# CLEAN AGENT FIRE PROTECTION WITH HYDROFLUOROCARBONS

**Mark L. Robin, PhD, Kenneth Blanchard and Souvik Ghosh**
**DuPont Fluoroproducts**

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## ABSTRACT

For more than 30 years, Halon 1301 and Halon 1211 served as ideal clean fire suppression agents. Due to their unique combination of properties, halon systems provided protection of valuable and sensitive assets in a wide range of applications including the protection of computer rooms, control rooms, electronic data processing facilities, museums, military installations and equipment, and oil and gas industry applications such as offshore platform and storage facility applications. However, Halon 1301 and Halon 1211 were identified as contributing to the depletion of stratospheric ozone, and as a result their production in developed countries was halted under the provisions of the Montreal Protocol on January 1, 1994.

In response to the banning of the halon agents, several classes of halon replacements have seen commercialization. Hydrofluorocarbon (HFC) clean agents are the most widely employed halon replacements worldwide, and currently protect billions of dollars worth of valuable and sensitive assets, in over 300,000 installations. HFC type clean fire suppression agents retain the desirable properties of the halon agents, but do not contribute to the depletion of ozone. Like the halons themselves, the HFC clean agents are characterized by high efficiency, low toxicity, high storage stability, high chemical stability, and electrical non-conductivity, allowing their use in traditional halon applications. In this paper we detail the development and properties of halon replacements, including the requirements of the ideal halon replacement, environmental properties, toxicological properties, physical properties, fire suppression performance, environmental regulation status and current and developing applications of these agents.

## HISTORIC [1]

Halogenated compounds have been employed as fire extinguishing agents since the early 1900s when handheld extinguishers containing carbon tetrachloride ($CCl_4$) were introduced. In the late 1920s methyl bromide ($CH_3Br$) was found to be more effective than carbon tetrachloride, and was widely used as a fire extinguishing agent by the British in the late 1930s in aircraft protection, and by the German military during World War II in aircraft and marine applications. Fire extinguishing systems employing bromochloromethane ($CH_2BrCl$) were also developed in the late 1930s and were employed by the German Luftwaffe. Bromochloromethane was evaluated in the United States during the late 1930s to the late 1940s and was eventually employed by the U.S. Air Force.

Although extremely effective as fire extinguishing agents, the relatively high toxicities of methyl bromide and bromochloromethane prompted the U.S. Army to initiate a research program to develop an extinguishing agent which retained the high effectiveness of these agents but was less toxic. Army sponsored research at Purdue University in the late 1940s evaluated over sixty candidate agents, most of which were halogenated hydrocarbons, for both fire extinguishing effectiveness and toxicity. As a result of these studies, four agents were selected for further evaluation: bromotrifluoromethane ($CF_3Br$, Halon 1301), bromochlorodifluoromethane ($CF_2BrCl$, Halon 1211), dibromodifluoro-methane ($CF_2Br_2$, Halon 1202), and 1,2-dibromo-tetrafluoroethane ($BrCF_2CF_2Br$, Halon 2402). These further evaluations eventually led to the widespread use of Halon 1301 in total flooding and small portable applications, and the use of Halon 1211 in streaming applications.

Halons 1301 and 1211 are characterized by high fire suppression efficiency, low toxicity, low residue formation following extinguishment, low electrical conductivity, and long-term storage stability. Because these agents produce no corrosive or abrasive residues upon extinguishment, they are ideally suited to protect areas such as libraries and museums, where the use of water or solid extinguishing agents could cause secondary damage equal to or exceeding that caused by direct fire damage. Because they are electrically non-conducting they can be employed to protect electrical and electronic equipment, and because of their low toxicity they may be employed in areas where the egress of personnel may be undesirable or impossible.

Due to their unique combination of properties, the halons served as near ideal fire suppression agents during the past 30 years. However, due to their implication in the destruction of stratospheric ozone, the Montreal Protocol of 1987 identified Halon 1301 and Halon 1211 as two of a number of halogenated agents requiring limitations of use and production. An amendment to the original Montreal Protocol resulted in the halting of the production of Halons 1301 and Halon 1211 on January 1, 1994.

## HALON REPLACEMENTS

As a result of the banning of the halon agents by the Montreal Protocol, intensive research efforts were undertaken in the industrial, academic, and governmental sectors with the goal of developing replacements for the halons. In addition to possessing the desirable characteristics of the halons, the ideal halon replacement is required to have a much lessened environmental impact with regard to its potential for ozone depletion. The ideal halon replacement would therefore be characterized by the following properties:

- Clean (no residues)
- High fire extinguishment efficiency
- Low chemical reactivity
  Long term storage stability
  Noncorrosive to metals
  High material compatibility (metals, plastics)
- Electrically non-conducting
- Low toxicity
- Zero ozone depletion potential (ODP)

- Zero global warming potential (GWP)
- Reasonable manufacturing cost

It should be noted that to date no halon replacement agent has been developed which meets *all* of the above requirements for an ideal halon replacement agent. Initial efforts seeking to develop viable halon replacements included the investigation of several compound classes which were later eliminated as halon replacement candidates [1]. Hydrobromofluorocarbons (HBFCs), and brominated olefins proved to be very effective fire extinguishing agents, but have been eliminated from consideration due to their non-zero ODPs and relatively high toxicity. Perfluorocarbons (PFCs) are toxicologically inert and effective fire extinguishing agents, but have been banned in fire extinguishing applications due to their extremely high atmospheric lifetimes and GWPs. Iodine-containing compounds, especially iodotrifluoromethane, $CF_3I$, are extremely efficient fire extinguishing agents, but are also characterized by high toxicity and as a result are not suitable for use in human-occupied spaces; in addition these compounds are characterized by a non-zero ODP and prohibitive manufacturing costs.

Four classes of chemical compounds have emerged as commercially available halon replacements: hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), inert gases, and perfluorinated ketones. Examples of fire extinguishing agents from each of these four chemical classes are shown in Table 1.

## HALON REPLACEMENTS: CLEANLINESS

Damage to Assets. The primary characteristic of the halon agents was their "clean" nature – no corrosive or abrasive residues are left on assets or equipment following fire extinguishment with the halon agents. Traditional extinguishing agents such as water, foam or dry powder will leave a residue following extinguishment. In some cases secondary damage due to the extinguishing agent can exceed the damage to assets and equipment caused by the fire itself, for example in the case of the use of water or foam type agents to extinguish fires in libraries or museums, where books, papers and other sensitive assets can be damaged by water and foam.

Cleanup/Business Continuity. An additional advantage of the use of clean agents is that because they leave no residues behind, there is no need for cleanup following their use. This allows for business continuity, i.e., no interruption of the services a business supplies is required following the discharge of a clean agent system. The financial impact of service disruptions can be significant, especially in telecommunications facilities and in data processing centers. The estimated downtime impact per minute for various business applications is shown in Table 2. The downtime impact for a typical computing infrastructure is estimated at $42,000 USD per hour; downtime impacts for companies relying entirely on telecommunications technology, such as online brokerages or e-commerce sites, can reach $1 million USD per hour or more.

## HALON REPLACEMENTS: EXTINGUISHING EFFICIENCY

With respect to fire extinguishing efficiency, the halon replacements can be separated into two classes based on their mechanism of extinguishment: inert gas agents (IGs) and halogenated

## Table 1: Commercially Available Halon Replacements

| | Designation | Chemical Formula | Trade Name | Manufacturer |
|---|---|---|---|---|
| **HFCs** | HFC-227ea | $CF_3CHFCF_3$ | FM-200 | DuPont |
| | HFC-125 | $CF_3CF_2H$ | FE-25 | DuPont |
| | HFC-23 | $CF_3H$ | FE-13 | DuPont |
| | HFC-236fa [a] | $CF_3CH_2CF_3$ | FE-36 | DuPont |
| **HCFCs** | HCFC Blend A | $CF_2HCl$ (82%),<br>$CF_3CHCl_2$ (4.75%)<br>$CF_3CHFCl$ (9.5%)<br>d-limonene (3.75%) | NAF-S-III | Safety Hi-Tech |
| | HCFC Blend B[a] | $CF_3CHCl_2$, $CF_4$, Ar | Halotron I | American Pacific |
| **Inert Gases** | IG-541 | $N_2$ (52%)<br>Ar (40%)<br>$CO_2$ (8%) | Inergen | Ansul |
| | IG-55 | $N_2$ (50%), Ar (50%) | Argonite | Ginge-Kerr |
| | IG-01 | Ar | Argotec | Minimax |
| | IG-100 | $N_2$ | N-100 | Koatsu |
| **Perfluorinated Ketones** | FK-5-1-12 | $CF_3CF_2C(O)CF(CF_3)_2$ | Novec-1230 | 3M |

[a] Streaming applications (Halon 1211 replacements)

## Table 2: Downtime Impact per Minute for Various Business Applications

| Business Application | Estimated Outage Cost per Minute |
|---|---|
| Supply Chain Management | $11,000 |
| Electronic Commerce | $10,000 |
| Customer Service Center | $3,700 |
| ATM | $3,500 |
| Financial Management | $1,500 |
| Messaging | $1,000 |
| Infrastructure | $700 |

Source: Alinenan ROI Report, January 2004.

agents (HFCs, HCFCs, and perfluoroketones). The inert gas agents extinguish fire via oxygen dilution, i.e., the inert gas agents reduce the concentration of oxygen in an enclosure to a level where the combustion reaction rate is slowed to the point where the reaction can no longer sustain itself. The halogenated agents extinguish fire primarily via the removal of heat, i.e., the flame temperature is reduced to a temperature below that required for the maintenance of combustion. The mechanism of heat removal is a much more efficient method of fire extinguishment compared to the mechanism of oxygen dilution. As a result, the extinguishing concentrations for the halogenated agents typically range from about 4 to 12 percent via volume, compared to the inert gas agents whose extinguishing concentrations range from approximately 40 to 70 percent by volume. Table 3 compares the agent quantities required for the protection of Class A and Class B (heptane) hazards with typical HFC, HCFC, IG and perfluoroketone agents.

**Table 3. Agent Quantity Required for Protection of a 100 m$^3$ Enclosure**

| Agent | Class A Hazard | | Class B Hazard [a] | |
|---|---|---|---|---|
| | Agent required, % v/v | Agent required, kg | Agent required, % v/v | Agent required, kg |
| **HFC-227ea** | 7.0 | 54.8 | 8.7 | 69.4 |
| **HCFC Blend A** | 8.6 | 36.3 | 12.9 | 57.2 |
| **IG-541** | 40.0 | 72.5 | 43.9 | 82.2 |
| **FK-5-1-12** | 4.2 | 61.0 | 5.9 | 87.2 |

[a] Heptane

The higher volumetric requirements of the inert gas agents, along with the differing physical properties of the inert gases compared to the halocarbon agents has a significant impact on system design and cost. The inert gas agents cannot be compressed to the liquid state, and therefore must be stored as high pressure gases. This in turn necessitates the use of high pressure storage cylinders and high pressure piping for inert gas systems, adding significant cost to inert gas suppression systems. The low volumetric efficiency of the inert gas agents and their inability to be stored as liquids leads to the requirement of a large number of cylinders compared to other halon replacement systems. This in turn leads to the requirement for additional storage space and increased system footprint, adding further to the cost of the systems.

In contrast to the inert gas agents, the halogenated agents can be stored as liquids, allowing for a much larger mass of agent to be stored in the same volume compared to inert gases. This significantly reduces the number of system cylinders required with these systems compared to inert gas systems. In addition, with the exception of HFC-23, the halocarbon agents can be stored in standard low pressure cylinders and employ standard piping. Due to the requirements of high pressure piping and containers and the large number of storage containers associated with inert gas systems, system costs increase with system size much more rapidly for the inert gas systems compared to halogenated systems. Table 4 indicates the cylinder requirements for a 1000 m$^3$ Class A hazard with a typical HFC (HFC-227ea) and a typical inert gas (IG-541) system.

### Table 4. Halocarbon vs Inert Gas System: 1000 $m^3$ Enclosure, Class A Hazard

| Agent | Design Conc., % v/v | Agent, kg | Number of Cylinders |
|---|---|---|---|
| HFC-227ea | 7.0% | 548 | 2 |
| IG-541 | 40.0 | 724 | 22 |

## HALON REPLACEMENTS: CHEMICAL REACTIVITY

Halon 1301 and Halon 1211 were characterized by very low chemical reactivity, and this property is critical to the efficacy and safety of halon replacements. Chemical reactivity impacts five major aspects of halon replacement systems: system performance, agent handling, human exposure, agent cleanliness, and environmental impact. With regard to chemical reactivity, the halons, HFCs, HCFCs and inert gas agents are all characterized by very low chemical reactivity. In contrast, perfluoroketones are characterized by high chemical reactivity.

<u>Chemical Reactivity and System Performance</u>. Clean agent systems are often in place for 10 to 20 years, and must remain leak-free throughout this period. Chemical reactions producing even small amounts of acidic or corrosive products are hence undesirable, as even small amounts of such products can potentially lead to corrosion and eventual leakage of the extinguishing agent, compromising the effectiveness and safety of the extinguishing system.

Halons, HFCs, HCFCs and inert gases do not react with water or with common industrial solvents. Perfluoroketones, however, are very chemically reactive, and undergo reactions with such commonly encountered chemicals such as water, alcohols and amines. The reaction of the perfluoroketone FK-5-1-12 with water is well-documented [2-5]. Reaction of FK-5-1-12 with water produces 1,1,1,2,3,3,3-Heptafluoropropane (HFC-227ea, $CF_3CHFCF_3$) and Perfluoropropionic acid (F-Propionic acid, $CF_3CF_2COOH$):

$$CF_3CF_2C(O)CF(CF_3)_2 + H_2O \longrightarrow CF_3CHFCF_3 + CF_3CF_2COOH$$

The reaction of FK-5-1-12 with water has three major implications with regard to system effectiveness. First, system effectiveness can be affected by the loss of extinguishing agent as a result of chemical reaction - any amount of agent undergoing chemical reaction is not available for extinguishment. As a result, design manuals for perfluoroketone agents caution that contact with water or solvents either polar or hydrocarbon could the agents ineffective [2]. Secondly, the reaction of perfluoroketones such as FK-5-1-12 with water produces ionic species (F-Propionic acid and salts of F-propionic acid from the attack of the acid on steel), which can render the agent electrically conductive [3]; potentially rendering the agent unsuitable for the protection of hazards containing electronic equipment. Finally, the production of corrosive compounds due to chemical reaction can lead to corrosion of the system cylinders and leakage of agent. As indicated above, the reaction of FK-5-1-12 with water produces F-Propionic acid [2,4-6]. F-Propionic acid is a highly toxic and corrosive acid [7]. It belongs to the class of perfluorocarboxylic acids (PFCAs), which are among the strongest acids known. F-Propionic acid attacks steel to produce the corresponding iron salt; the formation of this salt in FK-5-12 cylinders exhibiting signs of corrosion has been verified [8]. F-Propionic acid is also toxic, and is reported to cause eye and skin burns, damage to the digestive tract, and gastrointestinal burns [7]. PFCAs as a class are known tumor promoters causing damage to the liver [9].

Chemical Reactivity and Agent Handling. Halons, HFCs, HCFCs and inert gases do not react with water, and hence no special procedures are required when handling these agents to avoid the introduction of water. Perfluoroketones, in contrast, are known to undergo reaction with water, and hence special procedures are required when handling these agents to avoid the introduction of moist air into the product; perfluoroketone design manuals prescribe special handling procedures such as the use of vent driers and nitrogen purges to prevent contact of perfluoroketone with moist air [2,3,5].

Chemical Reactivity and Human Exposure. The ideal halon replacement would not react within the human body, i.e., the ideal halon replacement is not metabolized. The HFCs employed as clean agents, and the inert gas clean agents, are not metabolized within the human body and do not react with water. Perfluoroketones, in contrast, undergo reaction with water, and FK-5-1-12, for example, is hydrolyzed when it crosses the lung-air interface to produce HFC-227ea and F-Propionic acid [4].

Chemical Reactivity and Cleanliness. Chemical reactivity is also undesirable due to potential implications related to the cleanliness of the extinguishing system. Chemical reaction of the extinguishing agent with enclosure contents runs counter to the purpose of a “clean” extinguishing system. Halons, HFCs, and inert gas agents are chemically unreactive, and hence do not pose a threat to protected assets. Due to their high chemical reactivity, perfluoroketones can undergo reaction with certain materials, including water and both polar and hydrocarbon solvents. Figure 1 shows the results of the discharge of FK-5-1-12 in an enclosure lined with FRP cladding, where it can be seen that staining of the cladding results; identical exposure to HFC or inert gas agents does not produce any visual effects on the cladding.

Chemical Reactivity and Environmental Impact. Chemical reactivity also has an impact on the environmental impact of extinguishing agents. The HFCs are chemically stable, and hence their atmospheric fate is not complicated by chemical reactions such as hydrolysis. It is well established that HFCs undergo reaction with hydroxyl radicals in the troposphere and the ultimate products are well understood [10]. In the case of FK-5-1-12, however, the current GWP value is based solely on the photolysis of perfluoroketones, and does not take into account potential reactions with water in the atmosphere, which in the case of FK-5-1-12 would produce HFC-227ea and F-Propionic acid.

**Figure 1. FK-5-1-2 Discharge onto FRP Cladding**

## HALON REPLACEMENTS: ENVIRONMENTAL PROPERTIES

The environmental properties of the halon replacements are compared in Table 5. The inert gas agents afford the minimum environmental impact, as evidenced by their ODP and GWP values. The use of these systems is limited, however, due to a number of factors as discussed above, e.g., the requirement of high pressure cylinders and piping, the large number of cylinders required and the resulting large system footprint and system cost. The halons have already been phased out, and HCFC-based agents are scheduled for phase-out, due to their non-zero ODP. The GWP of the perfluoroketones is reported to be low, however, as discussed above, this analysis does not take into account the potential reaction of perfluoroketones with atmospheric water, which could significantly affect the GWP and ultimate environmental impact of this class of agents.

## HALON REPLACEMENTS: ENVIRONMENTAL REGULATIONS

Montreal Protocol. The Montreal Protocol is related to ozone depleting substances (ODSs), i.e., substances with non-zero ODPs. The Halons have been phased out under the requirements of the Montreal Protocol, and the HCFCs are scheduled for phase-out under the requirements of the Montreal Protocol. HFCs, inert gases, and perfluoroketones are characterized by zero ODPs, and hence are not subject to the provisions of the Montreal Protocol.

Kyoto Protocol. The sole intent of the Kyoto Protocol is to reduce the emissions of greenhouse gases (GHGs). The Kyoto Protocol neither proposes nor requires the limitation or banning of GHGs, but only calls for measures to be taken to reduce GHG emissions. Hence, the Kyoto

**Table 5. Environmental Properties of Halon Replacements**

| | **Halon 1301** | **HFC-227ea** | **HCFC Blend A** | **IG-541** | **FK-5-1-12** |
|---|---|---|---|---|---|
| **Composition** | $CF_3Br$ | $CF_3CHFCF_3$ | HCFC-22<br>HCFC-123<br>HCFC-124<br>d-limonene | $N_2$<br>Ar<br>$CO_2$ | $CF_3CF_2C(O)CF(CF_3)_2$ |
| **ODP** | 10 | 0 | > 0 | 0 | 0 |
| **GWP** | 6900 | 3140 | 1700 | $CO_2$ = 1 | 1 [a] |
| **Atmospheric lifetime (yr)** | 65 | 34 | 12 | | 0.014 |
| **Scheduled for Phase-out?** | PHASED OUT | NO | YES | NO | NO |

[a] neglects hydrolysis of FK-5-1-12 to produce HFC-227ea and Perfluoropropionic acid.

Protocol does not place any limitations or bans on the use of GHGs, including HFCs, in fire extinguishing applications.

F-Gas Regulations. Like the Kyoto Protocol, the F-Gas Regulation is primarily concerned with the reduction of GHG emissions. The F-Gas Regulations neither propose nor require any limitations or bans on the use of HFCs in fire extinguishing applications.

International regulations such as the Kyoto Protocol and the F-Gas Regulations recognize the essentially non-emissive nature of clean agent systems, the critical need for HFCs in fire extinguishing applications, and the extremely small contribution to climate change due to the use of HFCs in fire extinguishing applications. It has been estimated that total impact of HFC emissions represent less than 3 percent of the impact of all GHG emissions, and that the impact of HFC emissions from fire fighting represents less than 1 percent of the total impact of HFC emissions [11,12]. Hence, HFC emissions from fire fighting applications represent less than 0.03% of total impact of all global GHG emissions. Figure 2 shows the relative impact of the various GHGs to global warming (“climate change”) where it can be seen that the impact from the use of HFCs in fire fighting is miniscule.

## HALON REPLACEMENTS: TOXICOLOGY

Inert gas toxicity is due primarily to asphyxiation (low oxygen level) at elevated inert gas concentrations, i.e., at inert gas concentrations exceeding approximately 43 % v/v. The toxicological properties of HFCs, HCFCs and perfluoroketones are compared in Table 6. As seen from Table 6, the HFC agents are the least toxic of the agent types listed, being characterized by very low acute and chronic toxicity, and a lack of metabolism within the human body. HFC-227ea is characterized by extremely low acute and chronic toxicity, and has been approved by the US Food & Drug Administration for use as a propellant for metered dose inhalers, in which the HFC-227ea is used to propel a medicament down the patient’s throat.

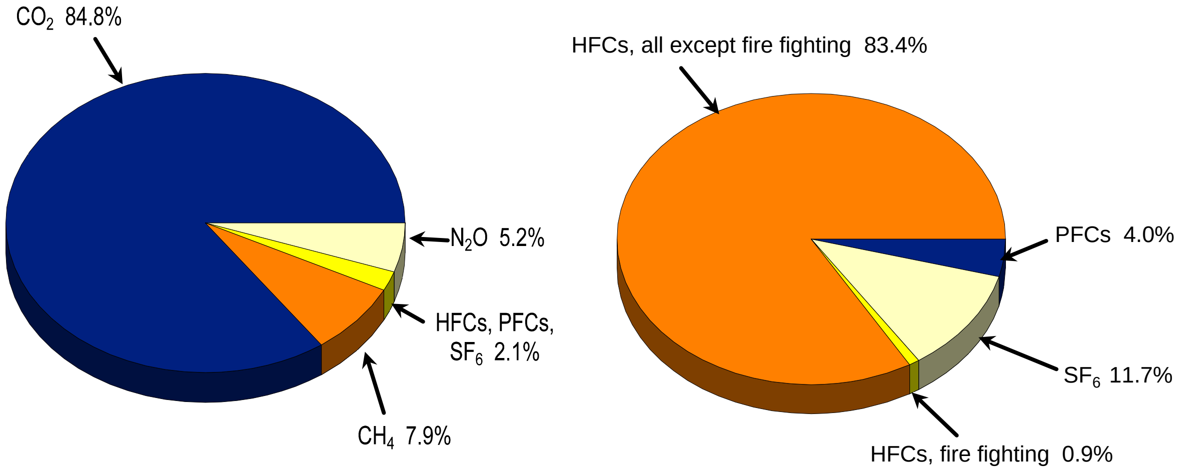


**Figure 2. Impact of GHG Emissions (as tons of $CO_2$ equivalents). The impact of emissions of HFCs from fire fighting represent < 1% of the impact of all HFC emissions, < 0.02% of the impact of all GHG emissions [based on Reference 12]**

### Table 6. Toxicological Profile: HFCs and Perfluoroketones

| | **HFC-227ea** | **FK-5-1-12** |
|---|---|---|
| **Inhalation LC50 (4h, rat)** | > 80 % | > 10% |
| **Cardiac Sensitization NOAEL** | 9.0 % | 10 % |
| **Cardiac Sensitization LOAEL** | > 10.5 % | > 10 % |
| **PBPK Safe level** | 10.5 % | PBPK data not available |
| **Repeated Dose Inhalation (28 bay, rat)** | NOAEL > 10.5 % [a] | LOAEL = 0.0997 % [b]<br>Peroxisome proliferation in liver<br>Increased lung & liver weights |
| **Metabolism** | Negligible | Hydrolyzes to F-Propionic acid |

NOAEL = no observed adverse effect level; LOAEL = lowest observed adverse effect level

[a] 90 day study

[b] NICNAS Std/1019[Reference 5]

## HALON REPLACEMENTS: COST

Table 7 compares the cost of typical HFC, inert gas and perfluoroketone suppression systems as a function of the enclosure size protected [13]. Cost estimates in each case include the cost of the required discharge, detection, alarm, purge, and ventilation systems. Increased agent costs for inert gas systems compared to HFC or perfluoroketone systems are due primarily to the cost of high pressure system cylinders and piping, and also due to the increased storage space required. The perfluoroketone agents are the most expensive of the halon replacement agents, and the increased cost of perfluoroketone systems compared to HFC systems is due primarily to this increased agent cost of perfluoroketone agent and also due to the requirement of greater quantities (more kg) of agent for the case of the perfluoroketones (see Table 3).

**Table 7. Suppression System Total Cost**

| Protected Volume | Total Suppression System Cost, $ USD | | |
|---|---|---|---|
| | HFC-227ea | IG-541 | FK-5-1-12 |
| 15,000 $ft^3$ (425 $m^3$) | $19,200 | $26,700 | $27,900 |
| 80,000 $ft^3$ (2265 $m^3$) | $113,300 | $162,500 | $150,700 |
| 150,000 $ft^3$ (4248 $m^3$) | $212,000 | $316,000 | $279,100 |
| 300,000 $ft^3$ (8495 $m^3$) | $413,700 | $662,000 | $553,500 |

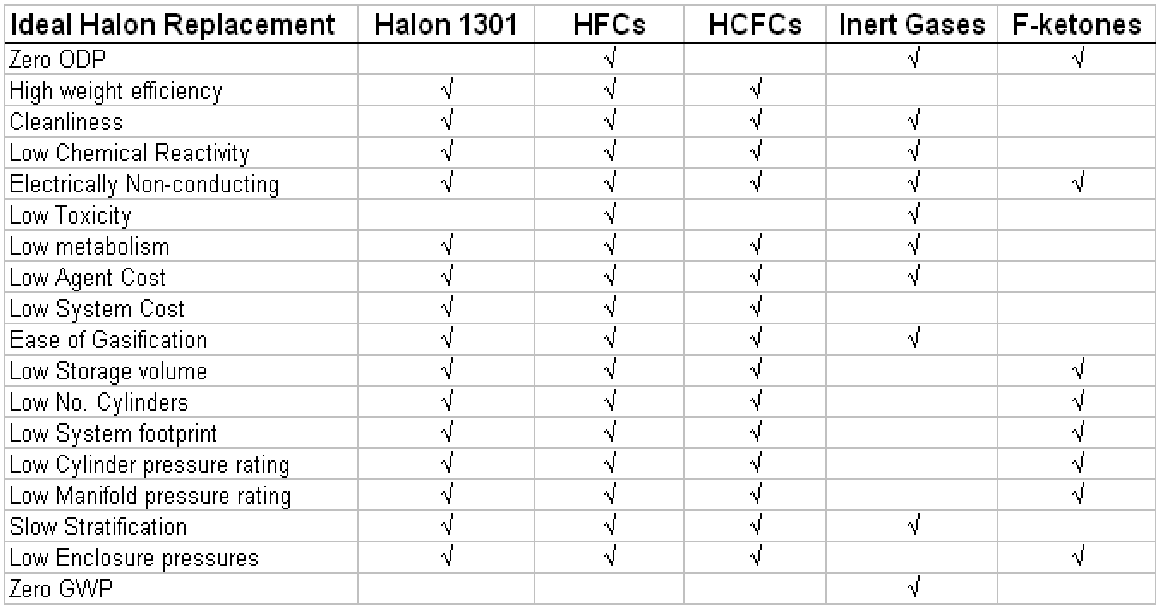
## HALON REPLACEMENTS: OVERALL COMPARISON

The above discussions have compared the properties of commercially available halon replacements with respect to several critical characteristics: fire extinguishment efficiency, cleanliness, chemical reactivity, environmental properties and toxicological properties. Table 8 provides a summary comparison of the halon replacements in terms of the desired properties of the ideal halon replacement. As seen from Table 8, no agent satisfies *all* of the requirements of the ideal halon replacement; however, it can be seen from the table that the HFCs represent the best overall combination of the desired properties. The halons and HCFCs both meet a large portion of the desired requirements, but are (in the case of the halons), or will be (in the case of the HCFCs) phased out due to their non-zero ODPs. It can be seen from Table 8 then that the agent class offering the second best combination of desired properties is the inert gases. As discussed in the next section, this is exactly how the clean agent market has developed worldwide – HFCs are the most widely employed halon replacements, followed by the inert gas agents.

## HALON REPLACEMENTS: MARKET & APPLICATIONS

Figure 3 shows the breakdown of the global clean agent market by agent type. HFC systems dominate the global clean agent market, accounting for approximately 70% of all installed clean

**Table 8: Overall Comparison of Halon Replacements**



| Ideal Halon Replacement | Halon 1301 | HFCs | HCFCs | Inert Gases | F-ketones |
|---|---|---|---|---|---|
| Zero ODP | | √ | | √ | √ |
| High weight efficiency | √ | √ | √ | | |
| Cleanliness | √ | √ | √ | √ | |
| Low Chemical Reactivity | √ | √ | √ | √ | |
| Electrically Non-conducting | √ | √ | √ | √ | √ |
| Low Toxicity | | √ | | √ | |
| Low metabolism | √ | √ | √ | √ | |
| Low Agent Cost | √ | √ | √ | √ | |
| Low System Cost | √ | √ | √ | | |
| Ease of Gasification | √ | √ | √ | √ | |
| Low Storage volume | √ | √ | √ | | √ |
| Low No. Cylinders | √ | √ | √ | | √ |
| Low System footprint | √ | √ | √ | | √ |
| Low Cylinder pressure rating | √ | √ | √ | | √ |
| Low Manifold pressure rating | √ | √ | √ | | √ |
| Slow Stratification | √ | √ | √ | √ | |
| Low Enclosure pressures | √ | √ | √ | | √ |
| Zero GWP | | | | √ | |

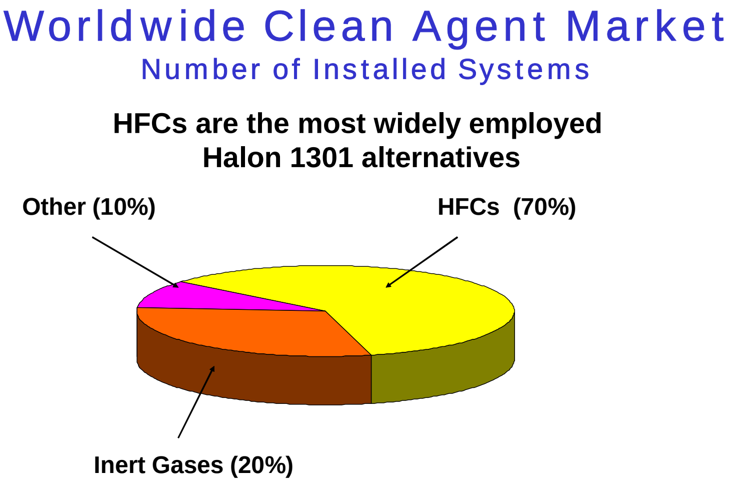


**Figure 3. Worldwide Clean Agent Market**

agent systems; inert gas systems account for approximately 20% of the total market, and other agents represent approximately 10% of the total installed clean agent systems.

As seen in Figure 4, the global halon replacement market is dominated by two agents, HFC-227ea (FM-200®) and IG-541 (Inergen™), which together account for approximately 90% of installed clean agent systems. HFC-227ea is the most widely employed Halon 1301 replacement

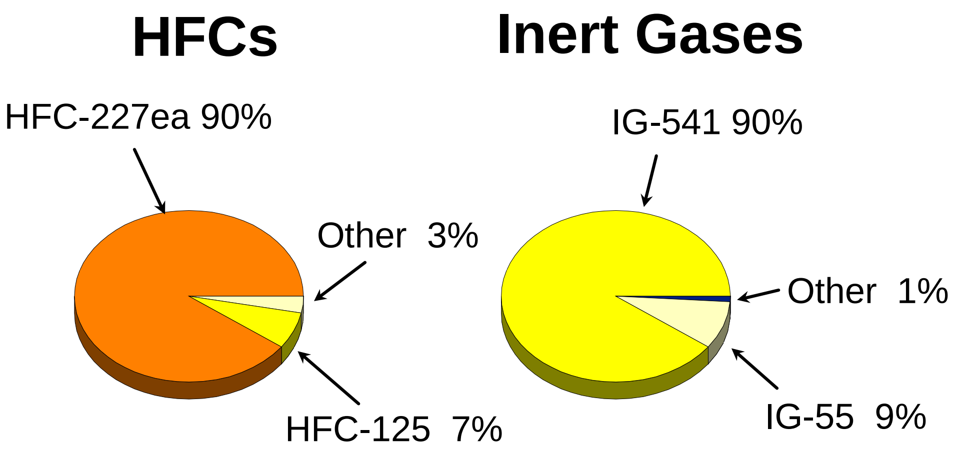


**Figure 4. Clean Agent Market: Installed Systems**

worldwide, and is also the most tested clean agent. It is estimated that there are approximately 300,000 HFC-227ea systems installed worldwide, in more than 65 countries. HFC-227ea systems have been installed beginning in 1991, and hence there exist 17 years of experience with these HFC clean agents systems, during which time the systems have demonstrated their safety and performance.

Applications of the HFC clean agents include the classic Halon 1301 applications: telecommunication facilities, computer rooms, data centers, museums, libraries, hospitals, medical facilities, medical equipment, clean rooms, engine compartments, engine nacelles, petrochemical facilities, grain elevators, oil rig platforms, floating roof tanks, and aircraft.

Table 9 lists a number of facilities worldwide which employ HFC clean agent systems, and Figure 6 lists a selection of the numerous industry leaders which employ the HFC clean agent systems. It can be seen from these tables that the HFC agents have been widely accepted on a global basis.

## CONCLUSION

The HFC clean agents provide the best overall combination of the properties desirable in a clean agent replacement for the halons: high effectiveness, cleanliness, low chemical reactivity, low toxicity, minimal environmental impact, and competitive system cost. As a result, the HFCs are the most widely employed halon replacements worldwide, and these systems currently protect billions of dollars worth of assets in more than 65 countries. HFC clean agent technology is a mature technology, having provided protection of valuable assets for over 17 years with an excellent performance and safety record.

**Table 9. Select Applications of the HFC Clean Agents**

American Museum of Natural history
Smithsonian Institute
Library of Congress
Eiffel Tower
Alexandria Library, Egypt
National Museum of Prehistory, Taiwan
Field Museum, Chicago
Aristoteles Univ Rare Book Collection, Greece
Royal Thai Silk Museum, Thailand
North American DEW Line Radar Installation
Dusseldorf Airport
San Francisco Airport
US EPA Supercomputing Center
Caesar's Palace, Las Vegas
Harrah's Casino
MGM Casino
Cox Communications
F/A-18 E/F Aircraft
Abrams tank
US Navy ground and naval vessels
Madrid Int'l Airport
Charles DeGaulle Airport
Newark Int'l Airport
New Bangkok Int'l Airport

Impsat
Cisco
Pepsico
Westinghouse
Etisalat
Vodaphone
London eye
Harley Davidson
Sprint
MCI/Worldcom
YFP
Lockheed Martin
Exxon/Mobil
AT&T
GTE

Saudi Telecom
Federal Express
Nokia
Fluor Daniel
Johnson & Johnson
Pfizer
Deutsche Bank
Bank of New York
Motorola
American Express
Goldman Sachs
MTN Africa
New York Times
Saudi Aramco

Dubai Int Airport
Intel
IBM
Burj Al Arab
Vesper
Delta Airlines
Volvo
Mitsubishi
Nestle
Dow Jones
Amazon.com
Wal-Mart
Monsanto
Reynolds Metals

**Figure 6. Industry Leader Acceptance of HFC Clean Agents**

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