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# Aircraft Fire Detection and Suppression

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# Aircraft Fire Detection and Suppression

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ABSTRACT

A review of past and state-of-the-art aircraft fire/explosion detection and extinguishing components is presented. The lessons learned from previously fielded systems are briefly discussed so that they can be applied to the modern protection systems as they are implemented.

Also, the operational features and characteristics of both fire and explosion protection components and equipment are identified and discussed so that trade studies based on these components strengths and weaknesses can be conducted. By appreciating these components strengths and limitations, a system definition which is optimized for the given application can result. The application of detection and suppression technologies to select aircraft environments is also discussed. Environments considered included: fire protection for engine powerplant compartments, fire and explosion protection for vulnerable dry bay compartments, explosion protection for aircraft fuel tanks, and fire protection for aircraft cargo bay compartments.

Based on the parametric characteristics of the perceived hazard, the protection systems and components, and the specific environment of the aircraft which requires protection, the definition and configuration of an optimized approach for protection can better be defined.

INTRODUCTION

Active protection systems and components have always been the last resort for dealing with anomalous faults and other hazards which may lead to fires and explosions onboard aircraft. Historically, these components which are made up of detection sensors and frequently fire extinguishing vessels have been employed only after design measures could not adequately assure the elimination of a potentially catastrophic fire incident.

Over the last 60 years or so, aircraft power plants have received the most attention with regard to protection. However, over the last 25 years, the protection of the fuel system (especially in the case of military aircraft applications) has become increasingly important for enhancing aircraft safety and reducing aircraft vulnerability. And even more recently, the protection of select aircraft dry bays and cargo bays has been recognized as a major contributor toward safety and survivability enhancement.

The detection and extinguishing/suppression technologies used to protect these areas have evolved over this period of time. To fully appreciate where we stand today with respect to aircraft fire and explosion protection components and systems, one must appreciate the technological evolutions which have taken place. A brief historical synopsis of aircraft detection and extinguishing systems is offered for this reason.

HISTORICAL BACKGROUND AND LESSONS-LEARNED

DETECTION SYSTEM COMPONENTS – Fire detection has long been recognized as the single most important aspect of fire protection. If one is made aware of a hazardous condition early enough in its development, corrective action of some kind can be initiated; hopefully negating a catastrophic condition. Recognizing this fact, fire detection systems were first deployed in aircraft engine nacelle compartments some 60 years ago.

In the 1930's and 40's, a continuous type fire detector using a fusible alloy that when melted provided an electrical circuit between the outer sheath and the isolated center conductor was first employed. One of the early aircraft to use this system was the B-25; others included the B-26, C-47 and the C-54. After once giving an alarm, the detector could not eliminate the warning signal. Thus, no "fire out" message was issued. The melted element had to be replaced before the next flight.

In the 1940's thermocouple type point detectors were used to provide fire and overheat detection coverage in the engine nacelle. This technique represented a significant advancement in aircraft engine early fire warning in that these systems also provided "fire out" indications and were resettable. Systems of this type were deployed on many military aircraft of that day, including the B-29, B-36, C-119, and the F-86 to name just a few.

In about this same time period, unit type bimetallic thermoswitch sensors were developed and widely used on select jet engine installations. Detectors set at 450°F (232°C)were used to detect fire in the forward compartment and detectors set at 700°F (371°C) for overheat detection in the aft section of the nacelle. Aircraft using these bimetallic thermoswitch sensors included the B-45C, B-47, B-52, C-135, F-80, F-84, F-104, and the F-105.

Although the thermocouple and thermoswitch type detection systems were credited with saving numerous aircraft installations and crews, it was recognized that point detectors were very limited with regard to area of coverage. In that thermal monitoring devices rely on convective heat, transferred from a fire to the detector, and ambient airflow affects the heat transfer processes, the placement of the point detector in the engine nacelle became the most critical factor of how successful the detection system would be for providing early warnings of anomalous fire events.

When continuous element thermal detection systems were introduced to the aircraft industry in the early and mid-1950's, a major shortcoming of point detectors was overcome; i.e., greater detection coverage was achieved. Sensing elements, resembling long continuous wires, were routed throughout the length of the engine nacelle, and like the earlier fusible alloy elements, provided greater volume coverage, but these continuous elements were resettable. The continuous element thermal detection technology became the most popular detection approach for aircraft engines and has remained so still today.

Various versions of continuous element detection systems have been developed and fielded. Some versions are dependant on the amount of element heated to reach their alarm threshold level and have been termed "averaging" type. If only a small length of element is heated (say, six inches; 15 centimeters), a higher threshold temperature is required before the monitoring control/responder unit outputs a fire alarm. If a greater length of sensing element is heated, a lower alarm threshold results. This feature enables averaging type thermal element systems to be routed near recognized "hot spot" areas that may have a normal temperature well above the overall alarm temperature without causing the system to output an alarm condition. Conversely, if this feature is deemed non-desirable, a second alarm threshold can be added to the system architecture (one that corresponds to the unique higher temperature characteristics associated with the localized "hot spot" event) and a corresponding second output can be signaled. This multiple threshold property, unique to averaging type detection systems (including point detector systems), is commonly used to indicate an overheat warning, indicative of an engine bleed air duct failure or combustor-can burn-through event.

Averaging type continuous elements monitor either changing electrical resistance, changing resistance and capacitance, or changing internal gas pressure as function of temperature. The electrical based continuous sensing elements (ones that monitor changing electrical capacitance and/or resistance) have one or two wire conductors embedded in a ceramic-like material and are contained in a metallic outer sheath. As the surrounding temperature increases, the resistance between the conductors decreases and the capacitance increases. When the resistance of the sensing element drops to some pre-determined level (and/or the capacitance increases) which corresponds to the desired alarm temperature, a monitoring control unit signals an alarm output. When the hazard condition is eliminated and the temperature returns to normal, the resistance increases and the capacitance decreases, thereby canceling the alarm. This time to reset is by design less than 30 seconds. Multiple trip resistance/capacitance settings are used when multiple thresholds are pursued (to indicate fire versus overheat).

The pneumatic averaging continuous element system relies on increasing gas pressure to achieve its alarm threshold. These sensing elements have a hydrogen charged core surrounded by helium gas, contained by a metallic outer sheath. As the surrounding temperature increases, the helium gas pressure increases, closing a pressure switch, thereby issuing an alarm. As the temperature returns to normal, the pressure decreases and the alarm is canceled. If a localized very high temperature event is present, the hydrogen core outgasses, increasing the internal pressure and closing the pressure switch (or a second switch if multiple thresholds are used, such as a fire or overheat output). As the sensing element cools, the hydrogen ingasses back into the core so that the internal pressure decreases, removing the alarm output.

Shortly after the first continuous element "averaging" type detection system was introduced, a "discrete" type continuous element system was also introduced. Unlike the averaging detection systems, the discrete systems utilized sensing element which were essentially independent of the length of element heated to achieve its alarm threshold. There have been (and continue to be) only electrical based versions of discrete continuous element detection systems. These systems employ a sensing element which, like the electrical based averaging systems, have either one or two internal wire conductors embedded in a ceramic-like core material, surrounded by a metallic outer sheath. The ceramic core is impregnated with eutectic salt. The salt melts at its eutectic melt temperature, even when only a very short length of element is heated. When this occurs, the electrical resistance between the inner conductor and the outer sheath breaks down (also the capacitance increases), and a monitoring control unit signals a fire or overheat, whichever is appropriate for the intended application.

While the sensing element is essentially independent of the length heated (which is a critical feature for reliable, early warnings of small, discrete overheat events, such as bleed air duct failures), it cannot in its present form provide multiple alarm thresholds or any kind of analog temperature trend information as the averaging detection systems can.

In a similar time frame to the introduction of continuous element detection systems, an optical detector was also introduced.

A photoelectric lead sulfide cell used to monitor infrared radiation which flickered (around five to ten hertz, the flicker rate of fire) was deployed on the C-130 and later on the C-133's APU compartment (then called a GPU). While this detection approach, later tradenamed FIREYE®, served as a quantum leap in early warning detection, it like many of its optical detection successors was false alarm prone. In fact it appeared that its primary shortcoming was that its alarm threshold (i.e., sensitivity) was set too low. One of its primary false alarm scenarios occurred when an aircraft fitted with this detection system flew over a city at night. Since the detector had a truncated view of the lights which appeared to be chopped as viewed through narrow apertures (interface seams) of the nacelle structure, the flickering light was reported as a fire.

A cadmium-sulfide detector cell was later introduced and subsequently replaced the FIREYE® sensor on the C-130. This optical sensor monitored two narrow wavebands in the visible spectrum, red and green wavebands. The cad-sulfide detection sensor market grew in the 1960's and into the 1970's, but its market was primarily limited to military helicopters and some general aviation engine bays. While this concept was recognized to have operational limitations such as alarming to non-fire sources (such as rising and setting sunlight conditions, light reflected off bright colored clothing, flashlights, etc.), its marketshare increased; primarily so that logistical compatibility could be maintained with other aircraft utilizing this technology.

Also, in a similar time frame as the introduction of the cad-sulfide detector, the Europeans started fitting fuel tanks with active ullage protection systems. These systems utilized a cold cathode detection sensor which monitored for optical radiation in the near infrared (IR) region. This optical detection based protection system ended up being used on a number of aircraft including the Vulcun, Victor, Valient, and the Hunter aircraft. While there may be a few of these systems still flying today, for the most part, this concept was discontinued in the early 1960's; primarily because of false alarms with the detection system.

Other versions of detection sensors were also introduced during this time frame; the significant ones included pressure sensors and inertia or "g" sensors. The pressure sensor was primarily used in aircraft fuel tank ullage protection systems, and the "g" sensor was used to activate fuel tank suppressors in crash protection systems. Since that time, both of these detection concepts have been addressed as potential activation mechanisms for dry bay and fuel tank vulnerability reduction systems and crash protection systems. However, these two detection concepts have found limited application onboard aircraft.

Continuous element and optical detection systems still are the primary detection concepts used for aircraft detection systems today. These detectors are almost solely used for aircraft engine fire protection. While survivability and crash protection systems which utilized active detection equipment were employed back in the 1950's, their less-than-favorable performance never perpetuated their deployment.

While significant improvements have been made in optical sensor technology, which will be discussed in later discussions of this document, none of these improved design concepts has been deployed on a production basis for modern day aircraft. However, several design improvements have been incorporated into the continuous element detection systems, and these systems have been deployed. Some of the more significant improvements were:

- short circuit discrimination (electrical based systems),
- "fail safe" circuit design,
- use of dual sensing elements which utilize "AND" logic,
- on-command self test features (option for automatic test),
- self interrogation which automatically switches dual "ANDed" elements to single element operation if one element fails,
- ambient temperature trend monitoring,
- improved support/mounting hardware designs,
- use of terminal lug connectors to circumvent the most recognized cause of false alarms, connector contamination.

The terminal lug fitting feature is one of the most recent improvements to be implemented. Although hermetic connectors which were utilized in engine compartments were successful in minimizing contamination from entering the connector cavity, there were scenarios in which the connector's hermetic seal led to operational faults (specifically, false alarms). Certain aircraft maintenance procedures permit the use of chlorinated solvents to clean connectors. When the continuous elements' hermetic connectors were cleaned with these solvents and subsequently mated together and exposed to heat (such as the high temperatures associated with the engine compartment), an electrolytic decomposition of the solvent occurred. The decomposition forms a conductive acid which in turn allows electrical short circuits to occur between connector pins. Unfortunately, this electrical shorting is many times introduced in such a manner that it mimics a resistance change from a high temperature event; so that in the case of the electrical based detection systems, the "short discrimination" circuitry could not discern this type of event from a fire event. In the case of the pneumatic system, the electrical short occurs at the pressure switch/aircraft wiring interface.

Before many of these new system features were implemented (late 1960's to early 1970's), the U.S. Air Force conducted a detection system performance survey for their aircraft. They found a very high percentage of the fire incidents was not detected by the thermal detection systems. Plus, according to the performance statistics generated by this study, most of the time the detection system did issue a fire warning, it was false (1)*. Although the greatest percentage of the negative statistics toward detection systems were associated with archaic point detectors, it was still conclusive that continuous element detection systems were far from providing optimal performance. While the continuous element detection system design improvements, mentioned earlier, significantly improved the performance statistics, it took time for these improvements to be measured. It was at that time, the U.S. Air Force moved to develop a new detection system for the engine compartment. The result of this effort culminated in the development of the high temperature Ultraviolet Aircraft Fire Detection System (UVAFDS)(2).

USAF sponsored this activity in the late 1970's, with the objective of developing an "improved" method of fire detection for aircraft engine nacelles. This UV detection system utilized a cold cathode gas discharge tube responsive to radiation below 280 nanometers (nm). Figure 1 illustrates the detector tubes relative responsivity as a function of wavelength in conjunction with the radiant emission of a fire and sunlight. The sensor is

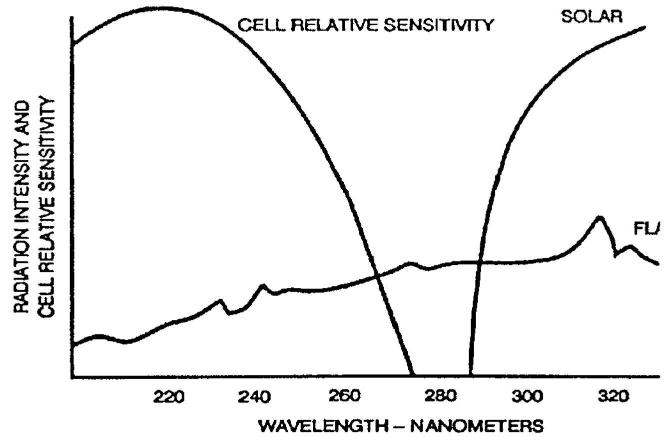



Figure 1. UV Cell Sensitivity

highly responsive to radiation in the 200 to 250 nm range and relatively insensitive to radiation of longer wavelengths. This very large difference in sensitivity is essential because the amount of short wavelength power radiated by a flame is only a small portion of the total radiant power emitted and is small compared to other radiation emitting sources which might serve as false alarm sources.

The sensor is made up of special UV transmitting envelope which contains two metal electrodes and a special gas mixture. The electrodes are connected to an established "high voltage" source (generally above 300 volts D.C.). When a photon possessing sufficient energy strikes the cathode, an electron is emitted and is accelerated towards the anode by the electric field existing between the electrodes. The inert gas filling of the photocell contains gas molecules that are electrically neutral and present in sufficient quantity to ensure that a collision takes place between a gas molecule and the accelerating electron. After collision, the gas molecule loses electrons and the gas molecule becomes a positively charged ion. The displaced electrons collide with other gas molecules which can cause an avalanche of electron flow, and conduction occurs between the two electrodes. Upon removal of the supply to the electrodes of the photocell (accomplished by electronic switching within the associated control unit), the positively charged ions and the free electrons recombine and the gas becomes nonconducting. This process is repeated in some gating fashion until the pre-determined sequence of tube conductions (which have been termed counts) are achieved.

In addition to the development of UVAFDS for engine detection, several other development efforts were

* Numbers in parentheses designate references at end of paper.

conducted to improve fire/overheat detection technology; however little enthusiasm to implement these new detection technologies was expressed by the aircraft user community. It is believed that the reasons for this were:

- Although there were numerous false fire warnings on certain aircraft designs (while the detection system vendors were developing an appreciation of the maintenance practices and application constraints associated with the end item environment and while the aircraft designers and users were learning the limitations associated with the detection systems which they were implementing), the number of false fire warnings and undetected fires continued to decrease. The trend was improvement.
- Different detection techniques implemented in the past, specifically optical detection, did not improve the perceived performance problems associated with continuous element detection systems.
- After witnessing past performance and operational problems of various detection systems when they were initially deployed, no one wanted to be the first to trouble-shoot new technology. The technical risk was deemed too high.
- Unless a specific aircraft user had several experiences with undetected combustor-can and/or afterburner nozzle burn-through events, the general consensus was that the level of detection coverage in aircraft engine compartments was adequate.

Therefore, unless there is a recognized fault mechanism which leads (or can lead if allowed to continue) to a fire or other hazardous condition and a continuous element detection system cannot provide timely warning of that event, continuous detection systems could continue to be the preferred method of engine fire and overheat detection. If the recognized fault mechanism becomes a safety-of-flight issue, which conventional detection technology cannot reliably accommodate, then different techniques for providing detection coverage might be more seriously entertained. An example of this is undetected combustor-can burn-through events. Heat transfer from a small, discrete burn-through event is many times not sufficient to allow a thermal element detection system to reach its alarm threshold, especially if the detection coverage is provided with an "averaging" continuous element detection system. When this is the case, either sonic detection of the acoustics associated with the event or UV detection of the burn-through flame are two techniques which have been demonstrated to be effective (3-8). Of these two, only the UV detection system technology appears aircraft-ready.

While cautious progression may be the attitude for new engine detection, new technology detection sensors will have to be implemented for explosion protection systems; i.e., the vulnerability reduction systems used for protecting aircraft dry bays (and possibly fuel tanks). Detection systems which rely on convective heat transfer are far too slow in response time to be utilized in these types of systems.

EXTINGUISHING/SUPPRESSION SYSTEM COMPONENTS – With the exception of cargo bay environments, which utilized portable hand-held $CO_2$ extinguishers, the engine compartment was the first area to receive suppression coverage. It was found that in order for the engine extinguisher to be effective, the source of combustible fluid entry (jet fuel, hydraulic fluid, engine oil) into the engine compartment had to be eliminated. This meant the engine had to be shut down. For this reason, which still applies today, only multi-engine aircraft typically utilize extinguishing systems.

Some of the first aircraft to deploy fixed fire extinguishing systems for engine protection included the C-46, C-47, B-17, and the B-26 aircraft, back in the early 1940's. While the system was effective when activated early in the fire development, it had a significant weight penalty associated with it. Nominally speaking, one pound by weight of $CO_2$ can only protect approximately a 15 cubic foot (0.425 cubic meters) volume for hydrocarbon based aircraft fuels. Plus, the pressures associated with a $CO_2$ fire extinguisher is relatively high at the maximum design temperature (3000 psi at 160°F; 207 bar at 71°C).

In the late 1940's time frame, halogenated hydrocarbon (later termed, halons) fire extinguishing agents were introduced. The primary agents used for fixed fire extinguishing systems were methyl bromide (Halon 1001) and bromochloromethane (CB, Halon 1011). Carbon tetrachloride (Halon 104) was also introduced but it was only used in hand-held portable extinguishers.

Halon 1011 agent eventually displaced Halon 1001 for engine extinguishing systems primarily because of toxicity and corrosion reasons. It became the extinguishing agent of choice until the "modern halons" were introduced. In fact some aircraft operators even used Halon 1011 in their hand-held portable extinguishers. It was much lighter than a $CO_2$ system. One pound of Halon 1011 was required to cover around 25 to 30 cubic feet (0.71 to 0.85 cubic meters) for jet fuel fire fighting. However, greater attention with respect to the distribution manifold and nozzle outlet designs was required because the agent typically discharged as a liquid as opposed to a vapor. Because of this particular property, the use of spray nozzles and piccolo spray tubes were introduced and subsequently used.

Even though Halon 1011 was less toxic than 1001, it was still higher than the halons which were introduced in the early 1950's. They included Dibromodifluoromethane (Halon 1202), Bromochlorodifluoromethane (Halon 1211), Bromotrifluoromethane (Halon 1301), and later 1,2-Dibromotetrafluoroethane (Halon 2402). As the number of halogenated hydrocarbons or halons increased, the selection of which agent to utilize for a given engine application became a matter of organizational preference and specific needs. The U.S. Navy opted to pursue and utilize the high vapor pressure Halon 1301; the primary reason being lower toxicity (which was a legitimate safety concern of carrier-type aircraft). This system was configured as a "high rate discharge" system. The U.S. Air Force, on the other hand, remained with a relatively low vapor agent; specifically Halon 1202. While 1202 was less toxic than Halon 1011, it was not as low as 1301. Since 1202 was demonstrated to be slightly more effective on a weight basis and the Air Force felt that these extinguisher devices would only be used to protect unmanned areas, such as engine compartments, the toxicity of 1202 was not felt to be a deterrent.

Because of its lower density, it appeared that the Halon 1301 systems would require more agent than 1202 systems and would require containers which could safely contain higher pressures, and thus result in a heavier system. This was not necessarily the case. Because of the high vapor pressure of 1301, the use of elaborate spray nozzles and spray bars were no longer required. Plus, since these new Halon 1301 extinguisher systems were designed to discharge at a very high rate, it was more important to get the agent into the protected area as quickly as possible, than to distribute it through nozzles which were designed to increase the volume of the discharge pattern, but in turn would slow down agent discharge times. The pressure of the 1301 as it transitioned from a liquid to a vapor was typically sufficient to ensure thorough volumetric distribution. This high rate discharge concept was also later deployed with Halon 1202 agent (on the F-111) and was deemed to be successful. However, more recent studies have questioned this design concept with Halon 1202.

Over the next 30 years, Halon 1301 has essentially displaced all Halon 1011, 1202, and 1211 systems. However, there are still some older aircraft flying today with these other agents.

The design of the vessel to contain the extinguishing agent has also evolved through the years. When the $CO_2$ systems were employed, heavy steels were used to form the bottle. With the introduction of the low vapor pressure halons which were only superpressurized to a nominal 360 psig (25 bar) with nitrogen at room temperature and the use of new stainless steels, very light-weight extinguisher vessel designs resulted. However, with the advent of high rate discharge systems which utilized high vapor pressure agent (Halon 1301) and were superpressurized to 600 psig (41 bar), the pressures that a vessel had to withstand again increased like the old $CO_2$ systems. Fortunately, new stainless steel alloys, including 304 and 21-6-9 (Nitronic 40), were also introduced. This minimized the impact of greater wall thicknesses needed to withstand these higher pressures.

Because a spherical shaped pressure vessel design represents the most efficient geometrical volume for containing the most agent, and this shape is the strongest with respect to tensile and yield stresses, it was and continues to be the most popular extinguisher vessel design. However, because of certain installation constraints, some applications have been forced to utilize cylindrical shaped extinguisher designs, even for the high vapor pressure 1301 systems. Figure 2 illustrates various versions of these two basic designs. Although non-standard sizes ranging from less than 40 to 2500 cubic inches (656 to 40,975 cubic centimeters) have been developed and fielded, standardized designs are preferred and specified by MIL-E-22284. The sizes include: 86 cubic inches (1,410 cubic centimeters ,$cm^3$), 224 cubic inches (3,671 $cm^3$), 378 cubic inches (6,195 $cm^3$), 536 cubic inches (8,785 $cm^3$), 630 (10,326 $cm^3$), 945 cubic inches (15,489 $cm^3$), and 1050 cubic inches (17,210 $cm^3$). These are the basic designs of the extinguisher vessels used today for engine protection systems.

These extinguisher designs almost all use pyrotechnic cartridges which rupture a burst disc. The more modern designs utilize cartridges that are certified to meet one amp at one watt without detonating and the electromagnetic requirements of MIL-I-23659 (HERO).

While these extinguisher designs were defined as high rate discharge systems, they were still too slow with respect to agent-out times to be used in the fuel tank ullage protection systems. Therefore, several more rapid release extinguisher designs were developed and subsequently fielded in the 1950's. Since the fuel tank structure is basically a closed system when it comes to venting extraneous overpressures and since the release of a pressurized Halon 1301 vessel creates significant overpressures when it is opened in a closed system, new suppressor designs were required to be used in the reactive fuel tank ullage protection system. Cylindrical canister suppression vessels, as well as hemispherical and tubular vessels, which contained low vapor pressure suppression agent were designed to meet the extremely high agent release times, in the range of less than five milliseconds. Figure 3 illustrates these three designs. Each was designed to petal open from the hydraulic ram forces created when a pyrotechnic device was initiated in the liquid agent. The hydraulic forces were sufficient to

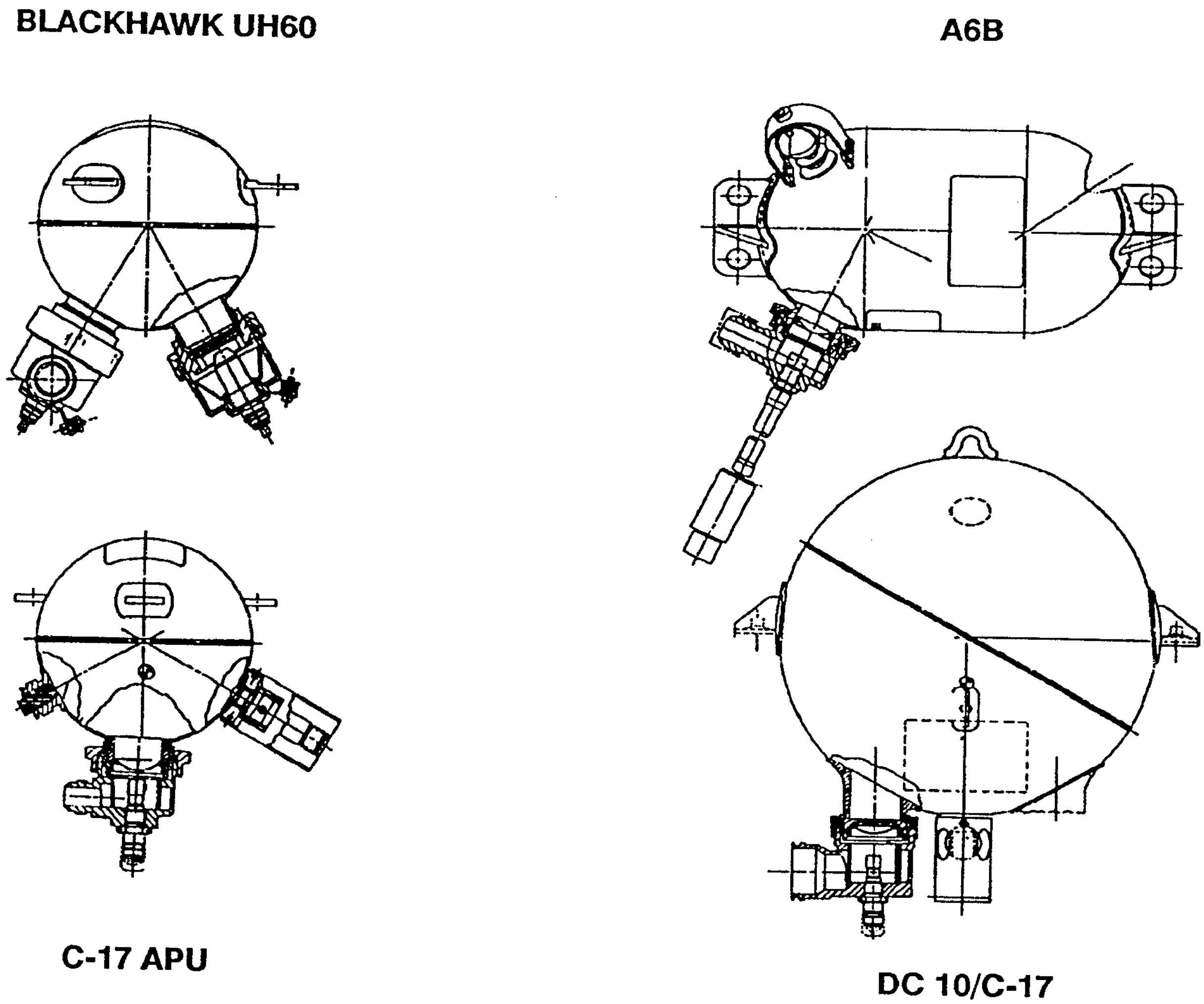
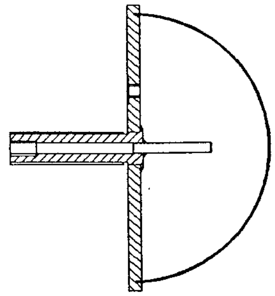



Figure 2. Typical Fire Extinguishing Assemblies

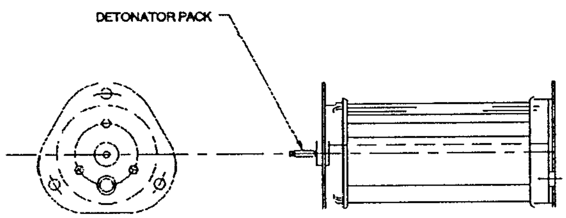
rupture the containing vessel along pre-scored etches and a very fine atomized liquid was dispersed. High speed motion pictures of the dispersion of liquid agent show that the agent droplets were dispersed around four feet (1.2 meters) radially for the cylindrical canister suppressors and around 15 feet (4.6 meters) linearly for the hemispherical and tubular suppressors (9). Figure 4 illustrates the linear dispersion rate of the Halon 1011 in a hemispherical suppressor as function of time. Similar dispersion times were measured with the other suppressor designs (10). Of these devices, only the cylindrical canister type suppressor was eventually pursued and deployed.

The canister type suppressor offered the unique feature of being able to be stacked on top of each other, so that this suppression system could be catered to each fuel tank system. A version of this design was used in a fuel tank ullage protection system for the F-105, the Buccaneer, the Canberra and some U.S. Navy aircraft (which all used Halon 1011); plus the Vulcun, Victor, Valient, and Hunter aircraft (which used pentane). While these suppression systems did not perpetuate into future suppression systems, the reasons were not because of their ineffectiveness; it was because the detection portion of the system was susceptible to false alarms.

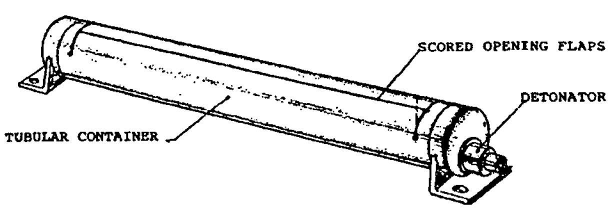
One of the interesting suppression concepts as mentioned above was the use of pentane as a fuel tank suppressant. The theory behind this form of suppression is to drive the combustion event to an overly rich condition; thereby, suppressing it. Obviously, this type of sup-



HEMISPHERICAL SUPPRESSOR




CYLINDER SUPPRESSOR UNIT




TUBULAR SUPPRESSOR

Figure 3. Explosion Suppressor Designs

pression system must be applied with care, but it has been shown to be effective. It offers the advantages of low weight and no fuel contamination when deployed.

DETECTION/SUPPRESSION PROTECTION SYSTEMS – With the "successful" protection of the aircraft engine compartment, primarily through the use of continuous element detection and Halon 1301 extinguishing equipment, and with a variety of fuel system protection techniques (typically implemented for vulnerability reduction), the military began focusing on other areas of the aircraft to make it more survivable. If the dry bays which surround fuel tanks and/or have combustible fluid-carrying lines in them were protected in a similar manner to the fuel system, significant reductions in overall aircraft vulnerability resulted. In fact, sources state that the aircraft fuel systems which include dry bays were by far the most susceptible areas for combat threat penetration for both fighter or transport aircraft. Data on combat vulnerability indicates that these same volumes are involved in at least 50% of all ballistic induced fire incidents depending on aircraft type (11, 12 and 13). While it is difficult to discern what percentage of these incidents were fuel tank related versus surrounding dry bays, it is commonly accepted that with the fuel systems protected (whether it be through use of explosion suppression foams, inerting, or by some other means), the next greatest reduction in overall aircraft vulnerability could be achieved by protection of the vulnerable dry bays.

The Europeans and the U.S. Military were the first to act on vulnerability reduction associated with their fuel systems. As mentioned earlier, they employed an active fuel tank ullage protection system back in the 1950's (one form for explosion protection and the other for crashworthiness). Infrared cold cathode tubes in conjunction with cylindrical suppressors which contained pentane fuel as its suppression agent were used as a fuel tank ullage protection system. The crash protection system utilized inertia sensors with Halon 1011 cylindrical suppressors. In both these systems, the sensor automatically activated the suppressors. While false activation and availability of other ullage protection technologies led to elimination of these detection coupled protection systems, the Europeans were quick to consider this technology when they initiated their dry bay protection studies in the mid 1970's. The primary reason that an active protection system made up of detection and suppression components was even considered for dry bay or fuel tank ullage was associated with the reduced weight penalty of this technology over other passive protection technologies (especially for the larger vulnerable volumes).

While the Europeans were quite active in the area of dry bay vulnerability studies in the early and mid 1970's, the U.S. military perpetuated these analyses and studies in the 1980's. While dry chemical powder extinguishant contained in packs or panels, as well as explosion suppression foams, were demonstrated to be effective in

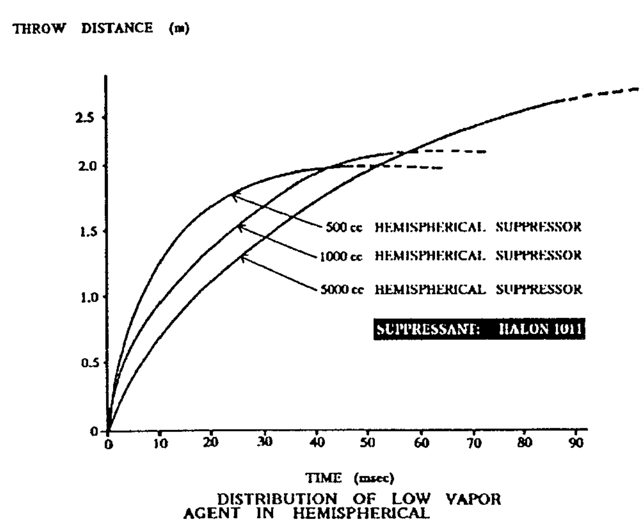



Figure 4. Hemispherical Suppressor Distribution

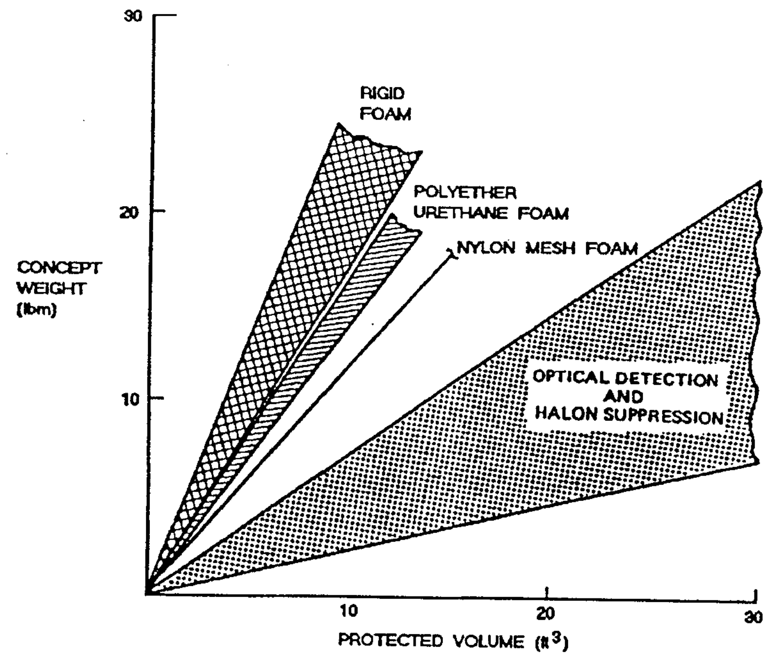



Figure 5. Protection System Weight Comparisons

reducing dry bay vulnerability (and they were even subsequently deployed on close air support helicopters and aircraft), they were heavy and sometimes not practical for large dry bays. Figure 5 illustrates a weight comparison of various explosion suppression foam materials compared to an active detection/suppression protection system (11). These weights which were extrapolated as a function of protected area indicate the larger the bay, the more attractive detection/suppression protection systems become on a weight basis. Dry chemical powder packs were also considered during this study. Their weight, however, is dependant on not only the volume of the bay to be protected, but also its geometry (i.e., surface area). In certain dry bay configurations, active protection systems were also found to be lighter than powder packs, but generally this was only true in the larger bays.

## STATE-OF-THE-ART AND FUTURE PROTECTION COMPONENTS AND SYSTEMS

Detection systems probably represent the single most important element of any protection related component or system. These components are typically the first (and many times, the only) indication that some hazardous condition is occurring or getting ready to occur. If the flight crew can be made aware of the hazardous condition early enough in its development, corrective action can be implemented immediately; thereby, eliminating catastrophic conditions. The response time associated with the detection system therefore becomes the most critical factor as to whether the aircraft can be successfully protected. Wright Patterson's Aero Propulsion Laboratory, through Boeing Military Airplane Company, conducted a study which supports this statement (14). Their program's initial objective was to evaluate the effectiveness of various extinguishing agents in a dynamic engine environment. While this objective was clearly met, another interesting fact was observed. When Halon 1301 was used to extinguish fires in a simulated engine application and it was introduced in a timely fashion (specifically, within 12 seconds for this particular application), its performance based on established sizing criteria was acceptable and included a large margin of safety. However, if a fire was allowed to exist in the engine compartment for as little as 15 seconds, the amount of agent as determined by accepted sizing requirements in MIL-E-22285 did not appear to be adequate. This finding, upon initial inspection, is somewhat deceptive. In actuality, there is enough agent to knock down the fire. But if there is airflow sufficient to dilute the concentration of the extinguishing agent and if a combustible is still present, hot surfaces created from the initial fire allow it to re-ignite. This study found that if agent was introduced within a 12 second period of time, hot surface formation was minimized. Thus, the rapid recognition of fire formation through detection, in conjunction with rapid reaction to implement corrective procedures, is of key importance to the success of any protection system (whether it be a fire fighting system, such as those used in aircraft engine nacelles, or an explosion protection system, such as those proposed for dry bay applications).

Tables 1 and 2 illustrate some generalized properties associated with various detection concepts. Table 1 is dedicated toward detection systems used in "fire fighting" type protection systems, such as aircraft engine protection systems. Table 2 addresses sensors which could be used in fast response vulnerability reduction systems, including dry bay and fuel tank ullage protection systems. As can be seen upon inspection of these tables, certain concepts have limitations with regard to certain features. Therefore, the end-item environment and the characteristics associated with the hazardous event must be known and a detection system trade study performed before a given detection concept is pursued.

Table 3 illustrates some generalized properties associated with various extinguishing agents. It should be noted that candidate agents being considered for halon replacement are not shown or discussed. The primary reason is that development activities, test efforts, and analyses are currently being conducted and conclusive recommendations of alternate agents are not yet available, although some candidate agents are still being offered to the market.

As most everyone now realizes, the use of halogenated hydrocarbons and chlorofluorocarbons (CFC's) will be at a minimum regulated, if not eliminated, in the very near future. At the international conference, sponsored by the United Nations Environmental Program, assembled in Montreal in 1987 for the purpose of addressing the ozone depletion attributed to the CFC's and halons, several key fire extinguishing agents were addressed. Included in the proposed reductions and bans were Halon 1211 and 1301. Halon 1211 represents two percent of the total U.S. production on a weighted basis of ozone depleting chlorofluorocarbons and Halons. However, Halon 1301 represents 12 percent of the total production on a weighted basis.(15) While the Halon 1301 weighted contribution to the ozone depletion problem appears quite significant, it should be pointed out that the amount of 1301 used in aircraft fixed fire extinguishing systems is a very small fraction of the total amount of Halon 1301 deployed. Because of this and the fact that aircraft fire is almost always catastrophic if not acted upon quickly and effectively, many informed sources feel that the aircraft industry will receive an exemption from any proposed ban (at least for 1301). However, even if an exemption is granted to use any of the halons on aircraft fire protection systems (specifically including Halon 1301), the availability will most likely be greatly impaired and the price greatly increased.

Most agencies sponsoring or working the "halon replacement" programs have prioritized their efforts for a replacement to Halon 1211, and based on most communications and reports being released to the industry, great strides toward developing, demonstrating, and certifying a replacement agent for 1211 are occurring. Based on these reports, it appears that the markets which utilize Halon 1211 will be supplied an alternate agent within the time constraints established by the Montreal Protocol.

If Halon 1301 does not receive an exemption from the proposed limitations and bans and an equivalent replacement agent is not developed or available, a critical safety-of-flight issue could result. One potential option is to go back to some of the lower vapor pressure "streaming" agents and utilize spray tubes again. Halon 1202, or 1011, or the replacement agent for 1211 could be candidate agents if this option is pursued.

With regard to the "effectiveness" of fire extinguishing agents, as shown in Table 3, Halon 1301, 1202, and 1211 are all similarly effective on the basis of weight of agent required to extinguish jet fuel vapor fires. While there are measureable differences between these agents' effectiveness, these differences are made almost negligible by employing different safety margins to the respective agent's sizing criteria.

Halon 1301 is excellent with respect to complete dispersion when used as a total flooding agent, but it is far from adequate when the extinguishing system must throw agent some distance to reach a hazard. Because of 1301's high vapor pressure, it disperses in vapor form very quickly. When distance must be transversed or agent must be dispersed against high air flow, then a streaming agent, such as Halon 1211 or 1202 or 1011, should be considered. Thus, a trade study which takes into account the requirements of the end-item environment should be conducted before identifying a particular extinguishing approach. Agent properties and storage vessel characteristics at a minimum should be addressed during these trade studies.

Halon 1301 is also effective as an explosion suppression agent. Several agencies conducted numerous live fire ballistic tests and found that 1301 to be a key factor in minimizing overpressures and eliminating fires (11 and 12). Nevertheless, it is interesting to note that no explosion protection system fielded to date has used Halon 1301. The military aircraft used either pentane or Halon 1011 and the commercial aircraft used Halon 2402 (Boeing's 707 surge tank and early 747 wing tip protection systems).

Considering the characteristic properties associated with each protection component (detection or extinguishing related), qualitative analyses can be performed so that the optimum solution, possibly unique to a given environment on a given aircraft, is identified. Below is a brief discussion of various aircraft environments and how specific protection technologies can be applied and catered to these environments.

TABLE 1. FIRE DETECTION SENSOR PROPERTIES
(NEAR-READY FOR EXISTING AIRCRAFT TECHNOLOGIES)

| SENSOR | UV* | IR | CL ELEMENT* | SMOKE |
|---|---|---|---|---|
| SPEED OF RESPONSE (NOM) | 1-2 SEC | 0.1 - 2 SEC | 5-30 SEC | 5-30 SEC |
| RELATIVE RESPONSIVITY (S/N) | HIGH | MEDIUM | LOW | LOW |
| APPROXIMATE FIELD-OF-VIEW | APPROACHES 180° SOLID CONE (+ REFLECTIONS) | APPROACHES 120° SOLID CONE ANGLE | RELIES ON CONVECTIVE HEAT TRANSFER | RELIES ON CONVECTIVE MASS TRANSFER |
| RELATIVE FALSE ALARM IMMUNITY | GOOD, PRONE TO ARC WELDING, SUSTAINED ELEC. ARCS & "SUNTAN" LAMPS | BETTER | EXCELLENT, IF UN-DAMAGED | GOOD |
| OPERATING TEMPERA-TURE | 400°F W/TRANSIENTS UP TO 500°F | 260°F W/TRANSIENTS UP TO 300°F | ≤ 1200°F DEPENDING ON DESIGN | 160°F |
| SENSOR WEIGHT (NOM). | 0.1-0.3 LBS. | 0.3-0.5 LBS. | 0.01 LBS./FT. | 0.75-1.25 LBS. |
| OTHER CHARAC-TERISTICS | NON-SMART | SMART | NON-SMART | SMART |
| | LOW COST | AVG. MTBF | LOWEST COST | AVG. MTBF |
| | HIGH MTBF | REMOTE MOUNTING | HIGHEST MTBF | REMOTE MOUNTING |
| | REMOTE MOUNTING | FIELDED CONCEPT | LOCALIZED ROUTING | FIELDED CONCEPT |
| | DEMONSTRATED CONCEPT | | FIELDED CONCEPT | |
| | *CONTROL ELECTRONICS/CIRCUIT CARD INTERFACE AND/OR REQUIRED RESPONDER SWITCH | | | |

TABLE 2. EXPLOSION DETECTION SENSOR PROPERTIES
(NEAR-READY AIRCRAFT TECHNOLOGIES)

| SENSOR | UV* | IR |
|---|---|---|
| SPEED OF RESPONSE (NOM) | 5 msec | 1-3 msec |
| RELATIVE RESPONSIVITY (S/N) | HIGH | MEDIUM |
| FIELD-OF-VIEW | APPROACHES 180° SOLID CONE + (REFLECTIONS) | APPROACHES 120° SOLID KCONE ANGLE |
| RELATIVE FALSE ALARM IMMUNITY | GOOD, PRONE TO ARC WELDING, ELEC. ARCS, "SUNTAN" LAMPS, LIGHTNING | BETTER |
| OPERATING TEMPERATURE | 400°F W/TRANSIENTS UP TO 500°F | 260°F W/TRANSIENTS UP TO 300°F |
| SENSOR WEIGHT | 0.1-0.3 LBS. | 0.3-0.5 LBS. |
| OTHER CHARACTERISTICS | NON-SMART | SMART |
| | LOWER COST | AVG. MTBF |
| | HIGH MTBF | REMOTE MOUNTING |
| | REMOTE MOUNTING | FIELDED CONCEPT |
| | FIELDED CONCEPT FOR ENGINE A/B MONITOR; DEMO FOR EXPLOSION | DEMO FOR EXPLOSION |
| | *CONTROL ELECTRONICS OR CIRCUIT CARD INTERFACE REQUIRED | |

TABLE 3. FIRE EXTINGUISHING AGENT PROPERTIES RELATIVE TO JET FUEL FIRES

| AGENT | HALON 1301 | HALON 1211 | HALON 1202 | HALON 1011 | $CO_2$ | HALON 2402 | DRY POWDER* |
|---|---|---|---|---|---|---|---|
| AGENT EFFECT/WT.** | 40-50 $FT^3$/LB. (2.5-3$M^3$/KG) | 40-50 $FT^3$/LB. (2.5-3$M^3$/KG) | 40-50 $FT^3$/LB. (2.5-3$M^3$/KG) | 20-30 $FT^3$/LB. (1.2-1.9$M^3$/KG) | 15-20 $FT^3$/LB. (0.9-1.2$M^3$/KG) | 40-50 $FT^3$/LB. (2.5-3$M^3$/KG) | 40-50 $FT^3$/LB. (2.5-3$M^3$/KG) |
| VAPOR PRES-SURE @ 130°F (54°C) | 435 PSIG (30 BAR) | 85 PSIG 5.9 BAR) | 25 PSIG (1.7 BAR) | 0 | 1140 PSIG (79 BAR) | 19 PSIG (1.3 BAR) | 0 |
| RELATIVE AGENT DISTRIBUTION<br>DISPERSION<br>THROW | EXCELLENT<br>POOR | GOOD<br>AVERAGE | AVERAGE<br>AVERAGE | POOR<br>GOOD | EXCELLENT<br>POOR | BELOW AVG<br>GOOD | POOR<br>AVERAGE |
| RELATIVE PERSISTENCE<br>IN AIRFLOW<br>NO AIRFLOW | VERY POOR<br>GOOD | POOR<br>AVERAGE | BELOW AVG<br>AVERAGE | BELOW AVG<br>AVERAGE | VERY POOR<br>GOOD | BELOW AVG<br>AVERAGE | GOOD<br>GOOD |
| RELATIVE TOXICITY | GOOD | AVERAGE | BELOW AVG | POOR | ASPHYXIATION | BELOW AVG | EXCELLENT |
| ENVIRON. | ODP:10 | ODP:3 | ODP:0.3 | ODP: 0.1 - 0.2 | N/A | ODP: 6 | N/A |
| STATUS OF TECH-NOLOGY | FIELDED FOR FIRE EXT, DEMO FOR EX-PLOSION | FIELDED FOR FIRE EXT. | FIELDED FOR FIRE EXT. | FIELDED FOR FIRE EXT, FIELDED FOR EXPLOSION | FIELDED FOR FIRE EXT. | FIELDED FOR EXPLOSION | FIELDED FIRE EXT., FIELDED FOR EX-PLOSION |
| OTHER CONSIDER-ATIONS | CLEAN AGENT | CLEAN AGENT | CLEAN-UP? | CLEAN-UP? | NO CLEAN-UP | CLEAN-UP? | CLEAN-UP |
| | WEIGHT EF-FECTIVE | | TOXICITY | TOXICITY | NON-HAB. COMP'T | TOXICITY | CORROSIVE |

*SPECIFIC PROPERTIES DEPEND ON DRY CHEMICAL AGENT ANALYZED.
**PRECISE VOLUME COVERAGE DEPENDS ON THE METHOD OF DISTRIBUTION AND MARGIN-OF-SAFETY EMPLOYED.

ENGINE PROTECTION – With regard to detection, as can be observed upon inspection of Table 1, two to three detection concepts could be (or has been) deployed for aircraft engine compartment protection, specifically: continuous element detection (either electrical based, pneumatic based, or fiber optic based), ultraviolet (UV) optical detection, and infrared (IR) for lower temperature engine applications.

Of these concepts, conventional continuous element detection probably represents the most versatile and lowest technical risk approach; primarily because so many lesson-learned have resulted through so many years of service. It can be used in the largest variety of engine applications because of its durable, high temperature design. UV detection can accommodate a temperature environment of at least 400°F to 500°F (205° to 260°C) which is adequate for most engine applications, but IR detection can only operate in a less than 300°F (150°) environment. Since the OEMs have a better appreciation of the operational characteristics and limitations associated with continuous thermal detection systems, more so than optical, and the thermal detection vendors have developed an increased understanding of the operational and maintenance characteristics associated with aircraft engine applications, most of the operational inadequacies associated with thermal detection systems from past years should be eliminated.

New features are also now offered in continuous element detection systems which further enhance their reliability and maintainability aspects. They include:

- automatic, periodic self-test and system reconfiguration,
- fault location/isolation to the line replaceable unit level,
- self-health monitoring which automatically notifies the maintenance crew that a component is deteriorating, before a fault occurs.

These features can lead to increased detection confidence and improved aircraft "dispatchability" (mission readiness).

When improved coverage is a necessity, a UV detection system deserves consideration, such as the system designed under USAF sponsorship, UVAFDS. A model of this system has undergone flight tests for over nearly ten years on a USAF FB-111A, although the aircraft has been grounded for the last two years (as last reported). No engine fire occurred so its detection performance could not be dynamically demonstrated, but it was exposed to and responded to the engine afterburner flame early in this flight test program. Also, no false alarms have been observed during this time period. Furthermore, when the aircraft was flying on a more regular basis, little contamination of the UV sensor heads was observed.

While an experience base has been acquired over the last 30 years with IR based detection systems in powerplant environments, it probably cannot be considered too favorable. It did serve as a reminder that either the OEM or the optical detection vendor had better be familiar with all the radiation emitting sources which may be present in the engine nacelle environment, or false alarm problems could result. For the most part, IR detection systems today are far superior with respect to discriminating a non-fire radiation source from a true fire event.

IR based detection system designs offer less attenuation from contaminants which may be present in the engine compartment, but it is theoretical fact that IR detection systems cannot achieve the same level of detection coverage (i.e., sensitivity) as UV detection systems without significantly impacting its false alarm susceptibility. There is a smaller signal to noise ratio associated with operation in a hot engine nacelle for most portions of the IR spectrum compared to other regions of the spectrum, such as the UV. Furthermore, IR radiation from a hydrocarbon fire attenunates with decreasing air pressure, so its sensitivity threshold must be extrapolated to accommodate high altitude engine fires (16). Nevertheless, state-of-the-art IR detection systems have been designed and demonstrated to provide adequate performance characteristics for lower temperature, lower altitude aircraft engine installations. A form, fit, but functionally superior replacement of the early cad-sulfide detector is now available. Aircraft systems with this early design could improve their performance and reduce their maintenance and spares costs without having to retrofit. The new IR sensor could be identified as a "preferred spare."

The form, fit, but functionally superior replacement of the cad-sulfide detector monitors the 4.3 micrometer $CO_2$ spectral emission band, unique to hydrocarbon fires. Estimates of 24% of the total infrared radiant energy is emitted in this narrow band.(17) This dominant emission band, coupled with the measured presence of flicker, gives a high degree of confidence that, when an alarm is issued, the source being detected is a fire.

This technology is currently completing TSO C1d certification.

The fire extinguishing technology for aircraft engine has not changed much in the last 30 years. The most significant change being that high rate discharge Halon 1301 systems have become more popular over the years, with fewer (if any) new aircraft systems being designed for Halon 1211 or 1202. The extinguishing vessels are generally always spherical and occasionally cylindrical stainless steel pressure vessels. Most military designs have been qualified to meet the "non-shattering" requirements associated with 50 caliber threat penetration. It is noteworthy to point out that very few (if any) of the smaller extinguisher vessels, around 86 cubic inches and below, have been designed or qualified to meet the gunfire requirement of MIL-E-22284. The primary reason is that as the volume of the extinguisher vessels decreases, the effects of hydraulic ram from threat impact increase. The only means to ensure that a vessel does not shatter is to increase its wall thickness. This, of course, means greater weight penalty, and the smaller the vessel volume, the thicker the walls must be to withstand the transient shock loads. This weight penalty is many times deemed unacceptable. The only consolation which might help to alleviate this vulnerability shortcoming is to recognize that the smaller the extinguisher vessel, the lower its cross sectional area and probability of threat impact.

As mentioned above, at present there is no equivalent replacement agent for Halon 1301; one which possesses all the favorable properties of 1301 without possessing some negative properties. If the aviation industry is not granted an exemption from the Montreal Protocol to use Halon 1301 in fixed powerplant extinguishing systems or an equivalent alternate agent is not developed and made available, one must consider analyzing the Halon 1211 replacement agent for this application. This could mean that a distribution system which uses spray bars in the surrounding engine space would have to be employed again.

DRY BAY PROTECTION – Dry bay compartments are generally defined as any internal volume of the aircraft which normally does not contain fluids, but could under a fault or a hostile damage scenario. While this definition generally could include every compartment of an aircraft system except the fuel tanks, this is not what is meant when dry bay vulnerability and protection is discussed. The connotation associated with dry bays in aircraft survivability circles has now come to mean vulnerable compartments which surround fuel tanks and or have a number of combustible fluid-carrying lines in it. Therefore, when one refers to dry bay compartments, it is generally inferred that the volume is deemed vulnerable and requires survivability enhancement of some kind.

The purpose of protecting dry bay compartments is to negate the effects of hostile threat penetration. When a ballistic round penetrates a fuel cell or some combustible fluid-carrying line via a dry bay, combustion can occur. If the round penetrates a fuel cell above the fuel level, the ignition of fuel vapors inside the fuel tank is likely to occur. This fire could easily transfer to the adjacent dry bay. If the round penetrates below the fuel surface, the hydraulic ram created from this event is likely to create a fuel mist which can enter the dry bay. If the round carries in own incendiary or creates an ignition source itself (whether it be an "impact flash" created by penetration or the severing of electrical line or some other similar scenario), flash fire with combustion overpressures are likely to occur. Note, overpressures may not be observed if the round created sufficient venting when it impacted.

To suppress any combustion overpressures by quenching the fuel mist flash fire and to ensure that no pool fires develop, a detection system senses the presence of this event and initiates a signal to discharge one or more suppressors. To maximize the probability of quenching the event, the active protection system must respond rapidly. Measurements support that the detection system should be no longer than twenty five to thirty milliseconds to initiate a signal for the suppressors to discharge their agent. The suppressors must achieve rapid agent-out times, also. It is estimated that the suppressors should not take any longer than 100 milliseconds to discharge all their agent (11 and 18). These response times are based on actual measurements but should not be construed as applicable to all dry bay protection scenarios, since overpressure is a direct function of volume size, geometry, and several other governing parameters. Regardless of this response time criteria, the more rapid the suppression agent is initiated, the higher the probability of successfully suppressing the event.

Recognizing this fact, the use of sensors which discriminate between a ballistic impact and/or incendiary flash and a true hydrocarbon based fire requires comment. The U.S. Army has defined a sensor which can do this as "discriminating," and if a sensor which initiates an alarm signal whether an event was fire or a ballistic flash has been termed "non-discriminating." Discriminating sensors have traditionally been IR based, where the detection device monitored at least two wavebands in the IR spectrum. The non-discriminating type sensors are made up of UV and IR based detection devices and are the more common type of optical sensor.

Discussing whether a particular dry bay protection system should utilize a discriminating sensor, the following considerations are offered. An aircraft dry bay is typically surrounded by combustible fluids. This is the primary reason why these bays are considered vulnerable and protection is deemed necessary. While one particular bay may be relatively large, its volume and surface area are often small when compared to the overall volume and surface area of the entire aircraft. Thus, the probability of taking a ballistic hit in this one particular bay is relatively small. This is not to imply, however, that it is insignificant, because if it was, no protection system would be warranted. The probability of taking two hits in this same bay, though, becomes the probability of one hit multiplied by itself. This probability now is becoming extremely small. Unless the second round impacted the same bay after 100 milliseconds had elapsed after the first round impact, the corrective action initiated as a result of the first round should protect the dry bay from the effects of the second round. This fact should make the two ballistic impact events statistically independent of each other.

Having discussed all of this, the fact that repeated hits might occur to the same bay may be a significant risk. If the aircraft is a low flying, close air support aircraft or helicopter and the dry bay is relatively large in surface area, use of a discriminating sensor may be warranted. The advantage of utilizing a discriminating sensor is that if the first ballistic round did not initiate a fire, the sensor would not issue a suppressor discharge signal, thereby saving the suppressant for a potential second round penetration. The benefit, obviously, is no suppressant is released. Suppression agent is saved until it is needed. The penalty is it takes a discriminating sensor some additional period of time for it to process the optical radiation input to determine whether the event was a fire or a ballistic flash (either incendiary or impact). The longer the time to initiate suppression, the higher the risk is of non-successful suppression. Therefore, before a discriminating sensor is specified for a given dry application, a susceptibility/vulnerability analysis should be conducted and carefully analyzed to assess whether the risks of saving agent for subsequent ballistic hits outweigh the risk of rapid corrective action (which would be releasing suppression agent for this case). It should be noted that measurements of the duration of ballistic flashes have been characterized. While it is safe to convey that an high explosive incendiary is of longer duration than an impact flash, the actual times may be considered sensitive information.

Addressing which type of sensor is most suitable for a dry bay protection system, Table 2 indicates that either UV or IR have rapid enough response times, but the IR detection system is undoubtedly faster (when both are designed to an acceptable level of false alarm immunity). A UV detection sensor could offer improved protection coverage from fault related pool-type fires, but both sensor types are capable of detecting this type of event (as well as the higher energy ballistic flash fire event). Because of the rapid response time requirement for this type of application, IR is probably the lower risk approach. There could be more transient non-fire sources which emit UV radiation in a given dry bay (e.g., lighting reflections in a wheel well) and this could affect the operation of a UV based protection. Unlike the UVAFDS system which analyzes/processes the UV radiation for one second to maximize its false alarm immunity, a dry bay sensor cannot afford this amount of time to decide what is a false alarm source and what is a fire. But with proper application engineering, this technique can be made to operate at low risk.

IR based sensors offer the necessary speed of response, adequate sensitivity and field of view, and greater tolerance to contaminants which may coat the optics. Also, an IR detection sensor package can be made to be more survivable than a UV detector with its glass envelope (assuming a high temperature UV design is pursued). The IR detection sensor can have less vulnerable area exposed. Its sensing detector element is small in diameter (around 0.5 inches in diameter, 1.3 cm), much smaller than a UV tube. This area is the most vulnerable part of an optical sensor and the most apt to be damaged.

Some dry bay protection systems employ sensors (either IR or UV) which interface to suppressors via a control unit. Others have the mechanisms to initiate suppression vessels directly from the sensor. A direct sensor to suppressor interface approach requires that the sensor design have all of its processing and signal conditioning electronics inherent to its housing. The sensor must decide on whether radiation being detected by it is a fire or explosion event or some other radiation emitting source based solely on its input. This type of sensor has been termed a "smart" sensor. In addition to processing the radiation input signals it receives, it also must have the hardware required to initiate an explosive cartridge device on the suppressor (or have access to power to send a high current signal to the suppressor). A system which utilizes smart sensors with a direct interface is many times advantageous to pursue, especially in bays which require just one or two sensor and only one suppressor.

However, if multiple sensors are deemed necessary, reliability with regard to mean-time-between-failures (MTBF) and operational confidence can many times be enhanced if a control unit assembly is pursued. A control unit allows a single processing subsystem to analyze the output of several sensors, and after appropriately weighing each of these outputs, the control unit initiates the high energy suppressor initiate signal (if appropriate). This approach offers much flexibility, in that the number of suppressors can be increased without having to increase the number of sensors (to access their suppressor drivers). The "parts count" is minimized in that the processing electronics and suppressor driver circuitry can be shared. This increases the MTBF. Also, since the unit price of a sensor goes down the simpler its design and its MTBF goes up, the sensor can many times be classified as a non-repairable item, thus reducing maintenance costs. Lastly, since the decision on whether there is a fire or explosion event can now be made based on the output of multiple sensors, the confidence of the protection system operating as designed is greater. Some signal conditioning/processing electronics may still be necessary in the detection sensor, especially in the case of the IR based sensors, but the price of these types of sensor will be lower than a smart sensor with suppressor drivers.

The control unit hardware for this type of system does not necessarily require a housing. It can be placed on circuit cards and located in an equipment rack.

The devices which suppress the flash fire combustion event (and any resulting overpressures associated with it) or a fault induced pool type fire event, must be designed to get the agent out of its containing vessel and to the flame front or fire extremely rapidly. Extinguishers employed for engine protection systems were by requirement designed to get their agent out of the container within one second. Most were in the order of hundreds of milliseconds.

However, to quench a flame front which could be accelerating away from a suppressor device at very high speeds, the suppression device not only has to get the agent out quickly, the agent has to travel some distance to catch the flame front. High speed suppressors were designed to do just this.

The first suppressor designs intended for fuel tank coverage, but certainly could be used for dry bay coverage, used low vapor pressure agents and were not pressurized, as discussed in the Historical Background section. They used a pyrotechnic charge which detonated in the liquid agent, creating a shock wave which ruptured the vessel along pre-scored lines. While there were a variety of shapes which were investigated, only the cylindrical canister suppressor was ever deployed. While a hemispherical suppressor appeared promising and found application in industrial explosion protection systems, its design was never optimized to meet an aircraft weight constraints. The tubular suppressor design was too narrow and frequently fractured, creating shrapnel.

With the new emphasis on aircraft survivability, many of these active protection component designs are being analyzed again. This is primarily attributed to the advancements in optics and electronics, making the industry feel that these systems can now be a more reliable method of protection.

Tubular suppressors which use Halon 1301 and pressurizing nitrogen have been recently undergoing extensive testing, primarily by the U.S. Navy. These designs utilize a linear shape charge which cuts the tube open along its length (Figure 6). Tube openings and agent-out times of less than one millisecond have been recorded. While this is certainly the design goal of any suppressor design intended for use in a dry bay or fuel tank applications, implementation penalties have been observed. At high temperatures the vapor pressure of Halon 1301 and nitrogen increase substantially. When the tube opens and releases this high pressure in such a

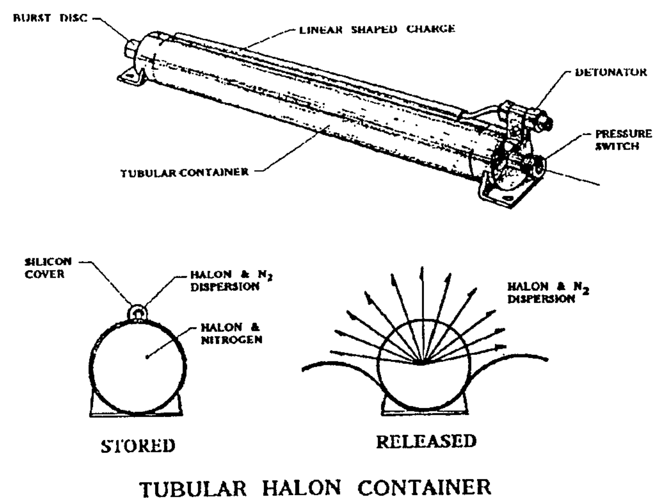



Figure 6. Pressurized Tubular Suppressor Operation

rapid manner, transient thrust loads are generated. While these loads are short in duration, they are quite substantial, as can be seen by Figure 7. These forces were measured using an 1.25 inch (3.2 cm) diameter tube which was eight inches long. The tube was filled with Halon 1301 to a 65 pounds per cubic foot (4.7 kg/m$^3$) fill density and pressurized to 600 psig (41.4 bar) at room temperature. As can be seen, at the higher temperature, which translates to higher pressures inside the tube, forces as high as 12,000 pounds-force (53,380 Newtons) were measured (19). It was noted during this testing that the thrust load of a tube was directly proportional to its length and this relationship varied linearly. Thus, this

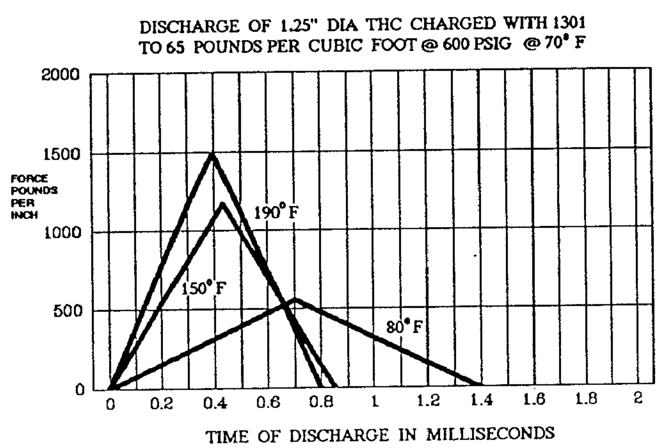



Figure 7. Tubular Suppressor Thrust Loads

graph presents these loads in force per linear inch of tube, thus allowing an extrapolation for different length tubes. While the diameter of the tube and the fill density of the device are also directly proportional to the force generated when the tube opens, this is not a linear relationship.

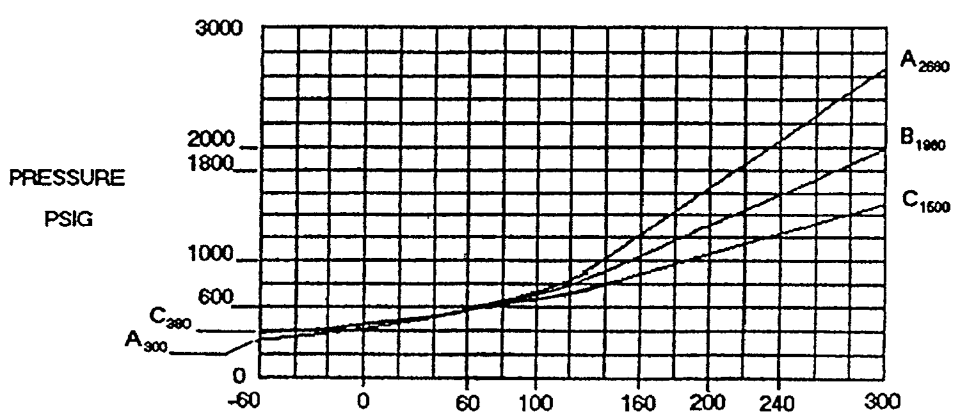
Methods which have been evaluated to reduce these loads included:

- utilizing baffles-The baffle which was required to distribute and/or reduce these loads were deemed too heavy or increased the profile of the tube to an unacceptable level.
- controlling the opening of the tube-Instead of opening along its entire length, only sections would open. This method was too hard to control in that after the linear shape charge cut a section of the tube, the tube would continue to tear open.
- the use of orifices-The suppression tube was place inside a larger diameter tube which had orifices in it. This was effective since it slowed down the agent-out times but it increased the overall weight of the assembly.
- reduced superpressurization of suppressor - This reduced the thrust loads but not to a level which was deemed acceptable.
- mixing different agents and gas fills - Mixtures of Halon 1211 and 1301 have a lower vapor pressure than 1301 alone. Also, using a helium/nitrogen mixture, instead of a pure nitrogen gas, to superpressurize the suppressor also reduces the vapor pressure inside a suppressor at high temperature (see Figure 8). The thrust loads were reduced, but not to acceptable level.
- placing tubular suppressor back-to-back and opening the tubes simultaneously, and relying on canceling forces to negate the thrust load.

The last method was the most effective, but it increased the weight of the unit and put installation constraints on its application relating to shrapnel generation when it was discharged. Using a combination of the other "fixes," thrust loads just below 100 pounds per inch (175 N/cm) were achieved at room temperature. No high temperature tests were conducted. While this thrust load level was about five times less than a non-baffled tubular suppressor, it was still deemed too substantial for aircraft use; unless it was a very small suppressor or bulkhead mounting could be assured.

Other suppressor designs have been demonstrated also. Spherical containers and tubular containers with radial outlets in its discharge head have been demonstrated to provide adequate agent-out times to suppress most dry bay flash fire events. While these designs are not as rapid to discharge their agents as the tubular suppressor which discharges longitudinally or non-pressurized cylindrical canisters and hemispheres, they still can achieve agent out times in the 20-50 millisecond range. These devices are so similar to the engine extinguishers, except for the discharge head, that are considered very low technical risk, and ready for aircraft application.

One other concept which merits discussion is the same suppression concept used 30 years ago; the non-pressurized suppressors which use pyrotechnics for their expulsion force. These concepts are designed for low vapor pressure agents which remain in a liquid over the ambient temperature range of its end-item environment. A significant amount of data currently exists for Halon 1011 for this type of application. While tubular type sup-




CURVE A: HALON 1301 57 LB/CU FT WITH 600 PSIG NITROGEN AT 70°F
CURVE B: 50% 1301, 50% 1211 WITH 600 PSIG NITROGEN AT 70°F
CURVE C: 50% 1301, 50% 1211 WITH EQUIVALENT PARTIAL PRESSURES OF HELIUM AND NITROGEN TO A TOTAL PRESSURE OF 600 PSIG AT 70°F

Figure 8. Halon Mixtures Vapor Pressures

pressors with a low vapor pressure agent could be utilized, experience has shown that the cylindrical and hemispherical suppressors are probably the better choice for safety reasons. These designs are much lighter weight than a Halon 1301 based suppressor because they do not have to withstand high internal pressures. Plus, an alternate agent besides the ones which may be regulated can be used.

One other feature associated with these low vapor pressure suppressors is that they stay in a liquid when they are discharged, in the form of an atomized mist. This characteristic is advantageous when the agent must travel distances in a short period of time to reach a flame front. However, it is a disadvantage when a dry bay contains a substantial amount of equipment, hardware, and other clutter. The liquid agent does not distribute as well as a gaseous agent in this type of environment. Additional suppressors would have to be used to get an acceptable level of volume coverage in a cluttered dry bay.

FUEL TANK PROTECTION – Similar to the detection/suppression technologies discussed for dry bay protection, a "re-active" fuel tank ullage protection system must be extremely rapid in response to successfully protect a fuel tank. In fact, since this type of protection system must be configured to protect a fuel system under the worst-case scenario, which includes a premix/stoichiometric (or slightly richer than stoichiometric) fuel-air vapor environment, an ullage protection system must be even faster than a dry bay protection system to deploy suppression agent if combustion overpressures are to be suppressed to acceptable levels. Again optical detection is deemed the only near-ready detection system for this application. While fast response pressure sensors which detect the pressure rise inside the fuel tank and then initiate the suppressors have been investigated, this method of detection was deemed too slow; overpressure was already increasing before the suppressors were activated. Inertia sensors were also investigated but there were activation limitations with this concept.

Since conventional UV radiation is attenuated much more severely than IR by jet fuels, and depending on the UV sensor design could require high voltage, IR detection is the preferred detection systems for an ullage protection system.

Because a suppressor may be activated when the fuel tank is nearly full (small ullage) and there is limited venting, it is critical that the suppressor when discharging its contents does not create excessive overpressures. This can be the case with a pressurized suppressor. Therefore, a low vapor pressure suppressor is also recommended for fuel tank environments. While these devices still introduce turbulence which can accelerate the flame front and its related pressure wave, it minimizes this effect.

While pentane is not considered an extinguishing agent, it can serve as a suppression agent in a fuel tank environment. By driving the flame front into an overly rich condition, it can quench the combustion event without the risk of fuel contamination. While a significant amount of field data exists on the application of this suppression approach, it still must be applied with care.

Other low vapor agents which have been demonstrated include Halon 1011, 2402, and water. Water was found to be the least effective of these agents.

While much of the detection/suppression technology appears ready for application in aircraft fuel tanks, it should be recognized that there are certain fuel tank configurations where this technology can only offer partial protection. This typically involves the applications where a small fuel tank is impacted by an HEI round. Since the HEI round can deposit multiple ignition sights into the ullage, several combustion events can occur simultaneously. The effect of this is the peak overpressure is reached much quicker. For this particular scenario, additional suppressors must be used, and still there is a probability that the agent will not be dispersed quickly enough. There is at least one software model currently on the market for predicting what scenarios an active protection system can and cannot protect (20).

CARGO BAY PROTECTION – Cargo compartments have traditionally been protected with smoke detectors and hand-held fire extinguishers (water or Halon 1211 or both) if the compartment was accessible and with a fixed Halon 1301 fire extinguishing/inerting system if the compartment was not accessible. Some commercially available ionization type smoke detectors have been used, primarily by commercial aviation, for use in lavatories and select cargo bays, but these are almost always accessible areas where a fire alarm indication can be verified. Most cargo bay applications use aerospace quality photoelectric type smoke detectors which rely on scattered or reflected light radiation caused by particulate matter between a radiation emitting source and a detector device. Figure 9 illustrates the operating principle of one particular photoelectric smoke detector design.

The smoke detector industry, like the thermal detection industry, has modified their design approach based on negative experiences on previously fielded systems; specifically, false alarms, missed or slow alarms, and low mean-time-between-failures (MTBF's). As the smoke detector industry transitioned their design to include solid state circuitry, the smoke detectors sensitivity as a function of time and temperature is less prone to threshold drift. This, in turn, has made solid-state smoke detectors less prone to false alarming in that their sensitivity setting remains within calibration threshold alarm limits for a longer period of time, and these threshold limits should have been specifically catered to the individual cargo bay environment. Another advantage of solid state smoke detectors is the use of longer life components. A good example of this is the light source used in photoelectric

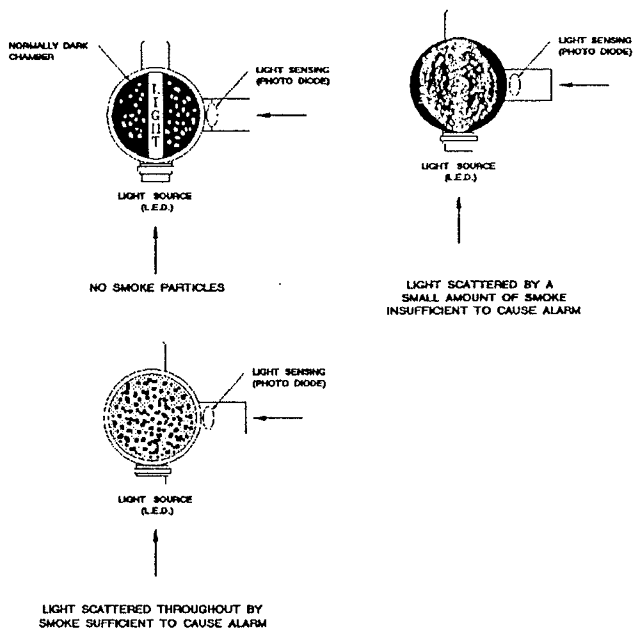



Figure 9. Smoke Detector Operation

smoke detectors. Early models used a low voltage light bulb which had an extremely short life. The solid state photoelectric smoke detectors use a long-life light emitting diode (LED) as its source of light.

Still there are many limitations associated with smoke detector applications. Since these devices rely on mass transfer of particulate matter as their means of determining whether a fire event is occurring, their operational success depends highly on the placement of these devices with respect to where a fire event is expected/suspected to occur. Air flow rate and its dynamic characteristics are the most important factors associated with whether the smoke detection installation is able to detect the early stages of combustion. The relative placement of the detector with respect to the fire must permit the airflow to carry the combustion by-products to the detection device. If adequate coverage is not obtained, either air samples must mechanically be obtained and transported to the smoke detector or the smoke detector must be brought closer to or in the airflow path of the hazard area.

Designs for a laser-based smoke detection system are currently being evaluated. This particular device would offer increased sensitivity with better resolution and discrimination from particulate matter which was not generated by a fire. Up to 0.1% obscuration levels are achievable. Plus, this smoke detector offers an analog output if "trend" information is of interest.

With regard to the extinguishing protection, hand-held Halon 1211 and/or water extinguishers are used in accessible cargo areas. The FAA has recently issued a new requirement to upgrade accessible cargo area (i.e., Class B cargo areas) to include some of the fire protection features used in the non-accessible areas (Class C cargo areas). This includes using a fixed Halon 1301 extinguishing system to knock down a fire by achieving a five percent initial volumetric concentration and to have a means to control the ambient air flow in the cargo compartment. The extinguishing system must also be designed to provide up to 15 minutes in Class B compartments and up to 180 minutes in Class C compartments of inerting coverage (three percent by volume of Halon 1301). These new features are in addition to the requirement of supplementing the smoke detection system with a thermal indication/detection system.

Many military cargo compartments, even if they are accessible, require fixed fire extinguishing systems. The purpose of these extinguishing systems is to provide total volume coverage in the advent that an uncontrolled fire could occur which may not be safely protected against with hand-held extinguishers. The C-5 aircraft is the only example where this additional protection has been deemed necessary. It employs a cargo bay fixed fire extinguishing to protect this volume when hazardous cargo such as ground vehicles or smaller aircraft systems is transported.

CONCLUSION - The aircraft type, the type of protection required, the area of the aircraft which requires protection, and the level of protection one can afford (with regard to cost, weight, supportability requirements, etc.) are all factors which affect the definition of the optimal protection system or component. The characteristics of various aircraft environments and of various protection system components were briefly discussed so that these factors could be considered during future design studies.

Concepts and technologies from the past were discussed at some length. The purpose of this to establish the fact that many of the "new and novel" concepts being considered today have field related performance data available on them and really are not so new. In fact, many design mistakes can be eliminated if one takes advantage of the many lessons-learned. Although many of the concepts may not be new, electronic hardware and materials are new which makes some of these concepts appear even more promising.

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