RECENT DEVELOPMENT IN FIRE SUPPRESSION SYSTEMS

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ABSTRACT

With halon phase-out, there has been a major thrust to find new advanced fire suppression systems in recent years. Some of the newly developed fire suppression systems include halocarbon and inert gaseous agents, water mist systems, compressed-air-foam systems, and aerosol and gas generators. This paper gives a brief description of the newly developed fire suppression systems, and provides technical information on the fire suppression performance of each system as well as the limitations or concerns related to using the new suppression systems.

INTRODUCTION

The traditional means of providing fire suppression in buildings is a sprinkler system. However, water is not a suitable suppression medium for all types of fires. Water, when sprayed in coarse droplets such as in sprinkler spray, is not effective in suppressing liquid fuel fires. Also, in some cases, water damage is a concern because of the large amount of water used for sprinkler systems.

In the 1940's, an effort was made to develop more effective fire suppression agents. The first systematic search for effective gaseous fire suppressants can be traced to the late 1940s when the Purdue Research Foundation conducted an extensive study of more than 60 chemical compounds for the U.S. army[1]. This study led to the development of halon chemicals as a superior performing suppression agent. Halon is a chemical agent, which combines hydrogen, carbon, chlorine and bromine atoms. The chlorine and bromine reacts with the O-H radicals produced during combustion to inhibit the combustion reaction.

Halon is a very effective suppression agent which performs well with most types of fire. There are several types of halon chemicals, but the most commonly used ones in North America are Halon 1301

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and 1211. Halon 1301 is mostly used in a fixed discharge system for occupied spaces, and Halon 1211 is mostly used as a streaming agent. Because of its low cost and superior fire suppression performance, halon was the agent of choice and was used widely, including in applications where halon is not necessarily the only option. This prevented development of other fire suppression technologies that had good potential.

This paper gives a brief description of the newly developed fire suppression systems, and provides technical information on the fire suppression performance of each system as well as the limitations or concerns related to using the new suppression systems.

Halon phase-out

Halons are excellent fire suppressants, however, they contribute significantly to stratospheric ozone depletion. Fire protection halons were phased out of production in developed countries due to an international consensus to regulate the use of ozone-depleting substances (ODSs) as reflected in the Montreal Protocol (1987, London Amendments 1990, Copenhagen Amendments 1992). There is a major thrust, therefore, to find an appropriate fire suppression agent to replace halon.

Efforts so far show that there may not be one halon replacement agent but that several alternative fire suppression technologies may be required to replace halon, depending on the application. The present challenge is to find halon substitutes that have sufficient fire suppression ability for various applications without harming the environment and human health. There has, in recent years, been extensive research to develop halon replacements and alternatives.

Halon replacements are gaseous agents with similar physical properties and fire extinguishing mechanisms as halon. Most research effort for halon replacements has been directed toward modifying the molecular structure of halons to reduce or eliminate the chlorine and bromine atoms which are responsible for ozone depletion. This category of halon-like halocarbons includes perfluorocarbons (PFCs or FCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), hydrobromo-fluorocarbons (HBFCs), and fluoroiodocarbons (FICs)[2].

Possible alternatives to halons include both long established technologies and new concepts or agents that have emerged recently. Traditional fire protection systems include sprinkler, dry chemical, carbon dioxide, and foam systems. Newly developed alternatives include water mist, compressed-air-foam and inerting gas systems, and gas and aerosol generators.

Traditional fire suppression systems

Automatic sprinkler systems are the most common type of fixed fire protection system and are a long established technology with acknowledged reliability. However, they should not be used for certain risks including live electrical equipment, fires of flammable liquids and any risk that would react violently with water. For shielded fires, such as those in computer cabinets or in switch gear housing, water cannot penetrate in the same way as gaseous agents and sprinklers would not provide the necessary fire protection.

Dry chemical systems are effective against flammable liquid fires, including spray fires. However, these systems provide little cooling effect and are ineffective once the powder has settled. There are different types of powders available to address different types of fire. Dry chemical powders

commonly used are mono-ammonium phosphate, potassium and sodium carbonate or bicarbonate (NH_4PO_3, K_2CO_3, $KHCO_3$, Na_2CO_3 and $NaHCO_3$). Powders are not recommended for use in occupied spaces, and they settle out after use and present a post-fire clean up problem.

Carbon dioxide flooding systems have been in use for many years. However, carbon dioxide is an asphyxiant at the concentrations necessary to extinguish fire, and should be regarded as toxic at these concentrations. Because of this, carbon dioxide total flooding systems should not be on automatic control for occupied spaces. Carbon dioxide is stored at high pressure, and high concentrations are required for effective extinguishment. As a result, such systems involve bulky and heavy hardware and are not suitable for use where space and weight are important considerations.

The use of low and medium expansion foam systems is most suited to liquid pool fires. The foam forms a barrier between the fire and the supply of oxygen and also cools the fuel. Foam systems are not generally effective against running or spray fires. Some liquid fuels, such as alcohols, can destroy a foam blanket by chemical reaction and care must be taken to ensure that an appropriate foam compound is chosen. Since foams are aqueous solutions, they should not be used to protect any risk that would react violently with water.

These traditional fire suppression systems perform well in specific applications. However, they are not sufficiently effective in some applications to replace the use of halon.

RECENTLY DEVELOPED FIRE SUPPRESSION SYSTEMS

To satisfy the need of finding suitable fire suppression systems to replace halon, several fire suppression systems have been developed recently or gained renewed interest. Most attention was focussed on inert and halocarbon gaseous agents, water mist systems, compressed-air-foam systems, and solid gas and aerosol generators.

Gaseous systems

Total flooding gaseous systems use nozzles, pipes and pressurised cylinders to discharge the gas into an enclosed space. The enclosure must be capable of holding the gas and coping with the pressure of the gas discharge. There are two types of gaseous agents available: inert gases and halocarbon agents.

Inert Gas Agents

Inert gas agents extinguish fire by oxygen depletion. These inert gases, such as nitrogen, argon and helium, are clean and naturally occurring in the atmosphere. They have zero ODP and no Global Warming potential. Also, inert gases are not subject to thermal decomposition when used in extinguishing fires, and hence form no combustion by-products.

To suppress a fire, a sufficient volume of inert gas must be injected into the enclosure to reduce the oxygen content to a level at which combustion cannot be maintained. This is generally considered to be about 14.3%. In order to provide an adequate safety factor, the normal objective is to reduce the

oxygen level to about 12.5%. This requires a concentration of about 50% of the inerting gas in the enclosure.

Currently, there are 3 inert gas systems that are commercially available: Argonite (IG-55) which is a mixture of 50% nitrogen and 50% argon, Inergen (IG-541) which is a mixture of 52% nitrogen, 40% argon and 8% carbon dioxide, and Argon (IG-01) which is 100% argon.

The three agents are similar in fire suppression performance, but the addition of a small percentage of carbon dioxide in Inergen induces a higher breathing rate, which enables people to continue to function unimpaired by effects of oxygen depletion for a reasonable period of time. In a real fire however, the benefit may be reduced as the inhalation of combustion products must be taken into account.

Inert gases are not liquefied gases. They are stored as high pressure gases and hence require high pressure storage cylinders which has implications for space and weight.

Halocarbons

Halocarbon agents are chemicals similar to halon with molecular structures modified to reduce or eliminate the chlorine and bromine atoms which are responsible for ozone depletion. Halocarbon agents extinguish fires primarily by cooling. Some of the halocarbon chemicals, which have been tested recently, are listed in Table 1 along with their physical properties, environmental impacts, toxicity and fire suppression efficiency factors.

Fire suppression performance of the halocarbon agents are primarily evaluated using small-scale tests. The most widely accepted technique for laboratory screening of fire suppression agents to determine their fire suppression effectivenesses is the cup burner method. A cup burner consists of a fuel cup inside a chimney. Liquid fuel is gravity fed to the cup from a reservoir and maintained at the cup edge level. After ignition and stabilisation of the diffusion flame on the cup, the agent is gradually added into the chimney through an agent/air mixture supply system until the liquid pool flame is extinguished. The corresponding concentration of the agent in the mixture is referred to as the cup burner flame extinguishing concentration for that agent [3].

Table 1 lists the agents' concentrations for extinguishing heptane cup-burner flames. It should be pointed out that the cup burner value for the same agent may be different for other fuels. Regardless of fuel types, however, most agents listed in the table have higher extinguishing concentrations in the cup burner tests than Halon 1301 and, therefore, are less effective.

For fire suppression agents, two toxicological aspects must be considered. One is the toxicity of the agent itself, and the other is the toxicity of combustion reaction products of the agent produced under fire conditions. Acceptability of an agent by regulatory authorities is mostly determined by agent toxicity.

Inhalation of halocarbons and hydrocarbons can cause the heart to be abnormally sensitive to elevated adrenaline levels, and can lead to cardiac arrhythmia and possibly heart attack. Cardiotoxicity tests are usually conducted using beagle dogs to determine the potential of an agent to cause cardiac sensitisation. The results are provided as "no observed adverse effect level" (NOAEL) and "lowest observed adverse effect level" (LOAEL), as shown in Table 1. Since cardiac sensitisation is the toxic effect that occurs at the lowest concentration, the US Environmental Protection Agency (EPA)

compares the cardiac NOAEL and LOAEL of halocarbon agent with its extinguishing concentration to determine whether the agent is acceptable for total flooding applications in occupied spaces.

Among the halocarbon chemicals listed in Table 1, several agents have come to the fore, namely FM-200 (HFC 227ea), FE-13 (HFC-23), NAF S-III (HCFC blend), and CEA-410 (FC-3-1-10). These four agents have several common characteristics; they are stored as liquefied gases in cylinders, and they are clean agents, leaving no residue after discharge and are electrically non-conductive. Also, as Table 1 shows, these four gaseous agents have NOAEL values higher than the extinguishing concentration, acquiring listing under the Significant New Alternatives Policy (SNAP) program of EPA for use in occupied space.

The extinguishing concentrations of gaseous agents are determined by small-scale tests. However, several research laboratories have conducted intermediate and full-scale fire suppression tests to evaluate the true fire suppression performance of these agents.

Intermediate-scale fire suppression tests, coupled with real-time FTIR measurements for agent and acid gas products, were conducted by University of New Mexico Engineering Research Institute (NMERI) using an 18.3 m^3 chamber to evaluate HFC-23, HFC-227ea, FC-3-1-10 and HCFC Blend A[4]. Fire scenarios included Class A wood crib fires, Class B heptane pool fires and diesel spray fires.

The heptane pool fire tests revealed no substantial differences in fire suppression performance among the four agents. In order to minimise the amount of acid gas products, agent concentrations of cup burner values + 40% and 5 s discharge times were required to extinguish the fires within 7 s (for HCFC Blend A, a concentration of 12% was used). Even under such conditions, the four agents produced at least a 10 times higher HF concentrations than Halon 1301. HFC-23 and HCFC Blend A produced more HF than the other two agents, and also produced significant amounts of COF_2.

In general, the concentrations of the acid gas products depend on the extinction time and fire size. In addition, the distribution of the agent was shown to be a significant factor affecting its fire suppression performance.

The US Naval Research Laboratory (NRL) performed a series of intermediate-scale and full-scale tests with HFC-23, HFC-227ea and FC-3-1-10 to evaluate the effect of their discharge characteristics and distribution on fire suppression effectiveness. The intermediate-scale tests were conducted in NRL's 56 m^3 compartment[5]. The three agents extinguished the test fires at the design concentrations. However, the tests indicated a 10-fold increase in HF production for these agents compared to that from Halon 1301.

Increasing the agent concentrations generally led to faster extinguishment and lower HF production for the same discharge time. However, HF production was not sensitive to agent concentrations above cup burner + 75%. Similarly, faster discharge resulted in faster extinguishment and lower HF production at the same design concentration.

The NRL's full-scale tests with HFC-23 and HFC-227ea were conducted aboard the Ex-USS SHADWELL in Mobile Bay, Alabama[6,7]. Four test series were carried out in an 843 m^3 machinery space.

Fire suppression tests were conducted using design concentrations of 8.2%, 9.2% and 10% for HFC-227ea and of 16% and 18% for HFC-23 with a 10 s discharge time (one test achieved a 6 s discharge time). All fires were suppressed successfully within 28 s for each test scenario, but reflashes and sustained re-ignitions occurred in several tests. Peak HF concentrations were 2400-7300 ppm, about 4 to 12 times those of the Halon 1301 baseline tests. The full-scale test results were similar to those from

the intermediate-scale test: extinguishment time and HF concentration decreased with increasing agent concentration and with decreasing discharge time; a larger fire was found to be easier to extinguish (but produced more HF) than a smaller one.

The U.S. Coast Guard conducted a series of full-scale (560 m^3) tests in a machinery space on a test ship located in Mobile, Alabama[8]. Test agents included HFC-23, HFC-227ea, FC-3-1-10 and HCFC Blend A at the design concentrations recommended by their manufacturers. The performance of the agents was evaluated using three test scenarios: a 500 kW heptane spray fire with a 500 kW heptane pan fire, a 2 MW heptane spray fire with a 500 kW heptane pan fire, and a 5 MW diesel pan fire with a 500 kW PVC cable fire. It was reported that HFC-23, HFC-227ea and FC-3-1-10 extinguished all test fires within 22 s, while HCFC Blend A required more than 1 min to extinguish the test fires due to the low design concentration of 8.6% and "problems associated with achieving this design concentration". The measured HF productions from HFC-23, HFC-227ea and FC-3-1-10 were 5 to 10 times that of Halon 1301, while the HCFC Blend A produced about 40 times more HF than Halon 1301. These full-scale tests also indicated that faster discharge and higher design concentrations of the agents can result in earlier fire extinguishment and less HF production.

The National Research Council of Canada (NRC) carried out full-scale fire suppression testing of HFC-227ea and HCFC Blend A in a 121 m^3 compartment[9]. HFC-227ea was tested at concentrations of 7.6 and 8.8%, and HCFC Blend A was tested at concentrations in the range of 8.6 to 14%. The test results showed that HCFC Blend A, at a design concentration of less than 10%, was not successful in extinguishing all fires. HFC-227ea, at a design concentration of 7.6% or higher, and HCFC Blend A, at a design concentration of 12%, extinguished all test fires. HF and COF_2 were produced during fire suppression tests with HFC-227ea and HCFC Blend A (the latter also produced HCl during the tests). The quantity of the acid gases generated during suppression increased with increasing fire sizes and discharge times and decreased with increasing agent concentrations. The concentrations of HF and HCl produced during the HFC-227ea and HCFC Blend A tests were much higher than the Halon 1301 test. The test results also showed that an increased quantity of carbon monoxide was produced during fire suppression tests with HCFC Blend A and HFC-227ea, caused by agent-flame interaction.

Test data from small-scale to full-scale have shown that the halocarbon replacements extinguish fires at their design concentrations. However, the design concentrations of the halocarbon agents are much higher than Halon 1301, resulting in volume and weight penalties. The test data also show that the current halocarbon agents produce at least 5 to 10 times more HF and COF_2 than Halon 1301 during fire suppression. The HF and COF_2 levels produced in the test fires were significantly higher than all human exposure limits. The level of HF and COF_2 production during fire extinguishment depend on many factors such as agent type and concentration, fire type and size, and discharge and extinguishment times. The NRC tests[9] also indicate that halocarbon agents produce CO during fire extinguishment, which could raise another safety issue.

Some of the halocarbon agents have long Atmospheric Life Times and they could make long-term contribution to global warming if emitted to the atmosphere. The green house effect has now become an environment concern, and will become a determining factor in selecting suitable suppression agents in the future.

Water mist

The term "water mist" refers to fine water sprays in which 99% of the volume of the spray is in drops with diameters less than 1000 microns. The study and description of the fundamental principles of extinguishment of liquid and solid fuel fires by water mist can be traced back to the mid-1950s[10].

Research continued to be carried out during the 1960s and 1970s at university, industry and government research facilities[11]. These early studies focused on the extinguishing mechanisms of water mist and the optimum droplet parameters for efficient fire suppression. At the same time, however, Halon 1301 and 1211, the most effective chemical fire suppressants, were introduced. The application of water mist to fire suppression was, therefore, not considered practical until the recent requirement to phase out halon agents due to their negative environmental effects.

Fire suppression by water mist is mainly by a physical mechanism and no significant chemical effects are involved. The early studies[10,12] identified flame cooling and oxygen displacement as the dominant mechanisms in water mist fire suppression. Recent investigations, however, suggested that there are additional mechanisms in water mist fire suppression[13,14]. One such mechanism is the radiation attenuation provided by water mist which can stop the fire from spreading to an un-ignited fuel surface and reduces the vaporisation or pyrolysis rate at the fuel surface. Tests conducted at NRC [14] showed that the radiant heat flux to the walls of the test compartment was reduced by more than 70 percent by the water mist. Other extinguishing mechanisms, considered as secondary, include dilution of flammable vapors, and direct impingement wetting and cooling of the combustibles.

Water mist characteristics, such as drop size distribution, flux density and spray momentum, have a direct effect on its fire suppression effectiveness. To effectively suppress a fire, a water mist system must generate and deliver optimum sized droplets with an adequate concentration to the fire. The selection of the optimum size of droplets for fire suppression is dependent on the potential size of the fire, properties of the combustibles, and the degree of obstruction and ventilation in the compartment[14]. There is no one drop size distribution to fit all fire scenarios.

There are currently several water mist systems available commercially. Some use high or intermediate pressures of water through small orifices of a nozzle to produce water mist whereas others use twin fluid nozzles (water and air). Some of the commercial water mist systems are listed in Table 2. Water mist fire suppression systems have demonstrated a number of advantages, such as good fire suppression capability, no environmental impact and no toxicity. As a result, the use of water mist as a fire suppression system has been considered in a wide range of practical applications.

One application in which water mist was shown to have considerable potential for fire suppression was in shipboard machinery spaces. NRC and other research agencies have conducted many full-scale tests[15,16,17] to evaluate the fire suppression performance of water mist systems in such spaces. These tests[15,16,17] showed that water mist systems can effectively extinguish large fires in unventilated machinery spaces using a small amount of water. The performance was comparable to that of gaseous halon replacements.

Water mist systems were able to extinguish a wide variety of fires when natural ventilation such as open doors and hatches were allowed, while gaseous agents were not effective under such conditions[16]. Water mist systems also rapidly reduced the compartment temperature and significantly improved visibility. This would allow accessibility to the compartment during fire suppression. However, the tests showed that water mist in fire suppression does not behave like a "true" gaseous agent, and is affected by fire size, degree of obstruction, ceiling heights and ventilation conditions in the compartment.

Another area where water mist has potential as an effective halon alternative is the protection of electronic equipment. However, the telecommunications and utilities industries have traditionally been reluctant to use water as a fire suppressant on electrical and electronic equipment because of concerns about potential water damage. A preliminary study[18] to determine the feasibility of using a water mist system to suppress in-cabinet electronic fires showed that the fine water mist was effective in

extinguishing fires without causing short circuits or other damage to electrical and electronic components.

NRC has carried out a project to study the feasibility of using water mist as an alternative to gaseous agents to protect facilities with substantial amounts of electronic equipment[19]. As a part of this project, a series of full-scale fire suppression tests were conducted using water mist in electronic cabinets, underfloor cable plenums and overhead cable trays. The experimental investigations demonstrated that the traditional total-flooding approach (used for Halon 1301), was unreliable when applied to water mist. On the other hand, reliable fire suppression was achieved with water mist by exercising rigorous control over spray direction to the hazard. This was accomplished by laying out the nozzles to suit the physical arrangement of the obstructions or structural elements. The studies also showed that coarser sprays ($200 < D_{v0.9} < 400$ microns) which produced wetting of surfaces and water dripping down into recessed places, had better performance than very fine sprays ($D_{v0.9} < 90$ microns) against fires in electronic equipment. The investigations also showed that a water mist system can be used to suppress fires in electrical and electronic equipment with minimum water damage.

A potential advantage of water mist is that the damage to the electronic equipment could be far less than the damage caused by thermal decomposition products of gaseous halon replacement agents. A recent study[9] with halocarbon gaseous agents indicated that when they are applied to a smoldering electrical fire, the gaseous agents can decompose and produce high concentrations of corrosive gases such as HF. Also with gaseous agents, the compartment has to be evacuated completely during the agent discharge, disabling the operation of the room. However, with water mist, the evacuation of the compartment may not be necessary, especially if a zoned water mist system is used. This may allow a continuation of limited operation in the compartment when such operation is critical in carrying out a mission.

A recent NRC study[20] has shown that the fire suppression performance of water mist can be further improved by using a cycling discharge. The cycling discharge mode involves a continuous alternation of the On and Off cycle of the water mist discharge. The study clearly indicated that the fire extinguishing performance of the water mist system was substantially increased when a cycling discharge mode was used instead of a continuous discharge. When a fire challenge was small, the water mist system easily extinguished the fire, thus the improvement with the cycling discharge was small. However, even under those conditions, the amount of water required to extinguish the fire was reduced by using the cycling discharge. For more challenging conditions, such as small fires and ventilated conditions, the use of a cycling discharge significantly reduced extinguishment times and the water requirements. When a cycling discharge was used, more water vapour and combustion products were produced during the test, which increased the rate of oxygen depletion in the test compartment. In addition, the recurrent dynamic mixing created by cycling discharge effectively dilutes the oxygen and fuel vapour available for the fire.

Compressed air-foam systems

For decades, fire-fighting foams delivered from fixed-pipe systems have provided effective fire suppression for applications in the chemical and petroleum industries and military installations. The overall effectiveness of current fixed pipe foam systems, which incorporate aspirating-type nozzles and blower-type foam generators, is limited since they are unable to provide foams with high injection velocity. Also, the foam produced using traditional systems is not as stable and consistent, and expansion ratios are not as high as would be desired for some applications because the air to generate foam at the nozzle, which comes from the fire environment, may be contaminated. However, if

compressed air is used for foam generation, the resulting foam possesses superior quality and substantial injection velocity, as well as requiring much lower quantities of water and foam concentrates.

Injecting air under pressure into a foam solution stream generates compressed-air-foam (CAF). The process of moving the solution and air mixture through the hose or piping, if done correctly, forms a foam. The energy for the CAF comes from the combined momentum of the foam solution and air. One significant advantage of such systems is the increased momentum of the foam, enabling it to penetrate fire plumes and reach the seat of the fire, Another advantage of CAF is that it possess better stability with respect to drainage than aspirated foams, since it is characterised by a narrow distribution of bubble sizes.

Until now, attempts to adapt CAF to fixed installations have failed due to two fundamental technical difficulties: firstly, traditional sprinkler-type nozzles cannot distribute compressed air foam without collapsing it, and secondly, the foam itself degenerates in fixed piping. Recently, NRC has overcome these difficulties, and developed a means of producing Class A and Class B CAF in a fixed pipe system, using a new and innovative foam distribution nozzle[21]. Foam break-up, which prevented the development of this technology in the past, was avoided by the careful engineering design of the nozzle and of the piping system.

An effective CAF system produces foam consisting of similar-in-size bubbles, delivers the foam to nozzles without changes in foam properties, and provides a means of uniformly distributing foams over a prescribed area. NRC's fixed pipe CAF system consists of three zones: Air injection zone, Development zone and Discharge zone. In the air injection zone, air is injected into a stream of foam solution, ensuring that the air pressure is balanced with the water pressure. In the development zone, foam solution and air flow through a segment of flexible tubing, which acts as a foam improver. Abrupt bends in the piping as well as flow contractions and manifolds promote redistribution of foam into separate gas and liquid phases. In the discharge zone, foam is distributed over a wide area without losing its momentum. To permit the smooth discharge of foam, a special nozzle was designed that had no sharp bends and contained no impact points.

A series of full-scale fire tests were conducted to evaluate the performance of a prototype CAF system[22]. The fire scenarios used were 0.9 m diameter heptane and diesel pool fires and 0.6 m x 0.6 m x 0.3 m wood crib fire. The tests demonstrated the superior performance of a CAF system in extinguishing both the liquid fuel and wood crib fires with a small amount of water. Also, CAF requires a smaller amount of foam concentrate to provide effective suppression, compared to systems based on air-aspirated nozzles. In the NRC tests, 0.3% Class A and 1% Class B foam solutions were used without compromising the extinguishment efficiency of compressed-air-foams, compared to 1% Class A and 6% Class B foam solutions normally recommended for aspirated systems,

The research clearly demonstrated that fixed pipe CAF systems have a bright future; however, a practical application of CAF systems to protect very large spaces still requires further studies to establish good engineering design guidelines and approaches.

Aerosol and gas generators

The term 'aerosol' refers to a system of liquid or solid particles suspended in a gaseous medium. Fire extinguishing aerosols are usually created via a combustion process and delivered to the protected space either directly (on contact with the fire) or via devices located outside the protected volume.

Based on solid rocket fuel technology, a commercial aerosol system is available for fire suppression in unoccupied spaces[23]. It contains solid rocket fuel – solid potassium nitrate based oxidiser, plasticised nitro-cellulose based combustible binder and additives in a non-pressurised canister with end-plate delivery nozzles. When electrically or thermally ignited, the aerosol-forming composition produces dry chemical particles (K_2CO_3, $KHCO_3$) and gas products (CO_2, N_2, H_2O). The canister contains a polymer coolant, which absorbs heat before the hot aerosol leaves the nozzle. The solid particles are less than 1 micron in size, thus remaining suspended in the air for long periods of time. Suppression is achieved by removing and recombining flame propagation radicals (O, H, OH) and by absorbing heat and diluting the combustion zone. The ability of the aerosol to remain suspended for long periods of time and to fill and inert a volume, is an important factor.

Based on automotive airbag technology, gas generators have been developed for fire suppression applications[24]. Gas generators can instantly produce large quantities of inert gases (mainly N_2, CO_2 and H_2O vapour) by combustion of solid propellants. Solid propellants consist of both oxidisers and fuel ingredients and are able to burn without ambient air. Two basic types of solid propellants are used in gas generators — sodium azide (NaN_3 with iron oxide Fe_2O_3) based propellants and non-azide propellants. Gas generators can be very compact and can provide very fast discharge (in a few milliseconds). The discharge time can be varied by using various propellant formulations and different sizes and shapes of propellant pellets/grains. Current gas generators include two basic types — conventional gas generators and hybrid gas generators.

Conventional gas generators contain the main propellant grain and an electrical initiator. The electrical initiator ignites a booster charge upon receiving signals from a detection and control unit. This booster charge ignites the main propellant grain. Rapid combustion of solid propellants generates large amounts of N_2, CO_2 and H_2O vapour and micron-size particles, which cause the internal pressure to be increased rapidly, rupturing the hermetic seals. The gas products discharge in milliseconds to the protected space. The suppression action is mainly oxygen displacement and gas discharge dynamics.

Conventional gas generators generally produce very hot gases (as high as 500°C)[25] as a result of combustion of the propellant. However, fire suppression applications require significantly lower exhaust gas temperatures. There have been efforts to develop cooler propellant formulations in order to reduce overall combustion temperature[26]. High-energy and high-nitrogen fuels (such as 5-amino tetrazole and $C_4H_4N_{14}$) with oxidisers (such as potassium perchlorate or strontium nitrate) can produce cooler exhaust gases (about 10-20% cooler) and higher gas output. There have also been efforts to develop new propellant formulations with chemical additives. Most additives studied were potassium compounds, which provides chemical action for flame extinguishment[26].

Lower exhaust gas temperatures can also be achieved through hybridising the conventional gas generators with liquid agents[27]. A hybrid gas generator consists of an electrical initiator, a solid propellant chamber and a suppression agent chamber. The heat and pressure generated by the combustion of the propellant are used to heat and expel the liquefied suppressant. A hybrid gas generator can provide exhaust temperatures as low as 30°C above ambient[25]. Current hybrid gas generators have two basic configurations. In one configuration, the propellant chamber and the agent chamber are separated by a piston[27]. As the propellant combustion takes place, pressure builds up in the propellant chamber and pushes the piston to pressurise the agent chamber. At a designed pressure, the propellant release disk and the agent release disk are nearly simultaneously ruptured; both propellant gas and suppression agent flow into a mixing chamber where they mix and exchange heat before being expelled through the discharge ports. In another configuration, there is no mixing chamber and propellant combustion products are directly released into the agent chamber to pressurise and expel the agent[25,28].

Liquid suppression agents in hybrid gas generators include water, carbon dioxide, or halocarbon agents (HFC-227ea and PFC-514)[28]. Water hybrid generators are used to deliver fine water mist to protected spaces. The quantities of the propellant and the suppression agent can be sized to provide optimum heat exchange. For halocarbon hybrid generators, the propellant and agent quantities can also be controlled to enhance vaporisation and avoid thermal decomposition of the agent. The hybrid approach not only cools the propellant gases but also enhances the vaporisation and distribution of the suppression agent. In addition, the liquid suppression agent inside a hybrid generator is under low or no pressure and is only fully pressurised upon the generator activation.

CONCLUSIONS

With halon phase-out, there has been a major thrust to find new advanced fire suppression systems in recent years. Some of the newly developed fire suppression systems include halocarbon and inert gaseous agents, water mist systems, compressed-air-foam systems, and aerosol and gas generators.

Halocarbon agents are chemicals similar to halon with molecular structures modified to reduce or eliminate the chlorine and bromine atoms that are responsible for ozone depletion. Halocarbon agents extinguish fires primarily by cooling. Their fire extinguishing performance has been evaluated by many research groups. It has been shown that the agents are able to extinguish fires at their design concentration. However, thermal decomposition products are a concern. Most of the halocarbons produce TDP including HF at much higher levels than halon.

Inert gas agents extinguish fire by oxygen depletion. These inert agents, such as nitrogen, argon and helium, are clean and naturally occurring ingredients in the atmosphere and therefore have zero ODP and no Global Warming potential. Also, inert gases are not subject to thermal decomposition when used in extinguishing fires, and hence form no breakdown products. However, inert gases are stored as high pressure gases and hence require high pressure storage cylinders which has implications for space and weight.

Fire suppression by water mist is mainly by a physical mechanism and no significant chemical effects are involved. Water mist fire suppression systems have demonstrated a number of advantages, such as good fire suppression capability, no environmental impact and no toxicity. As a result, the use of water mist as a fire suppression system has been considered in a wide range of practical applications. However, water mist does not behave like a total flooding agent, thus the fire suppression effectiveness of water mist depends on the potential size of the fire, properties of the combustibles, and the degree of obstruction, as well as the water mist characteristics.

A newly developed CAF system produces foams with high momentum using less than half the amount of foam concentrate recommended for a traditional aspirated system. Fire suppression performance of CAF systems was demonstrated in full-scale tests conducted by NRC. The tests showed the superior performance of CAF systems in extinguishing both the liquid fuel and wood crib fires with a small amount of water. This makes it an ideal candidate for applications in areas where water supply is limited. However, CAF systems are not effective in extinguishing spray or cascading fuel fires.

Currently, there are several aerosol and gas generator systems commercially available for fire suppression. Aerosol systems produce micron size dry chemical particles (K_2CO_3, $KHCO_3$) and gas products (CO_2, N_2, H_2O) by combustion of a solid product, and extinguish fires by removing and recombining flame propagation radicals (O, H, OH) and by absorbing heat and diluting the

combustion zone. Gas generators produce a large quantity of inert gases (mainly N_2, CO_2 and H_2O vapour) by combustion of solid propellants, and extinguish fires by oxygen depletion. Also, there are new fire extinguishing products, called hybrid system, which is a combination of water or halocarbon agents with gas generators.

All of the recently developed fire suppression systems extinguish fires at their design conditions, however, no one system can be chosen as the best system for all applications. Some perform better than others in a particular application. All have some limitations and concerns that have to be dealt with in extinguishing fires.

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Table 1:. Toxic and environmental data, and fire suppression characteristics for some of the halocarbon agents.

Halocarbon / Inert Gas	Agent Formula Name	Chemical Name	Trade	M.Wt. g/mol	T_b oC	CB Ext. Conc.% (Heptane)	Inerting Conc. % (Propane (Hept.))	ODP (CFC-11)	GWP 100yr (CO2)	ALT year	NOAEL %	LOAEL %%	LC50
FC-14	CF_4	tetrafluoromethane		88.00	-128	13.8-16		0					
FC-116	C_2F_6	hexafluoroethane		138.0	-78.2	7.8-8.1		0	9000	10000			
FC-218 A -	C_3F_8	octafluoropropane	CEA-308	188.0	-36.7	6.1-7.3		0	6100	3200	30	>30	
FC-318	$c-C_4F_8$	octafluorocyclobutane		200.0	-6.0	6.3-7.2		0		>3000			
FC-3-1-10 A -	$n-C_4F_{10}$	decafluorobutane	CEA-410	238.0	-2.0	4.1-5.9	9.5-10.3	0	5500	2600	40	>40	80
	C_3F_6	hexafluoropropene		150.0	-29	7.3		0					
[HFC Blend] AP	unpublished,	proprietary	Halotron II	102.16	-78~-26	9	12	<<.001		330		50	
HFC-23 A	CHF_3	trifluoromethane	FE-13	70.01	-82.1	12-13	19.8-20.2(14.7)	<<.001	9000	280	30	>30	65
HFC-125 B	C_2HF_5	pentafluoroethane	FE-25	120.0	-48.5	8.1-9.4	15.7 <<.001	3400	41	7.5	10.0	70	
HFC-134a B	$C_2H_2F_4$	1,1,1,2-tetrafluoroethane		102.0	-26.5	9.4-10.5		<<.001	1200	16	4.0	8.0	50 D
HFC-227ea A	C_3HF_7	1,1,1,2,3,3,3-heptafluoropropane	FM-200	170.0	-16.4	5.8-6.6	11.5-12.0(7.7)	<<.001	2050	31	9.0	10.5	80
HFC-236fa P	$C_3H_2F_6$	1,1,1,3,3,3-hexafluoropropane	FE-36	152.0	-1.5	5.6-6.5		<<.001	8000		10.0	15.0	13.5
HCFC Blend A (82% HCFC-22+9.5% HCFC-124+4.75% HCFC-123)			NAF S-III	92.9	-38.3	9.9-11.6	18.0	.02-.05	90-1600	2-1>10.0	64 E		
HCFC-22 B	$CHClF_2$	chlorodifluoromethane		86.47	-40.8	12		0.05	1600	16	2.5		5.0
HCFC-124 B	C_2HClF_4	2-chloro-1,1,1,2-tetrafluoroethane	FE-241	136.5	-12	6.4-8.2		0.022	440	7	1.0	2.5	36
HCFC-123	$C_2HCl_2F_3$	2,2-dichloro-1,1,1-trifluoroethane	FE-232	152.9	27.1	7.1-7.8		0.02	90	2	1.0	2.0	3.2
HBFC-22B1 X	$CHBrF_2$	bromodifluoromethane	FM-100	130.9	-15.5	3.9-4.6	8.0-11.7	0.74		7-15	0.3	1.0	10.8
FIC-13I1 B	CF_3I	trifluoroiodomethane	Triodide	195.9	-22.5	3.0-3.2	5.1(5.1)	0.008	<1	0.003	0.2	0.4	27.4E
SF6 C		Sulfur fluoride		146.1	-63	10.6		0	16100	3200			
CFC-13B1 X	$CBrF_3$	bromotrifluoromethane		148.9	-57.9	2.9-4.0	4.3-7.7(3.1)	16	5800	110	7.5	10.1	80E

A EPA acceptable total-flooding agent in occupied areas (A - restricted use, A + CO2 must meet requirements of NFPA 12 and OSHA 1910.162(b)5, A> final approval forthcoming).

B EPA acceptable total-flooding agent in unoccupied areas.

C Discharge test agent for certification of new halon systems, allowed for military uses and civilian aircraft uses only.

F Composition of HCFC Blend A is given in percent by weight.

G An extinguishing concentration of 7.2% was determined by Underwriters' Laboratories of Canada.

H Composition of inert gases is given in percent by volume.

I The values shown inside the brackets are the resulting O2 and CO2 percentage concentrations (by volume) corresponding to the design concentration for an inert gas indicated outside the brackets; EPA requires that the design concentration must not result in O2 level dropping lower than 10% and CO2 level raising higher than 5%, and that CO2 must meet requirements of NFPA 12 and OSHA 1910.162(b)5 if used alone.

P EPA is waiting for further test data to be submitted, decision pending.

X Production ceased.

CB: heptane cup-burner value.

fW = (Cd x MWt)AGENT / (Cd x MWt)HALON , Cd = 5% for Halon 1301 and CF3I, and Cd = 1.2 x CB for other agents ; fV = fW (L, 25oC)HALON / (L, 25oC)AGENT (J estimated for compressed inert gas under 15.2 MPa (150 atm) at 25 oC, K estimated using critical densities). Note that fW and fV are nominal values and do NOT include the weight and volume factors of suppression system hardware.

LC50: the lethal concentration that kills 50% of tested animals within a specified inhalation exposure period (D 2-hour, E 15-minute, others 4-hour)

Table 2: List of commercially available water mist systems.

Manufacturers	System Name	Nozzle Type	Syem Pressure
Securiplex		Twin fluid	Low discharge pressure (6 bar)
Marioff	Hi-Fog	Single fluid	High discharge pressure (100 bar)
Baumac	Micromist	Single fluid	High discharge pressure (70 bar)
Reliable	Mistafire	Single fluid	High discharge pressure (70 bar)
Spraying Systems	FogJet	Single fluid	Discharge pressure varies from low (7 bar) to high pressure (70 bar)
Lechler		Single fluid (Cluster)	Low discharge pressure and high flow capacity
BETE		Single fluid (Impingement)	Discharge pressure varies from low (12 bar) to intermediate pressure (32 bar)
Fike	Micromist	Single fluid	Low discharge pressure (12 bar)
CHEMETRON	Chemetron Fire Systems	Single fluid	Intermediate discharge pressure (24 bar)
Grinnell	AquaMist	Single fluid	Low discharge pressure (12 bar)
ULTRA FOG	ULTRA FOG$^{@}$ AB	Single fluid	High discharge pressure (125 bar)
Kidde/Fenwal	AquaSafe	Single fluid	Low discharge pressure (12 bar)
Fogtec Fire Protection	Fogtec	Single fluid	High discharge pressure (120 bar)