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A Study on the Smoke, Fire and Fumes Early Detection Systems in Transport Aircraft

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Abstract

A review of past, recent, and future fire detection methods and components are presented. Aircraft fire detection applications reviewed are smoke detectors, thermal detectors, gas detectors, flame detectors, and multi-sensor detectors. A review of the history of each fire detection system is discussed to provide an idea about the main purpose of early fire detection in an aircraft and to show the flow of evolution of these systems from conventional systems design to current high-rate detection systems. Discussions of various types of fire detection system and its fundamental operation are presented together with illustrations and circuitry schematics. A deep explanation of the operational features, circuit operations, and characteristics of these detection systems and components are presented so that comparisons can be conducted. The installed location of particular fire detection system is presented so that the strength of each types of fire detection can be discussed. Fire protected aircraft areas presented are powerplant compartments, which include APU compartments, cargo compartments, lavatories, wheel well areas, and avionics bay. The current research for the development of multi-sensor detectors are discussed so that the reliability of this method can be evaluated. Technologies and methods implemented previously and currently for aircraft fire detection systems are then discussed.

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Key-word: - Smoke, Fumes, Fire, Detectors, Transport aircraft, Powerplant

1. Introduction

There are so many development has been made since the beginning of aviation. These efforts have made flying is one of the safest modes of transportation today. However, as far as the aviation industry is concerned, most important development of safety in aviation industry today are from the lesson-learned from the past incidents and accidents. Death of the balloonist Jean-François Pilâtre de Rozier is the first known aviation fatality when his balloon exploded, plunging him to his death (All Things Georgian, 2014).

These days, although fire is a rare event because of the rigid fire safety regulations and efficient flame detection systems on aircraft, yet in-flight fires have continued to occur every year. Therefore, authorities involved in this matter has made many recommendations to the FAA in order to overcome the problems. According to the FAA (2007) in one of its document has acknowledged that the in-flight fires risk will continue to be of concern, the FAA stated that they are unlikely to identify and eradicate all possible sources of ignition in an aircraft. In the other hand, the regulators, operators, and pilots group also have strived to eliminate some of the smoke, fire, and fumes related threats, but as the aircraft getting more advanced and offers on board high technology equipment and in-flight entertainment systems, the source of the smokes and fires are increases, and thus complicate elimination efforts. In the contrary, the Boeing Company also performed an analysis that involved in smoke, fumes, and fire on Boeing manufactured aeroplanes. Data were compiled and the result is as the following statement "for smoke events in which the flight crew could not determine the smoke source, most were subsequently determined by maintenance crews to be of electrical origin" (TSB, 2013). The statements above have proved that an effort to eliminate ignition sources will not eradicate the in-flight fire threat, but only through several layers of mitigation can the risk of smoke and fire issues be kept to an acceptable level. Because fire is one of the dangerous threats to an aircraft, the aircraft manufactures install fire, smoke, and fumes detection systems to increase the level of safety. This system also has become a fundamental component of the active fire protection strategy of most modern aircraft, particularly transport aircraft as it has become a popular means to travel. Many modern aircraft are designed with designated fire zones, the reason for having fire zones is to give an indication to the flight crews to where a fire has occurred. These detectors are installed in suitable place to optimise its function.

For instance, smoke detectors are installed in the cargo and avionics compartment where usually materials loaded in these areas burn slowly or smoulder and produce a lot of smoke. Besides smoke and overheat detector, carbon monoxide detectors are usually being placed in the flight deck to monitor the presence of carbon monoxide (CO) as it can be harmful to human health. The overall goal of the present research is to provide and assess information on the current and future development of fire detection systems in transport aircraft. Specific goals of this study are to list all available technologies of fire detection systems with regard to aviation field and then evaluate and compare the capability of these fire detectors based on information collected from a range of sources.

2. Methodology

The readily data will be used to collect data and information. It is involved in form of statistic, report, graph, books, journals, articles, newspapers and bulletins. The books written by Royal Aeronautical Society (*Smoke, Fire, and Fumes in Transport Aircraft* and book from Tooley, M. Wyatt, D. (*Aircraft Electrical and Electronic System)* are the major reference in doing this research.

3. Current Technologies of Smoke, Fire, and Fumes Detection System

This chapter describes about the current technology of fire detection system been used mostly on commercial aircraft these days. Some fire detectors discuss in this chapter are:

1) Fire Detection/Overheat Systems
2) Smoke Detection Systems
3) Flame Detection System
4) Carbon Monoxide (CO) Detectors

3.1 Fire Detection/Overheat Systems

A fire detection systems are designed to give a signal in the presence of a fire in its early stage of growth. High temperature caused by fire can be detected by various types of devices. Units of the systems are applied in locations where there are high chances of fire braking out or spreading. There are three types of overheat and fire detection systems, among these are:

i. Thermal Switch
ii. Thermocouple Systems
iii. Continuous-Loop Systems

Continuous loop system or also known as tubular detectors are usually used in wide body aircraft for heat and fire detection. Whereas, for overheat warning or fire warning purposes, the detection systems are of either the unit or continuous type. These detectors of either type may be used together, or separately in order to detect a fire or overheat condition on the engines.

3.2 Thermal Switch

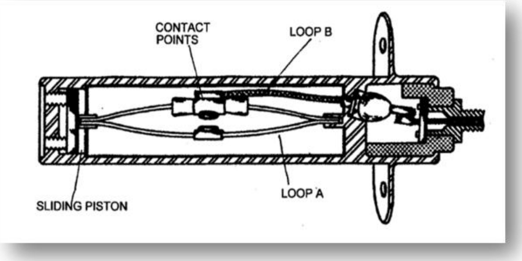


Figure 1 Thermal Switch Cross Section

These detectors are usually located at areas where fire likely to occur. For instance, hot air ducting or an engine breather outlet. As shown in Figure 1, the thermal switch comprises left and right leads that are initially unconnected (Pathirana, 2012). Many older-model aircraft still operating today used thermal switch system for overheat detection and they commonly called as point or spot detector. A thermal switch system is a simple circuit in which one or more lights are connected in an electrical circuit and thermal switches that govern operation of the lights. These thermal switches have a high sensitivity metal to fire or heat exposure that complete electrical circuits at a certain temperature. These thermal switches are connected in parallel with each other but in series with the indicator lights, so that closing of any one switch will provide a warning (Wijerathne, no date).

3.3 Thermocouple Systems

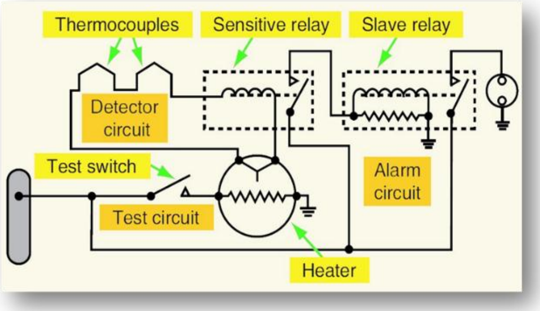


Figure 2 Thermocouple Fire Warning Circuit

FAA (2012) in its technician book describes that in the event of a fire, the thermocouple creates a current due to the temperature difference between the hot junction and cold junction. Moreover, there will be no current is produced if both junctions are heated at the same rate of temperature. This feature is important to prevent the system giving the false alarm as in the engine compartment the temperature is raised gradually; because it is gradual, therefore, both junctions are heat at the same rate and no warning signal is given. When there is a fire, the hot junction heats more rapidly than the cold junction. When sufficient current is being created is greater than 4 mA (0.004 ampere), a sensitive relay in the relay box closes, activating a slave relay and causing an alarm to activate.

The set number of thermocouples used in an individual circuit are usually determined on the total circuit resistance and the size of the fire zones. Also included in the circuit shown in Figure 4 is the circuit has two resistors. The purpose of the resistor being connected across the slave relay is to absorb the coil's self-induced current in order to prevent arcing across the points of sensitive relay. This is due to the fragile wire connections of the sensitive relay that could lead to burn or weld, if arcing is allowed. Since this system response time is depending upon its thickness and materials, there is no specific time respond for the system. However, according to requirements by FAA in TSO-C11e, it is safe to say that the thermocouple respond time is within 5 seconds (FAA, 1991).

3.4 Continuous-Loop Detector Systems

3.4.1 Fenwal System

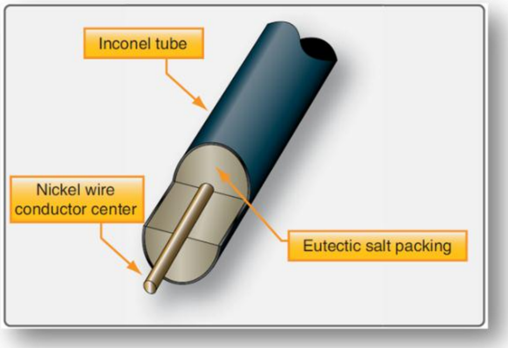


Figure 3 Fenwal Sensing Element

The Figure 3 shows the fenwal sensor comprises of a flexible, light weight, and slender Inconel tube packed with a pure nickel wire centre conductor (FAA, 2012). The space between the nickel conductors is filled with a porous aluminium oxide. In addition, the clearance between the tubing and aluminium oxide are filled with a eutectic salt mixture, which has low melting point. These sensing elements are connected in series to a control unit. This control unit is operated directly from the power supply, provides a small current on the sensing elements (Integrated Publishing, no date). When any part of these elements are exposed to the overheat condition, the resistance of the eutectic salt contained in the sensing element drops drastically. In turn, causing current to flow between the centre wire and the tube wall. The increasing current flow is sensed by the control unit, which produces a signal to actuate the output relay and activate the alarm systems. When the fire is eliminated or the temperature lowered below the set point, then the fenwal system will automatically set to standby alert mode, the mode where it's ready to detect any subsequent overheat or fire condition.

The fenwal system could be deployed as a loop circuit. With regard to this, when an open circuits occur, the system still able to give a signal in the fire or overheat condition. Furthermore, should multiple open circuits occur, only that section between breaks becomes malfunction (Wijerathne, no date).

3.4.2 Kidde Systems

The kidde sensor comprises of an Inconel tube filled with a thermistor core material (FAA, 2012). Two electrical conductors are imbedded in this material and one of the conductors has a ground connection to the tube (see Figure 4) and the other conductor connects to the fire detection control unit (FAA, 2012). In the kidde sensing elements, as the temperature of the core increases, the resistance of the thermistors element decreases rapidly. The change in resistance is detected by the fire detection control unit whose monitors the system. Typical reaction times from detection to full suppression are 120 - 150 milliseconds.

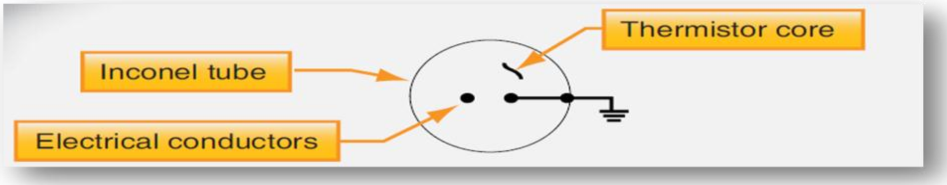


Figure 4 Kidde Sensing Element Cross Section

On one hand, when the resistance is lowered to the set overheat point, the control provides the warning signal to illuminate the warning light in the flight deck. Usually, a 10 second time delay is incorporated for the overheat indication. On the other hand, when the resistance further decreases to the fire set point, the fire warning light illuminates and in the same time activates the aural warning devices. It returns to a normal condition when the fire or heat condition is gone. In some aircraft, these systems can supply nacelle temperature data to the aircraft condition monitoring function of the aircraft in-flight monitoring system (AIMS).

3.4.3 Pneumatic Continuous-Loop Systems

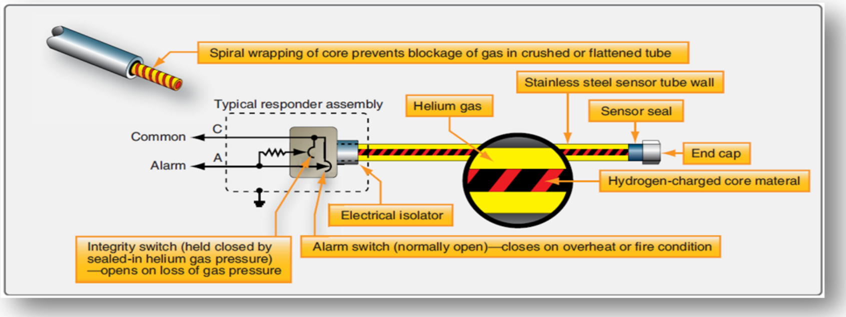


Figure 5 Pneumatic Pressure-Loop Detector System

The sensing elements introduced by Systron Donner Company are pneumatic in operation. These systems have a purpose of detecting engine fire conditions in transport type aircraft as similar as the Kidde system. Nevertheless, they operate on a different principle. Moreover, similar to Kidde system, they are usually employed in a dual-loop design to increase the reliability of the system. The Figure 5 shows that the sensing element consists of a hydrogen charged core surrounded by helium gas, housed in a stainless steel tube connected at one end to a responder assembly (Wijerathne, no date). As the element heated, the helium gas pressure inside the tube increases, closing a pressure switch, thus output an alarm signal inside the flight deck. The pneumatic detector relies on increasing temperature to achieve its alarm threshold. Therefore, it has multi sensing functions, some of which are to respond to an overall average temperature threshold and to a localised discrete high-temperature conditions caused by hot gasses or flame. Since this system mainly located on the engine compartment, the response time required is within 5 seconds.

3.5 Smoke Detectors

A smoke detection system is the primary means of fire detection used in cargo baggage compartments and lavatories. The primary design consideration for smoke detector is to ensure that the smoke reaches the detector in a timely way. Therefore, smoke detection instruments that collect air for sampling are installed in the cargo areas at strategic locations. A smoke detector is located at the point where the type of fire anticipated is expected to produce a large amount of smoke before the actual fire is occurred to trigger the fire alarm. The response time for a smoke detector to output a signal is around one minute. There are two basic principles of smoke detectors, which are:

i. Ionization
ii. Photoelectric.
i. Ionisation Smoke Detector

The system activates an alarm signal (both indicator and aural) by monitoring ionised products of combustion as they pass through a charged electrical field. These detectors are capable of detecting smoke particles that are often too small to be visible. The system is supplied with 28-volt DC electrical power from the aircraft. The typical approach of this system is by using a small amount of radioactive isotope which is source of alpha radiation to ionise the air between two electrodes (EPA, 2012). The positive atoms flow towards negative plate and vice versa. This ionised-air cycle causes a very small flow of electrical current between the electrodes. Smoke entering the chamber will attach to the ions and further reduce in the flow of current; this reduction alerts alarm that smoke is present. According to Hillman, Hill, and Sturla (no date) since this smoke detector is so sensitive, ionisation detectors detect fires sooner than photoelectric detectors. However, they have several disadvantages:

- This system will output an alarm signal if fine water droplets or dust enter the chamber.
- The detector’s sensitivity changes with pressure as altitude of an aircraft changes, and they also deteriorate with age.

ii. Photoelectric Smoke Detectors

Most modern photoelectric detectors of the spot type use a photoelectric cell that detects light refracted by smoke particles. A typical arrangement of functional parts; an air sample is passed through the detector by means of pipes or ducts (Tooley and Wyatt, 2011). This air then passes through a sphere shape chamber called labyrinth. A photoelectric cell, with its optic, located at right angles to the light beam. When smoke enters the labyrinth chamber, the smoke particles reflect and scatter off a small portion of the light beam toward the photocell, causing energy to decrease on the second cell and causes an alarm.

3.6 Flame Detectors

i. UV Flame Detectors

According to Fire Alarm Parts Guide (2010) ultraviolet (UV) detectors operate by detecting the UV radiation emitted from fire sources in the spectral range of approximately 180-260nm (nanometres). The detector offers quick response of detecting fires and explosions within 3-4 milliseconds and can detect a 24-inch flame up to 500 feet. UV detectors however, susceptible to halogen lamps, sunlight, and lightning that could triggers false alarm indications.

ii. IR Flame Detectors

IR detectors operate at the infrared spectrum from 1.1µm (micrometres) and higher. These detectors look for the 4.4µm wavelength of CO_2 given off by hydrocarbon fire. In addition, they have a slightly slower response time which is under 50 milliseconds and are relatively immune to attenuating source to the same false alarm triggers as the UV type (General Monitors, 2013).

iii. UV/IR Flame Detectors

These detectors are sensitive to both UV and IR wavelength and considered as the best of both worlds. Since it comprises both UV and IR characteristics, it offers excellent flame detection and covers a large spectral range whilst maintaining outstanding false alarm. The hydrocarbon fuel fire emits high energy of the UV and IR frequencies waveband. Therefore, the flame detector is designed to detect the presence of radiation from one or both of these frequency wavebands.

3.7 Carbon Monoxide Detectors

The most common types of CO detectors are electronic, whereas some are panel mounted and others are portable. Chemical colour-change types are mostly portable. They come with different shapes such as cards or badges that have chemical applied to the surface (NTSB, 2004). The response time of this type of CO detectors are inversely related to the concentration of CO present. At 50 parts per million (50 ppm) CO concentration the chemical changes its colour within 15-30 minute, which indicates low concentration of CO. A high concentration level of CO as much as 100 ppm changes the colour of the chemical as quick as 2-5 minutes. However, these chemicals are vulnerable to exposure to a wide range of chemicals from all sorts of solvents, aromatic cleaners, and other chemicals which commonly used around aircraft (Busch, 2003).

4. Near-Ready Aircraft Technologies

4.1 Multi-sensor Detectors

Multi-sensor detectors, also referred to electronic noses is a new technology which combined one or more conventional smoke detector technologies; a different type of sensors for detecting such gases as hydrocarbon, carbon monoxide, or carbon dioxide. These technologies also equipped with a thermal sensor to increase its effectiveness to locate overheated or burning materials.

Multi-sensor detectors enhance conventional fire detection by locating and discovering potential fires sooner and eliminate the incidence of false alarms. These technologies are highly immune to nuisance sources, such as dust and condensation that are responsible for activating false alarms in the conventional systems (General Accounting Office, 2003).

i. Micro-Fabricated Gas Sensors

The micro-fabricated gas sensor introduced by the NASA is a miniaturised CO_2 and CO gas sensor. This gas detectors consist of Nano-crystalline materials which offers more sensitivity and stable detectors compared to the conventional fire detectors. Apart from sensing the presence of CO and CO_2 , this detector provides gaseous product-of-combustion information obtained from a sensor array whose can detect wide range of gas species. Moreover, unlike conventional fire detectors, micro-fabricated gas sensors are equipped with intelligent software for pattern recognition. All these advantages possessed by MEMS sensing technologies enable effective detection of fires and minimising false alarms while highly reduce power consumption and weight. Another additional features of these sensors are it can operate in extreme environment and has a very fast response time for approximately less than 10 seconds.

ii. The Combination of Photoelectric Detector with NDIR CO_2 &CO Gas Detector

According to Chen et. al (2007), a fire detector which combines a photoelectric smoke detector and a NIDR CO_2 and CO gas detector that share a common light source can improve detection and reduce nuisance alarms. This technology is developed based on simultaneous measurements of CO, CO_2 concentrations, and smoke. The combination of the rate of rise of smoke provided by the photoelectric detector and either CO or CO_2 concentration from NDIR provides a basis of fire alarm algorithm that detects fire that were not alarmed by smoke detectors and alarmed in shorter times than smoke detectors operating alone.
The combination of these technologies also can differentiate between flaming and non-flaming fires by using the rate of rise of CO and CO_2 from cargo atmosphere. The system consists of a fire algorithm that monitors the rate of rise of smoke level, when the smoke level exceeds its threshold rate, the rate of rise of CO and CO_2 concentrations then are checked. Should either the rate of rise of CO or CO_2 concentration surpasses its threshold level, a fire alarm is issued (Chen et. al, 2007).

5. Advanced Technology

5.1 Video-Based Detection Systems

Development of the video-based Cargo Fire Verification System (CFVS) for commercial aircraft was motivated to overcome the problem of frequent false smoke alarms especially for long range flights of passenger aircraft. Besides that, current smoke detectors employed in an aircraft are point type detectors which detects at a certain point in space. This point however may not be affected by fire or smoke thus the smoke would not be detected. Moreover, with conventional detectors used in enclosed cargo area, the smoke alarm system will continuously to report an alarm condition although the fire has been eliminated. Therefore, the pilot is not knowledgeable of a fire condition whether it has been successfully extinguished or continuing to grow. This case is found to be unsatisfying, and the pilot should be provided with reliable information about the fire growth and the effectiveness of fire suppression actions (Krull et. al, 2005).

i. System Architecture

Krull et. al (2005) describe that the CFVS uses low-cost charged-coupled device (CCD) cameras operating in the near infrared range in order to detect hotspots and fire. Moreover, the system consists of LED illumination units which are switched on and off in sequence in order to obtain images that were then been analysed to detect the presence of smokes. By combining the results from image processing with humidity and temperature data allows reliable detection of true fires and elimination of nuisance alarms that usually caused by dust and moisture. For the systems to work in aircraft cargo compartment, there are two cameras are mounted in opposite corners of each cargo compartment to provide full visibility of the entire areas as shown in Figure 6 (Krull et. al, 2005). These cameras were installed with optical filters to block visible light that usually comes from cargo illumination sources.

Typically, each camera is built in with its own controlled near infrared (NIR) LED illumination sources. Moreover, additional NIR illumination units are mounted in the ceiling of the compartment. These NIR illumination units will appropriately switched on and off, thus enable the system to obtain different views of the scene.

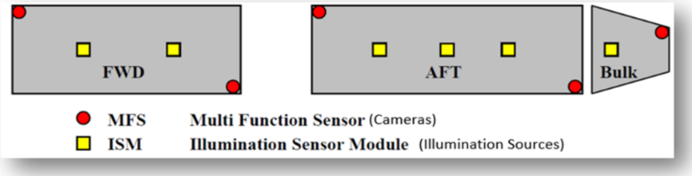


Figure 6 CFVS Aircraft Installation (Top View)

Both camera and NIR illumination sensor equipped with sensors to collect humidity and temperature measurements inside the cargo compartment. These collected data are used to analyse possibility of false alarm such as ascent-related fog. The central system then analyses the images, temperature and humidity readings to confirm the occurrence of the fire with the appropriate image that will be appeared on the screen in the flight deck (Figure 7).

Figure 7 Images Appear on the Video Display

ii. Light Switching Sequences

The CFVS is capable of differentiate between fire and smoke condition and non-fire conditions such as dust and fog, this is done by the central processing unit whose job it is to analyse different images obtained under different illumination conditions. As shown in Figure 8, usually 4 different views are used to be analysed by central processing unit.

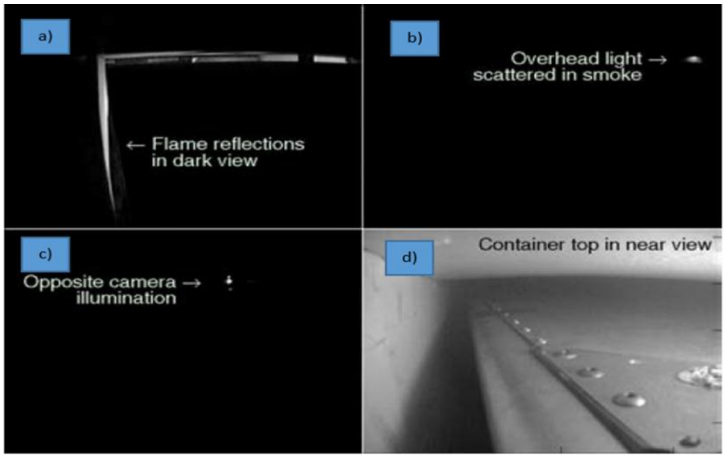


Figure 8 Four View with Different Illumination

As illustrated in the (a) section of Figure 8, the camera is in the dark view mode where all illumination sources are turned off. Therefore, since the area is dark, so that the presence of any high intensity image areas indicates a heat source. This mode is used to detect the presence of flame and hotspots, which is sufficient in majority fire occurrences. In the case of fully loaded cargo compartment, the occurrence of flames may be hidden behind containers. Similarly, for smouldering fire which burn slowly and produce a lot of smoke.

In this case, the CFVS will operating in smoke detection mode where it used another three illuminated views (b), (c), and (d). In this mode, the camera's LED sources are turned off, whereas the NIR illumination units are switched on. Therefore, in the presence of smoke, illumination lights are scattered which in turn make the areas brighter as shown in the (b) section of the figure.

In the contrary, the opposite camera's LED sources are turned on, while the NIR illumination units are turned off. This configuration enables opposite camera light to be well visible from the image, as shown in (c) section. In presence of smoke, the light is absorbed, thus the image becomes dimmer and smaller until it disappears completely. This is due to the capability of the opposite CFVS that acts as a very long optical smoke detector, whose covers the entire compartment.

The CFVS system alone offers outstanding detection capability surpasses an entire set of multiple conventional smoke detectors. The last section of the picture, which is (d) shows a near view image. The near view is a mode where the only light turned on is the one collected with the camera and then recoded for later use by the crew.
The advantages of CFVS system over conventional smoke detection:

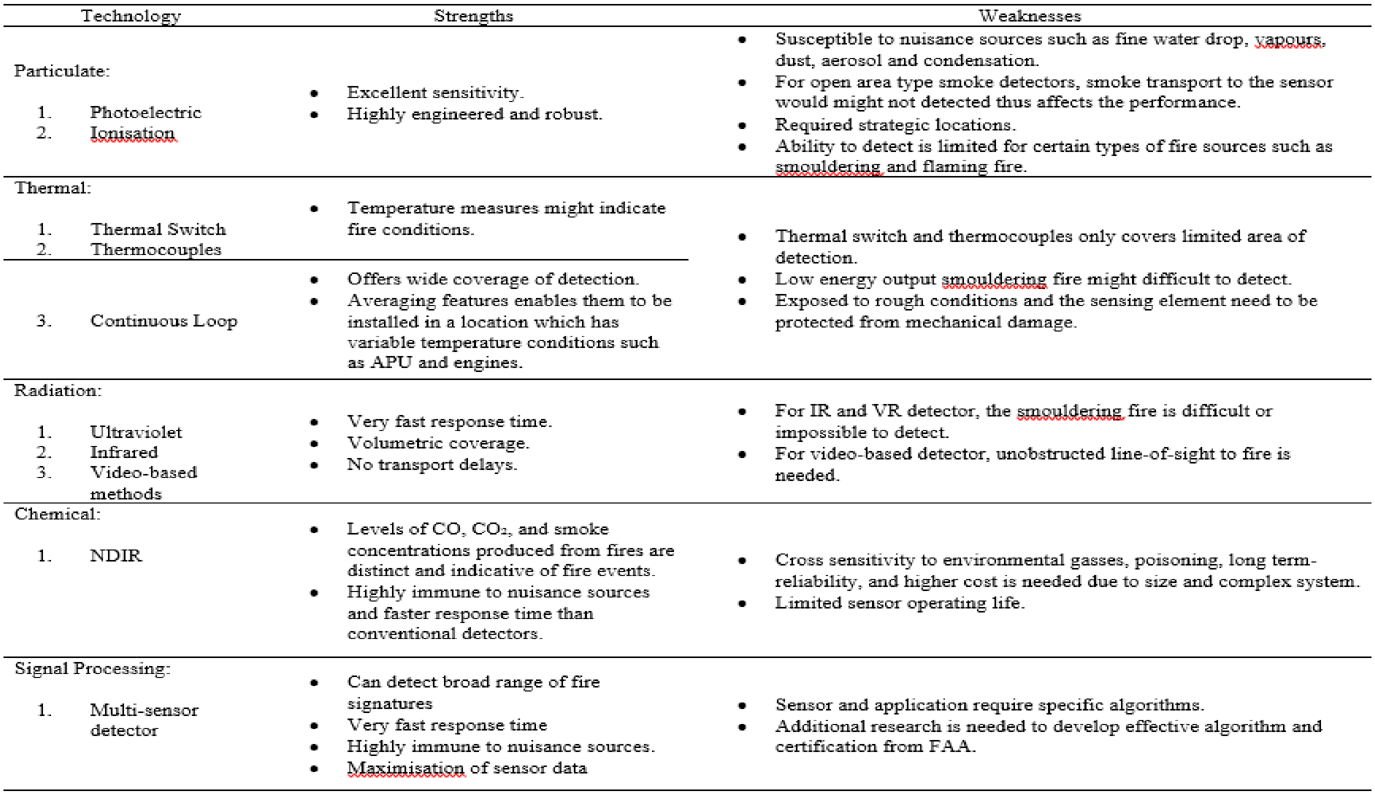
i. The CFVS is able to detect hotspots and flame directly from the images, thus enables it to detect low-smoke fires much faster than conventional smoke detectors.
ii. The video-based system makes use of the distributed nature of video information that covers an entire space, instead of a small number of discrete points that usually used by the conventional detectors. This unique features enables the CFVS detects fire promptly than conventional detectors.
iii. The CFVS fire detection algorithms enable it to differentiate between all smoke and dust cases, and between fog and smoke cases.
iv. Fire detection by video-based system can cover wide areas of observation and allows visual inspection directly from the flight deck.
v. The CFVS is able to detect both open and smouldering fire sources, although the fire source is not visible or hidden behind a container.

7. Findings

Table 1 Fire Detection Sensor Properties

	Thermal Detectors			Smoke Detectors		Flame Detectors	
	Thermal Switch	Thermocouples	Continuous-loop	Photoelectric	Ionisation	UV	IR
Relative responsibility to Fire Hazard	Low	Low	Low	Low	Low	Very High	High
Relative False Alarm	Susceptible to Ambient Airflow and Covers limited Area of Detection Coverage		Excellent, if Undamaged	Susceptible to Humidity and Dust		Prone to sunlight and Lightning	Better than UV
Operating Temperature	<1200°F Depending on Design			160°F		400°F-500°F	260°F-300°F
Speed of Response	5 Seconds Maximum			Less than 60 Seconds		1 to 2 Seconds	
Locations	Powerplant Compartment			Cargo Compartments/Avionic Bay/Lavatories/Crew Rest Area		Engines	
Other Characteristics	Installed at Specific Point		Localised Routing	Installed at Specific point or Aspirated Systems		Remote Mounting	
	Non-Smart sensors			Smart Sensors: Output its Own Fire Signal		Non-Smart Sensors	Smart Sensors
	Suited For Detecting Overheat Conditions			Suited for Detecting a Smoldering Fire	Suited for Detecting a Flaming Fire	Suited for Detecting a Flaming Fire	Suited for Detecting a Flaming Fire

Table 2 Fire Detection Systems Strengths and Weaknesses



Technology	Strengths	Weaknesses
Particulate: 1. Photoelectric 2. Ionisation	• Excellent sensitivity. • Highly engineered and robust.	• Susceptible to nuisance sources such as fine water drop, vapours, dust, aerosol and condensation. • For open area type smoke detectors, smoke transport to the sensor would might not detected thus affects the performance. • Required strategic locations. • Ability to detect is limited for certain types of fire sources such as smouldering and flaming fire.
Thermal: 1. Thermal Switch 2. Thermocouples	• Temperature measures might indicate fire conditions.	• Thermal switch and thermocouples only covers limited area of detection. • Low energy output smouldering fire might difficult to detect. • Exposed to rough conditions and the sensing element need to be protected from mechanical damage.
3. Continuous Loop	• Offers wide coverage of detection. • Averaging features enables them to be installed in a location which has variable temperature conditions such as APU and engines.	
Radiation: 1. Ultraviolet 2. Infrared 3. Video-based methods	• Very fast response time. • Volumetric coverage. • No transport delays.	• For IR and VR detector, the smouldering fire is difficult or impossible to detect. • For video-based detector, unobstructed line-of-sight to fire is needed.
Chemical: 1. NDIR	• Levels of CO, CO_2, and smoke concentrations produced from fires are distinct and indicative of fire events. • Highly immune to nuisance sources and faster response time than conventional detectors.	• Cross sensitivity to environmental gasses, poisoning, long term-reliability, and higher cost is needed due to size and complex system. • Limited sensor operating life.
Signal Processing: 1. Multi-sensor detector	• Can detect broad range of fire signatures • Very fast response time • Highly immune to nuisance sources. • Maximisation of sensor data	• Sensor and application require specific algorithms. • Additional research is needed to develop effective algorithm and certification from FAA.

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