay is an area which surrounds the fuel tank [58]. A fire here would cause the fuel tank to heat and could potentially cause an explosion. Fire could be started by fuel leaking into the bay and combining with a spark. This is a concern for military aircraft with incendiary rounds puncturing the fuel tanks; an on-board inert gas generator is used, as it is for the fuel tank. There is rarely suppression in these areas on passenger aircraft due to the size of the dry bays and the unlikeliness of a leak.

5 Discussion

This section critically discusses the findings of the literature review. It discusses the implications, whether progress in designing new systems is adequate, where improvements can be made, and if the methodology of designing new systems is appropriate.

5.1 Problems of fire on aircraft

To develop a fire-safety strategy, the problem needs to be understood. The methodology used to determine fire risks has to be adequate.

5.1.1 Where critical areas are

Fire could occur anywhere on an aircraft, but replacement of halon is focused on four areas:

- Cabin
- Cargo Bay
- Lavatory Trash Receptacle
- Engine and APU
- Fuel tank and dry bay also use suppression, but already have alternatives to halon (4.9.1) (4.9.4)

This means other areas are not considered as much for suppression. These areas focus on fire prevention and detection, not suppression:

- Avionics bay
- Landing gear

5.1.2 What is needed

Performance-based design requires occupants to be able to evacuate before the fire poses a threat to life. As it can potentially take 200 minutes before egress can begin (4.2.6), it is difficult to guarantee fire-safety by a performance-based approach.

Current methodology for fire-safety has been based on limited loss due to fire in recent years. Therefore, if standards continue, there will not be much loss in the future (Example 4.7.6). This means efforts are focused on finding an equivalent to halon suppression and ensuring no new fire threats develop. If any new risks are discovered, they are corrected.

5.1.3 Learning from disaster

Most modern fire developments exist to prevent past disasters from reoccurring:

- Access for wall cavities
- Suppression in fuel tank
- Flame resistant tires
- Stricter regulation of cargo bays

This requires a disaster to occur before improvements can be made. All possible steps are taken to prevent a life-threatening fire from occurring, such as developing suppression and detection. However, scenarios could potentially occur which are beyond prediction.

5.1.4 Future Fire threats

Currently known future fire threats include:

- Lithium batteries
- Magnesium seats [27]
- Composite materials

This only looks 2-3 years ahead; future fire threats need to be considered when designing current fire-safety strategies. If these threats are not considered then suppression systems would need to be updated in the future; this would be unsustainable. Five years ago, for example, fire-safety engineers were not aware that lithium batteries would be used on aircraft in the future.

This uncertainty should affect suppression development by requiring new systems to be overdesigned; however, it will not. As almost anything could be added to an aircraft, there is no way to determine just how overdesigned a system should be. For example, not even halon would suppress a sufficiently large lithium battery fire (3.2.5). Instead, emphasis should -- and is -- being placed on making sure future fire threats are mitigated:

- By preventing lithium batteries from catching fire
- Restricting transportable cargo, and ensuring no transported material is overly flammable

5.2 Composite Materials

Composites on aircraft could pose a significant new fire risk; composites can burn, whereas aluminium merely melts. This section discusses how serious this risk is, how it affects suppression, and what can be improved to reduce the fire risk.

5.2.1 Benefits

Although composites can add to the heat release rate and fuel load of a fire, they do provide some benefits to fire-safety. Where aluminium melts, composites take longer to burn through (3.1.3). This means that it will take longer before the structure is eroded and will provide warning of failure. However, due to different types of composites being used, the time to failure can vary. Composites should therefore be standardised.

Additionally, reduction in weight (3.1.1) would allow for more weight to be used on fire-safety systems. However, it is unlikely that aircraft operators would be willing to use this saved weight on fire-safety systems after all the efforts taken to lose weight.

5.2.2 How do composite materials affect the fire

Primarily, the use of composite materials will increase the heat release rate (HRR) of the fire. This could provide more of a challenge for suppression. However, if the fire has developed to the stage where it has ignited the composite material, then the extra HRR will be relatively minor.

Composites ignite at a lower temperature then aluminium melts (3.1.3), meaning lower temperature fires would pose a risk to structural integrity. Furthermore, composite materials could provide an extra route for flame spread. Steps need to be taken to ensure that fire cannot spread inside the composite material.

5.2.3 How do composite materials affect suppression

Composite materials are easier to damage than aluminium due to overly forceful release mechanisms from suppression. This could require stricter restrictions on the release mechanism used. Also, if corrosion is a factor, composites can potentially be damaged due to the substance used; further tests will be needed to prove suppression is safe.

As composites are a burning solid material, it is a Class A fire; this means that any suppression used must be capable of suppressing a Class A fire. Most suppression systems can do this.

Gases produced when the composite burns or reacts with suppression could be toxic or otherwise harmful. These reactions needs to be analysed, and could provide restrictions on composites and suppression available. If a fire has spread to the composite, however, there are likely toxic products already present in the air supply.

If a fire spreads internally in the composites, it could be difficult to suppress as suppression would be unable to reach the fire. There is also the potential for damage to the composite being caused during cooling of the composite (3.1.3). This needs further testing.

5.2.4 What can be improved

There is limited room for improvement: a composite cannot be significantly altered. The overall benefits of its use mean they will continue to be used and become more common. As long as it is analysed properly, not much can be done to improve upon its use. Ideally, composites would be difficult to damage and the ignition temperature would be equal to or greater than aluminium's melting temperature. However, this is unlikely to happen.

There should be some standardisation of thermal requirements:

- To determine ignition temperature
- Time to burn through
- Flame spread rate

However, this is also unlikely to happen as these factors are determined by the composite used, which varies between aircraft and section (3.1.2). Evidence needs to be provided to ensure that fire cannot possibly spread internally through the composite and that it will not be damaged during cooling.

5.3 Lithium Batteries

Despite fire-safety concerns, the benefits that lithium batteries have over traditional power sources make them preferable for use on an aircraft. This section discusses the problems posed by lithium batteries as well as analysing their overall safety.

5.3.1 Benefits to fire-safety

The use of these batteries means that significantly less wiring is required in the aircraft (3.2.3). This means less fuel is available for fire in concealed compartments. In the past, aircraft have crashed due to fire burning through vital wiring (2.1); with fewer wires, there is less opportunity for fire to cause damage to the aircraft.

Additionally, reduction in weight (3.2.3) leaves the option for more weight to be used on fire-safety systems. However, it is unlikely that aircraft operators would be willing to use this saved weight on fire-safety systems after all the efforts taken to lose weight.

5.3.2 Should suppression be provided for it?

In the cargo bay, a restriction in size means that traditional suppression can theoretically control the fire. However, in the avionics bay and the APU compartment, the cells are too large for suppression to be of use (3.2.4). Thermal runaway means that only specialist streaming or dry chemical agents could stop the fire; however, these would damage other systems in the avionics bay (4.3).

Furthermore, if a fire starts in the avionics bay, then suppression would likely be too late as vital electronics could already have been damaged. Therefore, it is logical that all efforts are focused on fire prevention.

5.3.3 Is it safe?

The chemistry of a lithium battery makes it fundamentally unsafe. If it does catch fire in the wrong spot at the wrong time, it will result in loss of control. Every conceivable scenario has been considered, and substantial measures have been taken in order to prevent fire from occurring (3.2.5). It is the inconceivable scenarios, however, which are of concern.

Assumptions are made that the battery is permanently in brand-new condition and will never be damaged or badly maintained. This is a dangerous assumption: over time, liberties may be taken with the design -- e.g. reducing the amount of steel used in the casing to save on weight. Only time will tell if these safety measures (3.2.5) are adequate to prevent fire.

5.3.4 What can be improved?

Safer battery cells of equal weight should be developed, though this may take several years to accomplish. Tesla's method using smaller cells (3.2.1) could be adopted -- it would prevent thermal runaway and make suppression effective enough so it could be used. However, as further protection would be required, the weight would increase.

5.3.5 Next steps needed

A test method needs to be developed for lithium battery fires in the cargo bay (4.6.6), and a suppression system needs to be developed which can control these fires. If no suppression system can control these fires, then the size of lithium batteries allowed should be further reduced or perhaps banned from cargo bays altogether.

Standards of safety need to be maintained and have to wait and see if any more fires aboard aircraft occur. If they do, it is unlikely that lithium batteries will be used on aircraft again.

5.4 Suppression

This section discusses suppression in each area of the aircraft to determine whether progress in developing new systems is adequate and what can be improved.

5.4.1 Are Requirements appropriate

Halon suppression is used to determine the MPS of new systems (4). Whilst this will ensure that an equivalent system is installed and that new systems have a recognised benchmark, it is not ideal for fire-safety or fair to manufacturers. It relies heavily on the assumption that old halon systems are infallible in suppressing fire on aircraft, yet studies have shown this is not always the case (2.1.5). It also requires a system to be developed which can equal halons' efficiency-to-weight ratio (4.2.2), which may be impossible. Moreover, it is probable that an equivalent to halon would be overdesigning for certain areas.

Lightness is considered vital as more weight entails higher cost in terms of fuel. Although rigorous testing is in place, emphasis on reducing weight could result in a potentially inferior system being used. Systems should be considered solely on what will safely extinguish the fire first, before commercial applications should be considered. Weight should not be part of the MPS, as the MPS exist to determine how the aircraft can be fire safe.

Toxicology tests assume a 5 minute exposure time (4.2.1). This presupposes that occupants will have access to breathing apparatus; however, this is a risky supposition. For example, several seats where breathing apparatus is located could be rendered unavailable due to radiation. Alternatively, the fire may spread or originate in the ceiling cavity, where breathing apparatus is located, thus making the apparatus inaccessible. It can be assumed in these two events that suppression will not be used in the same breathing area as occupants, yet this is still a risky assumption for life safety. However, if a fire has developed to a point where suppression is required, it is likely that toxic products will already be present from the fire.

5.4.2 Are changes sustainable

Replacement substances which are under consideration are soon to be banned due to global warming potential or ozone depletion potential (4.2.4). Although using these substances could provide a few more years to develop an appropriate replacement, there is no purpose in replacing a banned substance with another just as bad. Doing so is neither economically sustainable nor environmentally friendly.

Changing scenarios of fire on aircraft in the future could alter MPS:

- Fuel loads could be updated
- Aircraft layouts could change
- Requirements could change

New developments entail that what is acceptable today may not be acceptable a few years down the line. This could make suppression systems unsustainable, both commercially and environmentally. One option to fix this would be to use more rigorous standards and try to predict fire scenarios of the future. Yet at a time when developing a replacement for halon is already challenging, this is not ideal.

5.5 Cargo Bay

This section details problems with suppression used in the cargo bay, as well as discussing whether adequate progress is being made in developing a replacement for halon.

5.5.1 How serious is fire risk

The cargo bay can be an inaccessible and hidden area (4.6.1). As the bay is recognised as a large fire risk, restricting access is dangerous. This asks a potentially impossible demand of the suppression system: that under any fire scenario, in any area or configuration of the bay, suppression will be sufficient to extinguish the fire.

The nature of cargo bays signify that almost anything can be stored in it, meaning there is an undetermined fuel load (4.6.2) to contend with. This makes it difficult for designers to predict what the worst fire load will be. Some items are restricted, though this presents commercial issues by limiting how certain items can be transported. The worst possible case of fuel load should be considered by designers of suppression systems.

5.5.2 Problems with strategy

The primary drawback with the cargo bay is the lack of internal compartmentalisation (4.6.1). Although cargo bays are compartmentalised from occupied sections, they can still cover vast areas. These areas allow for a large supply of fuel and air, which can produce a hotter and larger fire.

5.5.3 Potential improvements for strategy

Internal compartmentalisation in cargo bays would limit the amount of oxygen and fuel available to the fire. Although this would add to the weight needed, the weight of suppression could be reduced as smaller spaces would need suppression. This would require a detection system which could determine which zone the fire is in. Portions of the cargo would also be protected from the fire and the suppression. This would make loading and unloading the aircraft more difficult, however, as multiple entry points would be required. Additionally, it would also increase the cost of the aircraft and the cost of travel due to the extra weight. Yet these factors could be mitigated, as the improved fire-safety would reduce the cost of insurance overall.

Access should always be access available from the cabin. In the event that suppression does not activate or is insufficient, handheld extinguishers should be used in an attempt to control the fire. This restriction is due to Class C and E cargo containers being used to the extent that there is no room for safe access to all areas of the compartment. Adequate heat and air supply may also not be available in these areas.

Ideally, suppression should be available in Class E cargo compartments. However, as the area is too large to guarantee complete suppression (4.6.1), this is not currently utilised. If suppression cannot be provided, the compartment should have a much higher resistance to fire. This would ensure that the fire runs out of oxygen before compartmentalisation fails. This should be done instated as soon as possible to prevent further loss of life.

5.5.4 Problems with testing

As full-scale simulation is the only test available at present (4.6.6), lab-scale testing is not readily available. If it were, it would be cheaper and easier to experiment, and for a better system to be developed.

Testing methods have not yet been written for lithium batteries (4.6.6). Hypothetically, this could prove to be the hardest test for suppression, as it is potentially a high fire load and would need to be in an inaccessible position. Otherwise the MPS test methods for suppression here are quite effective and will likely be sufficient in providing a suitable system. However, these tests are harder than in other sections, though this is a representation of the challenges in this area.

New testing criteria can be implemented, and the standards are frequently updated. Whilst this is beneficial from a fire-safety point of view, it is not ideal from a sustainability perspective – i.e. a system which meets the MPS today, may not succeed in the near future. This could mean that new systems need to be developed, with old systems frequently replaced.

5.5.5 Potential improvements for testing

Producing possible methods of lab-scale testing which can be performed cheaply and easily could offer potential improvements.

Tests to determine how much compartmentalisation is required for Class E cargo containers should be performed separately to halon-replacement projects, as no halon is used. This should be undertaken as soon as possible to prevent further loss of life from occurring, unless suppression systems or other forms of protection are also provided.

5.5.6 Next steps needed

1) Provide a simulation scale test for lithium batteries (6.2).

2) Conduct testing for new suppression systems. If no suppression system passes testing then further restrictions should be placed on cargo which can be transported. Alternatively, further compartmentalisation should be used -- if there is still no suitable replacement, halon use should continue.

3) Install new suppression systems

5.5.7 Is progress adequate?

A replacement design is required by 2018 for cargo containers (2.2.2). More time is allowed here than other sections due to the challenges it is providing. Although there is still much work needed for this section, there is sufficient time that a replacement should be found. However, it is likely that it will be heavier than halon.

5.6 Cabin

This section details problems with suppression used in the Cabin as well as discussing whether adequate progress is being made in developing a replacement for halon.

5.6.1 How serious is fire risk

Wall cavities

A fire here could result in loss of the aircraft (2.1.5); this is potentially the worst location for fire as it cannot be easily accessed (4.7.1) or located with no automatic suppression.

Overall

Toxic products from the fire could result in loss of life. Although gas masks are provided to prevent this from occurring, there is still a risk that gas masks will be unavailable. This could be due to some being damaged or fixed in untenable positions due to radiation from the fire.

5.6.2 Problems with strategy

Wall cavities

Hand extinguishers are used to extinguish fires by inserting them into a slot in the wall (4.7.1). Fewer of these slots there are, the more distance suppression has to travel. Sometimes a panel can be removed or punctured to allow access. The suppression must be capable of extinguishing any fire regardless of its location. Even a small fire here could compromise structural integrity, or damage electronics or machinery. This would cause loss of control.

As there is no opportunity to observe the fire, personnel expected to extinguish it cannot be sure of its size, location, the potential damage it is causing, or even whether the suppression is having any effect. Instead, they are to extinguish the fire by judging the original location of the smoke or by feeling for heat. Depending on conditions in the aircraft, this could be impossible. Not knowing where the fire is makes its suppression difficult.

Limited compartmentalisation is another problem. Although the wall cavities are protected from occupied cabins, there is no compartmentalisation within the cavity itself. This means a large supply of fuel and air is available. This makes it harder to determine the exact location of any fire and therefore harder to suppress. Also, MPS require hand extinguishers to be able to flood these compartments; however, the larger the compartment, the harder it is to flood.

Passenger section

Assumes trained and conscious personnel are present to use hand extinguishers. This is a risky assumption, as there are scenarios where personnel would be unable to use suppression:

- Post-crash conditions
- Unoccupied aircraft

Overall

Too much is expected from suppression in the cabin:

- A high flooding capacity
- Not damage electrics or mechanics
- Be highly effective at extinguishing a fire, so much so that it can extinguish an unseen fire
- Environmentally friendly
- Non-toxic
- Cannot obscure pilots’ vision
- Lightweight
- Must have a long range, but must not use too much force on release that it risks damaging the wall cavity

5.6.3 Potential improvements for strategy

Wall Cavities

An internal system should be used, though this would cause extra weight on the aircraft. This could be mitigated by sharing the suppression supply used for the cargo bay, though this would put extra requirements on cargo bay suppression -- i.e. must also be non-toxic and must not damage electronics or mechanics. Weight could also be allayed by reducing the number of extinguishers required, which would be reasonable if the strategy is improved in other ways.

Alternatively, all aircraft should have the ability to easily remove floor, ceiling and wall panels; although this is not ideal as it would allow air to access the fire, there is not much choice.

Passenger section
Reducing the number of extinguishers required would allocate each extinguisher a greater weight allowance. This saved weight could allow for more effective, heavier suppressants to be used.

Overall
Separating the systems used in wall cavities and passenger section would potentially reduce the requirements of the system -- i.e. it would not matter if the passenger cabin had flooding capacity, or if electronics were damaged in this section. However, this could not be done by using different types of hand extinguishers as it would be too confusing during a fire.

5.6.4 Problems with testing

Hidden compartment (wall cavity) test (4.7.6)
This is not a simulation and as such not suitable as a MPS. There is a simulation currently being developed, though there is no indication of if it will be included in the MPS or in FAA research plans. In all other areas, a simulation is used to determine the effectiveness of suppression; however, this is not the case for wall cavities. By not using more plausible conditions for a MPS, there is no way to predict how suppression will perform in a real fire scenario.

Only a lab-scale test is used, which tests flooding capacity. How far the agent spreads should also be tested. Flooding capacity is not all that applies to wall cavities. Wall cavities can cover large areas and distances as well as containing obstructions. Testing flooding capacity assumes the area is compartmentalised -- which is not the case in a cavity. Also, the entry point of suppression could be any distance from the fire.

MPS tests are used to determine if suppression replacement is the equivalent of halon. As halon has failed at extinguishing fires here before, using it as a benchmark is a risky assumption for this area. This is an area where finding an equivalent to halon is not satisfactory.

The test assumes it is known where the fire is; this is not necessarily the case. It also assumes the suppression method will be a handheld extinguisher. Limiting the MPS for only hand extinguishers is not ideal. Other tests need to be developed which would allow for alternate methods of suppression to be tested.

It is also assumed that a Class B fire will be present, despite a Class A or C fire being more likely. Suppression effectiveness is determined by the type of fire present -- for example, water is good for Class A and bad for Class B. This would mean a biased test. And a potentially superior system may not be considered if it did not match halon solely because halon is better at extinguishing class B fires.

Chair test (4.7.6)
This test assumes that chairs are the maximum fire load in the cabin and that only a Class A

fire will be present. However, lithium batteries could be present in laptops; this would not be a Class A fire and could be the highest fire load.

A standard chair is used in the test. If a new chair is designed after installation of suppression, it could alter the heat release rate and growth rate so that suppression is no longer effective. If suppression has to change, it would incur significant costs in designing new systems and replacing old ones.

There is no lab-scale test. Burning three chairs every test is expensive, which increases the cost of developing new suppression systems and reduces the opportunities to test them. This reduced testing ability means it is harder to determine the faults in systems and improve them. A lab-scale test should be developed so that faults can be fixed before a full-scale test is undertaken.

The simulation is biased in favour of the suppression. It assumes suppression will be applied 30 seconds after fire start, which may not be the case due to:

- Length of aircraft
- Distance between extinguishers
- Obstruction to extinguishers, such as people
- Personnel not knowing how to use suppression
- assumes normal conditions (not post-crash)

It also assumes that a fully trained fire-fighter in full gear is aboard the airplane. This is a necessary precaution for safety during testing and to provide feedback. However, it does favour the chances of suppression succeeding compared to what might happen with an actual fire on an aircraft.

5.6.5 Potential improvements for testing

Wall cavities

Include a simulation test in the MPS (6.3) -- the one being developed (4.7.6) could be suitable for this. The main problem with a simulation is that the dimensions of the wall cavity differ depending on the aircraft; however, this is no different than for any other section of the aircraft.

Remove the flood capacity test from the MPS. It is biased towards certain types of suppression and release mechanism; it is also not evidence that a system is effective for a wall cavity. However, it is a good benchmark for the development of new systems and should be kept for that purpose.

Develop a second lab-scale test for the range that suppression can cover in a wall cavity (6.1). This would work on a similar basis to the flood capacity test, but would instead examine how far suppression would spread. This could be used for development purposes.

Passenger section

Develop a lab-scale test to determine the effectiveness of suppression, similar to the chair test, but cheaper. Burning three chairs at a time is expensive and not ideal for development of new systems. This would be a simple test of a predetermined cheap Class A fire load being used for each system. This is not to be used in the MPS.

Develop a lithium battery simulation. Lithium batteries could be present in this section. These are potentially more difficult to suppress then Class A fires and as such should be considered when developing suppression. This should be included in the MPS.

5.6.6 Next steps needed

Wall Cavities

1) Attempt the development of a hand extinguisher alternative or ensure all panels can be easily removed

2) Develop a new simulation scale test (potentially another lab-scale test would be beneficial but it is not a definite requirement)

3) Develop and install an appropriate suppression system

Passenger Section

1) Develop a lithium battery test for the passenger section

2) Develop a lab-scale test for general suppression effectiveness -- this could be an improvement but it is not a requirement

Overall

1) Develop ways to separate the two systems -- if hand extinguishers are proven to be insufficient, this could be an improvement but not a requirement.

2) Develop and install an appropriate suppression system

5.6.7 Is progress adequate?

Progress in this area is not adequate. New system designs are required by 2014 (2.2.2), yet there has been little progress in the development of a new system. And the progress that has taken place contains multiple flaws. A full-scale simulation of cavities must be included in the MPS as soon as possible. New methods of suppression should be considered to provide fire-safety, particularly for wall cavities.

Halocarbons could be used once halons are banned. These substances may be sufficient to match halons if developed properly. However, these substances are to be banned soon after halon for the same reason as halon. Also, halocarbons have been proven suitable by tests which have multiple flaws.

A delay may be required on the ban of halon in this section if there is not rapid progress. If halon is banned prematurely, it could compromise life-safety. The weight requirements for this section may need to be reconsidered, as no substance matching the weight and effectiveness of halon has yet been found. Efforts into reducing weight should stop and efforts on designing a system which works should start. Once a system is found to be adequate for suppression in this area, efforts can begin on reducing the weight of it.

5.7 Engine Nacelle & APU

This section details problems with suppression used in the engine and auxiliary power unit (APU) as well as discussing if adequate progress is being made in developing a replacement for halon.

5.7.1 How serious is fire risk

The risk here is not too serious. Fires are common in the engine and APU, though suppression is focused on one specific task in a relatively small area. This makes suppression easier than for most other areas.

Aircraft have at least one redundant engine; if one is damaged in a fire, the aircraft is unaffected. The APU is used to tractor the aircraft on the runway (4.5.1); it is not a vital part of the aircraft. Fire is still hazardous if it is not suppressed. It could spread and damage the wings or other components, which would cause loss of control.

5.7.2 Problems with strategy

Combining APU and engine nacelles under the same MPS is not ideal. These two areas are combined because they are both similar in nature. However, some differences could mean that suppression which works in one area would not work in another:

- Different sizes
- Different heat release rates and fuel (though suppression is generally used for an undeveloped fire and both types of engine are likely tested)
- APU is in a compartmentalised area -- this may be easier to suppress, meaning a lighter system could be used.

5.7.3 Potential improvements for strategy

Improve the clarity of the minimum performance standards. Unlike with other sections, this is limited to just listing the test method and pass criteria (4.5.6). This is done in a document which is difficult to interpret.

Design APU and engine separately. This may be done already; however, the MPS suggest otherwise (4.5.6). This could improve the efficiency of each system, although it would require more work and additional testing.

5.7.4 Problems with testing

Testing does not consider the size of engine. Although the effectiveness of the substance used is the main test, volume and concentration must be determined too.

Engine test considered sufficient for APU. The engine is the worst case; this means APU suppression could be overdesigned.

No lab-scale test. Burning an engine (even a simulated one) is expensive. This does not allow for systems to develop from the results.

5.7.5 Potential improvements for testing

Separate tests should be used for APU. Although testing would be more expensive, it could provide a more efficient system for the APU. This could reduce the weight needed.

Lab scale tests should be available. This test would allow for cheaper development. Results can provide more efficient concentrations and volumes of suppression.
A full-scale engine should be used in testing. Although expensive, specific engines must be tested to ensure suppression is sufficient. If this is not done, suppression provided may be inappropriate for Nacelles used. There has been literature evidence to suggest this is already done.

5.7.6 Next steps needed

1) Finish testing, potentially with tests for the APU
2) Determine suppression systems to be used
3) Test this on actual engines to be used on aircraft to prove suppression is appropriate
4) Install suppression

5.7.7 Is progress adequate?

Progress is acceptable. Alternatives need to be available by 2014 (2.2.2). MPS are adequate, though there is room for improvement. Efforts are on-going to complete testing, with systems under consideration which will provide protection but are not as light as halon.

5.8 Lavatory Receptacle

This section details problems with suppression used in the lavatory trash receptacle, as well as discussing if adequate progress is being made in developing a replacement for halon.

5.8.1 How serious is fire risk

Fire risk here is not too serious. Unsuppressed, the fire would fill the cabin with smoke and could burn through the receptacle, threatening the external structure and electronics. However, providing suppression here is easy: it is a small compartment (4.8.1) with a low fuel load and no critical parts.

5.8.2 Problems with strategy

The receptacle is an unnecessary fire risk and does not need to be there. The receptacle is used for hand towels only, and other bins are provided in the aircraft. As well as removing the potential fire risk, using a hand-dryer instead would save weight on:

- Towels
- The receptacle
- Suppression

Moreover, there is no redundancy suppression provided. No detection present (4.8.1) means that if a fire occurs here and suppression fails, occupants would be unaware of the fire's location. Also, it is an inaccessible area which cannot be manually suppressed.

5.8.3 Potential improvements for strategy

Remove the receptacle and use a hand dryer instead. This would use less weight and would be safer; inconvenience caused to occupants would be minimal.

5.8.4 Problems with testing

The test does not account for alternate fuel loads; it assumes that the fire will consist of handtowels lit by a cigarette (4.8.6). It does not take into account that something malicious may be placed in the receptacle, such as fuel. This could mean suppression will not be sufficient for more serious fires. However, if alternate fire loads were used in testing, it would mean suppression would be overdesigned for unlikely scenarios.

5.8.5 Potential improvements for testing

There is no room for improvement. Testing considers the most likely fuel load and the simulation is cheap to perform. Altering the size of simulator used to match the receptacle for specific aircraft could allow for more efficient designs, though this could be an unnecessary expense.

5.8.6 Next steps needed

1) Decide if this receptacle is really needed
2) Test on actual receptacles to find appropriate concentrations -- optional, but could provide an improvement
3) Install suppression (many aircraft have already done this)

5.8.7 Is progress adequate?

Progress is acceptable. Adequate testing procedures are available and underway. Multiple candidates are available and some are already installed, though none are ideal due to weight or environmental impact. Halon suppression must stop by 2020 (2.2.2).

5.9 Other Areas

This section critically analyses the fire-safety strategy for parts of the aircraft which have not already been discussed.

5.9.1 Fuel tank

Suppression systems here are acceptable (4.9.1). Efforts should be focused on reducing the weight of suppression. Alternates to halon are available for this area and only installation is required. The fuel tank is still susceptible to heating from outside it, though it is protected by the dry bay.

5.9.2 Avionics bay

The assumption that fire will not occur (4.9.2) here is risky; if one does occur, not much can be done. Automatic suppression should be provided here, or the bay should be compartmentalised and lack the air supply needed for a fire to start. If this is not an option, it should be accessible in the event of an emergency; however, this is not ideal as fire in this confined space would be hazardous.

Electronics which cannot be suppressed in this area, such as lithium batteries (3.2.2), are a risk to the aircraft's safety. For adequate fire-safety, these items should not be present on an aircraft. If they must be used, then all possible measures should be taken to prevent a fire.

5.9.3 Landing Gear

The tyres are the main fire risk here. These are stored in small 'bins' (4.9.3) that would be easy to suppress. Steps are taken to make the tyres fire-resistant, though damage can occur on take-off and landing (4.9.3). Access is difficult as these bins are often at the very bottom of the aircraft. Removing air from the area is not possible as fire often occurs outside the aircraft.

Suppression is the only option and should be a requirement, regardless of the potential weight.

5.9.4 Dry Bays

The main fire risk here is fuel leaking from the fuel tank and igniting (4.9.4). On military aircraft, chances of damaging the fuel tank are high and suppression is provided -- due to small dry bays, suppression is easy. The suppression provided is an inert gas generator, which is sufficient. On a passenger jet, the fuel tank is less likely to be damaged. Fuel tanks on passenger jets are large and require a larger dry bay; thus, it would take considerable resources to provide suppression here with inert gas generators. Due to the low risk, suppression here is not needed, assuming no other flammable material is in the dry bay.

6 Proposed testing methods

This section details testing methods suggested in the discussion to help develop suppression, and provide a more comprehensive MPS. For each test its: purpose is described, the specifications of the apparatus are listed, the method is described, and the result criteria are explained.

6.1 Suppression range test, lab scale

This details a lab-scale test to determine the effective spread of suppression.

6.1.1 Purpose

This is a lab-scale test to determine the spread of suppression, which will be particularly useful for wall cavities. This is to be used for the development of suppression and is not recommended for MPS. This test method is optional, as it will not prove if suppression is appropriate for a wall cavity, it will only demonstrate how far suppression spreads.

6.1.2 Apparatus

Tunnel section

- Constant square cross-section of approximately 50cm x 50cm
- Between 2-4m in length -- the longer, the better
- One side should not exist -- i.e. it should not have a bottom
- One side should be glass or Perspex or another transparent fire resistant material; it must also be resistant to damage from suppression
- One end should have a hole in the top side for suppression head to be inserted; the centre of this hole should be 25cm from one end
- The section should be fire-resistant
- Should be open-ended, so that suppression can escape at both ends (this is not a flooding capacity test)

Suppression

- This is what is to be tested, as developed by manufacturers

Cup burners

- Numbering between 8 and 16, dependent on the length of the tunnel section
- Small cup burners should be used to prevent the section being damaged

- Heptane would be a suitable fuel

Bottom board

- Forming the bottom of the tunnel section, it must be the same length as the section (2-4m)
- Must be resistant to fire and the suppression being used
- A system could ensure it can be quickly and easily attached to the tunnel section, though this is optional
- Markings every 25cm along the length -- this is where the cup burners will be placed

6.1.3 Method

1) Place cup burners on markers of bottom board and light them
2) Place tunnel section over the board
3) Insert suppression in hole provided
4) Activate suppression
5) Count the number of flames which are extinguished
6) Remove tunnel section
7) Extinguish remaining flames

6.1.4 Results

The numbers of flames extinguished are an indication of how far suppression travelled; this should be compared to other systems tested.

6.1.5 Potential problems

As it tests liquid fuel fires, there is a possible hazard of fuel getting spilled by suppression; this would be unfair to some suppression as it is a Class B fire. There could be potential damage/mess to the lab due to suppression. Also, the section could be damaged if suppression is too forceful.

6.2 Cargo compartment lithium battery test, full scale

This details a simulation scale test for a lithium battery in a cargo bay. This would be of use for the MPS to prove the effectiveness of suppression.

6.2.1 Purpose

To be used with other MPS tests in cargo bay, to determine if suppression is able to extinguish lithium battery fires in the cargo bay. A testing procedure for a lithium battery fire in a cargo bay has been requested in FAA’s 2013 research plan [27].

6.2.2 Apparatus

Cargo container simulator

- Identical to the layout currently used in MPS tests

Metal Lithium battery

- Contained in a mock laptop
- Size of 160 Wh, this is the maximum allowed power of a lithium battery stored in the cargo bay [21]
- Must be rigged so that it overheats
- Suppression system must be in place

Suppression system

- This is what is to be tested, as developed by manufacturers

6.2.3 Method

1) Place battery in hardest to reach area in the simulator
2) Ignite lithium battery
3) After 30 seconds, activate suppression
4) If fire is not extinguished by the suppression, attempt manual suppression

6.2.4 Results

The test is a pass if the fire is suppressed.

6.2.5 Potential problems

Safety could be an issue. Lithium battery fires can be difficult to extinguish; if the suppression system fails, it could be hard to suppress. It is also difficult to accomplish: rigging a lithium battery to overheat poses a technical challenge.

There are fewer obstructions in a simulator than there would be in a cargo bay. Additional obstructions may be required.

6.3 Wall cavity test, full scale

This details a full-scale simulation to be used in the MPS of the cabin. It focuses on testing systems for use in a wall cavity.

6.3.1 Purpose

A full-scale simulation would determine whether suppression for wall cavities is fit for purpose. This should be part of the MPS.

6.3.2 Apparatus

Wall cavity simulator

- The shape should be a representation of a ceiling cavity: low wide arch with a base
- The length should be 8m -- the longer, the better
- The section should be open-ended
- The max height should be interchangeable; different arch sections should attach to the base (the floor of the overhead area). One section should be a few inches high; the other should be four feet high (4.7.1).
- The width should be between 4 and 5m -- the standard width of an aircraft fuselage
- It should be composed of fire-resistant material and should also be resistant to potential damage from suppression
- Access ports should be included in the base; these represent ports used on aircraft
- Fire-resistant obstructions should be included to represent the environment of the overhead area

- Optional factors which could potentially improve the simulator but are not essential:
    - It should be possible to easily remove panels for access
    - It should be possible to turn this section upside-down to transform it into the floor of an aircraft (cheek area)

Pool fire

- Heptane should be used in a 25x25cm pan. Although large, this fire is potentially realistic: it takes a long time to detect the fire, find an extinguisher and gain access through a port. In this time a large fire could of developed
- Enough fuel should be present to allow a burn of 4min.
- A system is required to ignite the pool fire from a distance.

Suppression system

- As designed by developers
- Test assumes this will be a handheld extinguisher
- Automatic suppression could be installed in the section; the installation process would depend on the system

Fully trained and geared fire-fighter, to operate the handheld extinguisher

- Required for safety purposes
- Maintains a fair test, where suppression is being operated to the same standard
- The user can give their opinion on the ease-of-use and effectiveness of the system
- This is similar to the chair test

Lifter

- A system should be in place to raise the arch off the ground to 2m (the average height of a passenger section)

6.3.3 Method

1) Place pool fire in what is considered the most inaccessible area, at least 1m from each of the ends
2) Attach top of arch
3) Lift section
4) Allow fire-fighter with handheld extinguisher underneath
5) Ignite fire
6) Allow the fire-fighter to find the fire and attempt suppression
7) If the test is a pass, repeat with the larger arch section

6.3.4 Results

Result criteria are based on: time taken to supress, ease of use and effectiveness. This should be compared to other suppression substances.

6.3.4 Potential problems

There is a safety issue. Putting a fire-fighter underneath a simulation section with a hidden pool fire is very dangerous. Test burns will have to be conducted to make sure that the structure does not falter and collapse. It will also have to be made certain that pool fire will not spill from suppression.

Focusing on Class B fires is potentially unfair to some substances. However, as fuel lines and hydraulics are involved in this section, a Class B fire could be present. It is also a potentially difficult test to perform. It would be challenging to repeatedly erect the structure, lift it, and ignite the flame.

7 Conclusion

Many potential faults have been suggested regarding the methods used for replacing halon suppression systems:

- Weight-saving seems to be primary concern
- Everything is compared to halon rather than the standard required
- Substances being considered for use have the same ODS problem that halon does
- A fixed date has been set and may be enforced even if no suitable replacement is available
- Method of suppression will not be changed -- i.e. only hand extinguishers are considered for wall cavities
- History has shown that a disaster has to happen before safety is improved.

Additionally, there are general faults in the suppression techniques used in aircraft. Literature has revealed that efforts for developing suppression on aircraft are split into four sections. Of these sections:

- The lavatory trash receptacle should preferably not exist -- it would remove fire risk and weight if it did not
- The engine nacelle and APU should probably be considered separately in order to increase efficiency of suppression
- The cargo container suppression system faces challenging tests that no suppression has been able to pass yet, with some stages of testing yet to start
- Much is expected of the cabin suppression systems. It is difficult to tell if systems are adequate or not due to ineffective testing methods. Better methods of suppression in wall cavities are suggested and should be considered. This area may not have alternatives available by the cut-off date.
- Other areas often have limited literature information available, making it difficult to determine if suppression is used or not. With the exception of the fuel tank and occasionally the dry bay, it is assumed no other suppression is used on an aircraft. Areas such as the landing gear and avionics bay are exposed to the risk of fire.

New developments on aircraft, such as lithium batteries and composite structures, pose an increased risk of fire. However, there are benefits to fire-safety by using these developments, and substantial steps have been taken to prevent fire. Only time will tell if these steps prove adequate. Ultimately, proposed testing methods could improve the MPS as well as develop more effective systems.

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Appendix A: Thesis Development

This appendix details what was not included in the thesis but was considered. And the next steps needed to improve the thesis.

A.1 What was not included in the thesis

Experimentation

It was originally planned that lab scale range test (6.1) would be conducted to prove its effectiveness as a test. This was cancelled as there would be no worthwhile results. Additional resources would have to be acquired in order to conduct the test properly. It would also have taken time away from more important research tasks. And the only result would be when you turn on suppression it does spread down the tunnel and extinguish flames.

Numerical analysis

Calculations were very briefly attempted to determine what volume and concentration of suppression would extinguish a fire in an aircraft. This was stopped as the mathematics was highly complex and would likely have required computer modelling. And the answer would not have contributed to the main thesis topics.

Detection and sprinkler activation

During the research huge amounts of literature was found on detection and suppression activation on aircraft. This was not included as there was limited room for discussion. It is also off topic from the thesis.

Is the ban justified?

Research and discussion on the EU ban on halon was intended. This would determine how necessary the ban is. This was only to be done if there was time. The discussion would be off topic and would not change the decision to ban halon. Although this would have been interesting, time to do it was not available.

Discussion about late instalment dates

Halon is banned two decades before the EU ban current systems from using halon. There was a brief attempt at discussion about this; however relevant review material on the subject was rare and unreliable. Meaning little evidence was available to be discussed.

More in depth details of suppression

Exact details of different systems were to be included. Although due to the number of systems in development it would be excessive to include details on every one. And potentially inappropriate to reference some systems over others in this development phase. Additionally these details would not contribute to the discussion. Instead general details of how each suppression system works was included.

Test results of different systems were also to be included. However detailed up-to-date and completed test results were not available. Additionally some tests have not started or been planned. Literature references on the progress of tests were used i.e. ‘cargo compartment systems are struggling in testing’ or ‘multiple successful candidates have been found for lavatory trash receptacle’.

Also there is much detail in the release mechanism of suppression. However there would be nothing to discuss about this. This was summarised in the literature review as ‘the release mechanism must release the substance effectively, and must not damage the aircraft’.

More detail of weights of suppression was also to be included. However this varied dependent on the aircraft size, so would not have been a useful statistic. With the exception of hand extinguishers which are relatively standard, these weights were included.

Wall cavities system design
An interesting addition the thesis would have been to include a rough design and weight analysis of an internal suppression system for use in wall cavities. But this would require too many assumptions to ensure accuracy.

General effectiveness lab scale test
There was a fourth test method written; this was a lab scale test for the general effectiveness of suppression. This was removed as it was an unsatisfactory unscientific method. As well as being an obvious way to test suppression. The method was stacking a pre-determined amount of solid fuel, igniting it, and seeing if suppression could extinguish it.

Additional case studies
There were case studies for additional areas, and more examples of wall cavity fires, and examples of suppression working. These were removed due to an excessive number of case studies being used.

A.2 Next Steps needed

Add in parts of what could have been included in the thesis (A.1).

Get more definite information on “other areas” such as is there suppression or isn’t there.

Keep the thesis up to date. This is an advancing area of discussion, information specific to systems being developed (particularly on testing) which is correct now, may be incorrect in the near future.

Develop content and layout to the stage where the thesis could be published.