SHIPBOARD TOTAL FLOODING FIRE PROTECTION SYSTEMS FOR HALON 1301 REPLACEMENT

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ABSTRACT

The Naval Research Laboratory (NRL, Code 6180) has successfully conducted extensive investigations for replacing shipboard Halon 1301 total flooding systems under the sponsorship of, and via interactions with, the Naval Sea System Command (NAVSEA, Code 05P9). The program has resulted in identifying agents of choice, with system design guidance. Several system types (HFC-227ea, HFC-227ea with Water Spray Cooling System, and fine water mist) are currently being implemented aboard the CVN 76 Class Aircraft Carrier and the LPD 17 Class Landing ship. Initial acceptance testing has also been conducted.

This paper includes a summary of the path and reasoning used to achieve halon replacement, and a discussion on ship systems/doctrinal implementation issues, including the desire to further implement water mist as a fire suppressant modality.

INTRODUCTION

Halon 1301 Total Flooding Systems have provided tremendous capability for efficiently and cleanly protecting entire spaces from fires, while not endangering occupants or damaging electronics due to unintended discharges. There have been concerns, including the ineffectiveness against smoldering Class A fires and halon-fire interaction products. More importantly, environmental considerations have evolved into a production cessation mandate – The International Montreal Protocol on Substances That Deplete the Ozone Layer.

The Naval Research Laboratory (NRL, Code 6180) has successfully conducted extensive investigations for replacing shipboard Halon 1301 total flooding systems under the sponsorship of, and via interactions with, the Naval Sea System Command (NAVSEA, Code 05P9). The program has resulted in identifying agents of choice, with system design guidance. Several system types (HFC-227ea, HFC-227ea with Water Spray Cooling System, and fine water mist) are currently being implemented aboard the US Navy CVN 76 Class Aircraft Carrier and the LPD 17 Class Landing ship. Initial acceptance testing has also been conducted. The NRL patented systems have also been installed replacing Halon 1301 systems in over 60 US Army watercraft engine rooms, up to 1700 m^3 (60,000 ft^3) in volume

The halon replacement efforts represent a long, sometimes discontinuous, evolution from defining the problem, better understanding suppression phenomena (a continuing task), suggesting replacements, intermediate and large scale evaluations, and finally, development of implementable shipboard system guidance. A large number of people played important and supporting roles over the years. While several sponsors contributed funding to these efforts, the US Naval Sea Systems Command provided the bulk of the support for systems development and transitioning these efforts into systems that are today in service aboard US Navy and Army ships.

This paper includes a summary of the path and reasoning used to achieve halon replacement, and a discussion on ship systems/doctrinal implementation issues, including the desire to further implement water mist as a fire suppressant modality.

HOLISTIC APPROACH

A proper effort required basic and applied science and engineering, as well as complying with the Navy business model for construction and operation of ships. To be able to maintain the fire protection capabilities provided by Halon 1301 but without the environmental damage to the stratospheric ozone layer, we needed a technology base including fire suppression, halon action, agent dissemination, distribution, and agent-fire interactions. We adopted a holistic approach merging integration of the above with interactive consideration of system desires, actual needs, platform implementation realities, and regulatory and legal guidelines and restrictions. For actual fire threat scenario design, we selected our evaluation of worse realistic (reasonable probability) challenge.

REPLACEMENT AGENT IDENTIFICATION

Research at NRL on halon replacements began in the early 1970s, before environmental concerns of stratospheric ozone layer depletion. We then did a chemical kinetics estimate in 1976 [1] that showed Halon 1301 would be at least as destructive at ozone depletion as the CFCs on a molecular basis. But halon usage was still relatively small and it was hard to convince others of the future impact. We performed halon related studies included smoldering combustion, kinetics, cup burner exploration, and quantified physical and chemical effects of various model and candidate replacement agents [2,3]. These included He, Ne, Ar, N_2, CO_2, CF_4, C_2F_6, C_3F_8, C_4F_{10}, CF_3Cl, CF_3Br, CF_3I, SF_6, SF_5Cl, SF_5Br, S_2F_{10}, CF_3H, C_2F_5H, and others evaluated later. These cup burner studies showed that Halon 1301 works 20 % by physical action and 80 % by chemical action. The 80 % halon chemical action is split between 25 % radical scavenging by CF_3 and 55 % radical catalytic recombination by Br.

We expanded the agent quantification model as a predictive tool for suppressant requirement for new aliphatic hydrohalocarbons and complex mixtures including with physical agents varying oxygen concentrations. Modeling suggested considering CF_2BrH and agents incorporating CF_3 groups for enhanced fire extinguishment efficiency while retaining shortened atmospheric lifetimes [4]. The reported high CF_3 suppression activity result was later used by Great Lakes

Chemical Corporation to select the molecular structure of 1,1,1,2,3,3,3-heptafluoropropane (HFC-227ea, HFP, later marketed as FM-200) as a promising candidate halon replacement to synthesize. The cup burner studies also quantified the non-linear effectiveness of chemically catalytic agents in mixtures, with relatively small amounts of Br or I containing agents showing significantly increased effectiveness in relation to concentration. The very significant boost in efficiency with small additions of chemically catalytic agent was explored and verified early in large scale tests with agent mixtures of CF_2HBr and HFC-227ea.

INITIAL INTERMEDIATE SCALE TESTING

We saw differing amounts of hydrogen fluoride (HF) from different agents in laboratory cup burner. Exploration with a multi-nozzle total flooding halon discharge system in a small compartment (1.8 m^3) quantified the very significant amounts of toxic and corrosive halide acid gases formed during Halon 1301 extinguished liquid fuel fires [5]. We demonstrated this issue was of real concern in full size (650 m^3) testing performed in a simulated destroyer machinery room [6]. The high HF production results foreshadowed the even greater production of HF from non-brominated fluorinated replacements, and accentuated the need for HF mitigation.

Our concern for issues with halon usage, both pragmatic and environmental, as well as our seeking understanding of combustion and suppression processes drove the laboratory explorations. The requirements for ship safety and survivability increasingly directed our further efforts. We used our laboratory results and modeling understanding to select ten prospective replacement agents, model compounds, and Halon 1301 for conducting total flooding discharge evaluation of fire extinguishment in a 56 m^3 (2000 ft^3) compartment [7]. Various size n-heptane pool fires were evaluated to determine the proper threat fire. As exemplified in the published literature (Goldilocks and the Three Bears), fires too small to generate turbulence were too easy to extinguish. Very large fires consumed too much oxygen and overheated the test compartment, also making it to easy for them to be extinguished. Just right middle-sized fires (0.23 m^2, 2.5 ft^2) were the most challenging threat. This selected size pool fire threat was made more realistic by having an array of angle iron positioned high within the pool fire flame. The heated metal provided both obstruction and hot flame holders to make extinguishment more difficult.

The purpose of testing was not to certify a particular gas and its concentration required to extinguish a fire, but to define satisfactory design criteria meeting safety requirements. While a spray fire proved easier to extinguish, it also was easier to reignite, due to its air entrainment and turbulent mixing behavior. Repeated reignition attempts following extinguishment told us what agent concentrations provided real protection.

Fluorocarbon compounds not containing bromine (or iodine) cannot take advantage of catalytic recombination of flame propagation radicals to help produce extinguishment. They rely primarily on energy abstraction via their heat capacities to cause physical pathway extinguishment. That is not to say there is not chemical involvement. The compounds do react in flames to produce high HF acid concentrations, typically five to eight times as much as does Halon 1301.

There is a unique cup burner extinguishment concentration for each agent – fuel pair (within apparatus, operator, protocol and experimental variation). There is not a corresponding one agent extinguishment concentration for each agent - fuel pair for large scale extinguishment. Varying design concentration and discharge time for the individual candidate agents gave a matrix of extinguishment times and HF concentration values. The agent concentration – fire extinguishment – HF concentration matrices will be different for different fire scenarios and distribution system configurations.

For fluorine containing agents, HF concentrations and time to extinction both increase greatly as agent concentration decreases. As an example for a hydrofluorocarbon agent (HFC), the knee of the curve for HFC-227ea (HF agent by-product concentration vs. agent concentration in Figure 1) is at approximately 8.5% agent. Fire extinguishment time likewise increases for agent concentrations above 8.5% (Figure 2). This is significantly higher than the cup burner extinguishment concentration of ~6.5% [8]. The point is that the minimum concentration able to effect extinction is not the preferable choice for liquid fuel fire threat protection. Naval vessels need to extinguish fires rapidly and recover operational capability. Rapid fire extinguishment and minimized damage and dangerous products must guide system parameter selection.

The following figures show the dependence of fire extinguishment time and resulting HF concentrations as a function of HFC-227ea concentration, measured close to the fire base.
While the plots are for HFC-227ea, other chemically reacting fluorine containing hydrocarbons behave similarly [7].

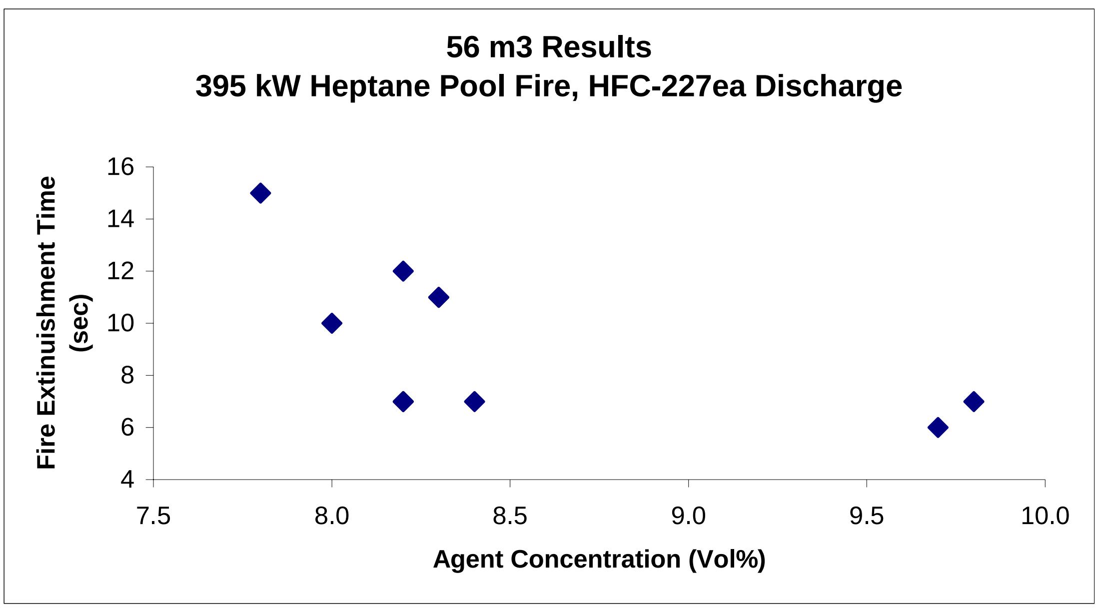

Figure 1. Fire extinguishment time as a function of HFC-227ea concentration.

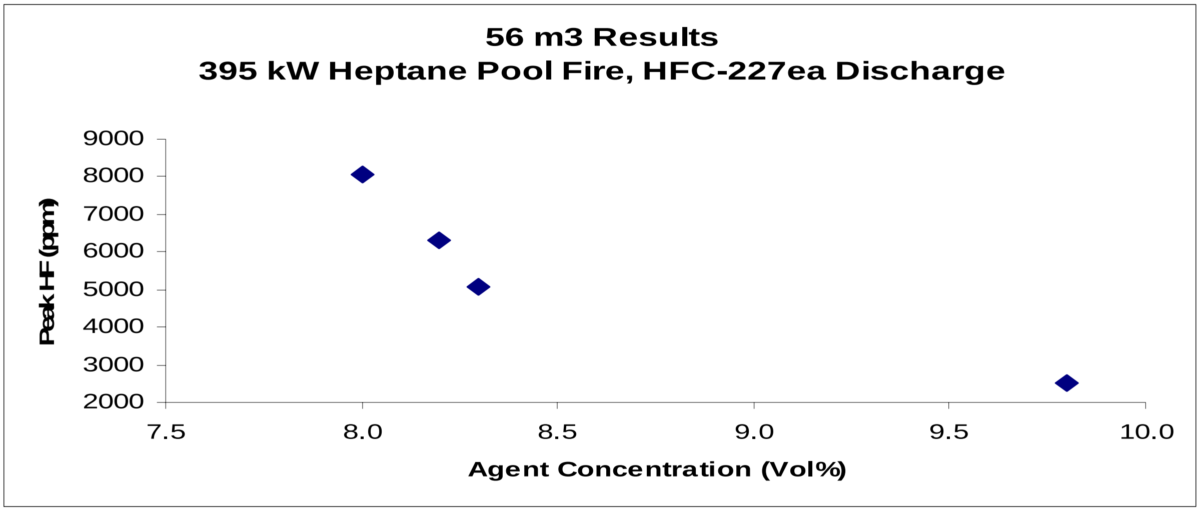

Figure 2. Peak HF concentration as a function of HFC-227ea concentration.

Ex-USS SHADWELL

Evaluating ten prospective and model agents in the 56 m^3 compartment let us select three occupied space suitable candidate agents and their desirable design concentrations, based on extinguishment times and acid production properties. We continued more extensive real scale evaluation on HFC-23 and HFC-227ea aboard the *ex*-USS SHADWELL, NRL's Fire Research Ship in Mobile Bay, Alabama. Perfluorobutane (n-C_4F_{10}) was eliminated from further consideration due to its long atmospheric lifetime and global warming potential.

The shipboard test compartment was outfitted with mockups representative of turbine and diesel Ship propulsion engines. Great care was exercised by MPR (a firm that had been employed by NAVSEA for validating shipboard halon discharge system design) in designing halon and replacement agent discharge systems for the specific test configuration [9-11]. Based on the specific relationships of obstacles and nozzle placement to judge where rapid agent distribution might be inhibited, we then selected threat fire locations consistent with the possible locations of fuel leak sources. In this way, we formulated a realistic worse case threat scenario.

The extent to which we took careful design of the agent discharge systems was driven by our knowledge that non-uniform agent distribution results in significantly reduced agent concentrations areas. These would cause delayed fire extinguishment and greatly increased HF production from fires located in reduced agent concentration areas. The reality is that very significant inhomogeneities are present in real world systems. Cruiser CG 62, the USS-CHANCELLORVILLE, is an extreme example with an over 12 m (40 ft) high main machinery space having a measured halon concentration variation from just above 3% to over 15%. The carefully designed discharge systems aboard the SHADWELL still had at least a relative +/- 20% agent concentration variation. This result led to our determination that agent design concentrations should be increased by at least 20% above the value yielding the minimum concentration desired for rapid fire extinguishment [12].

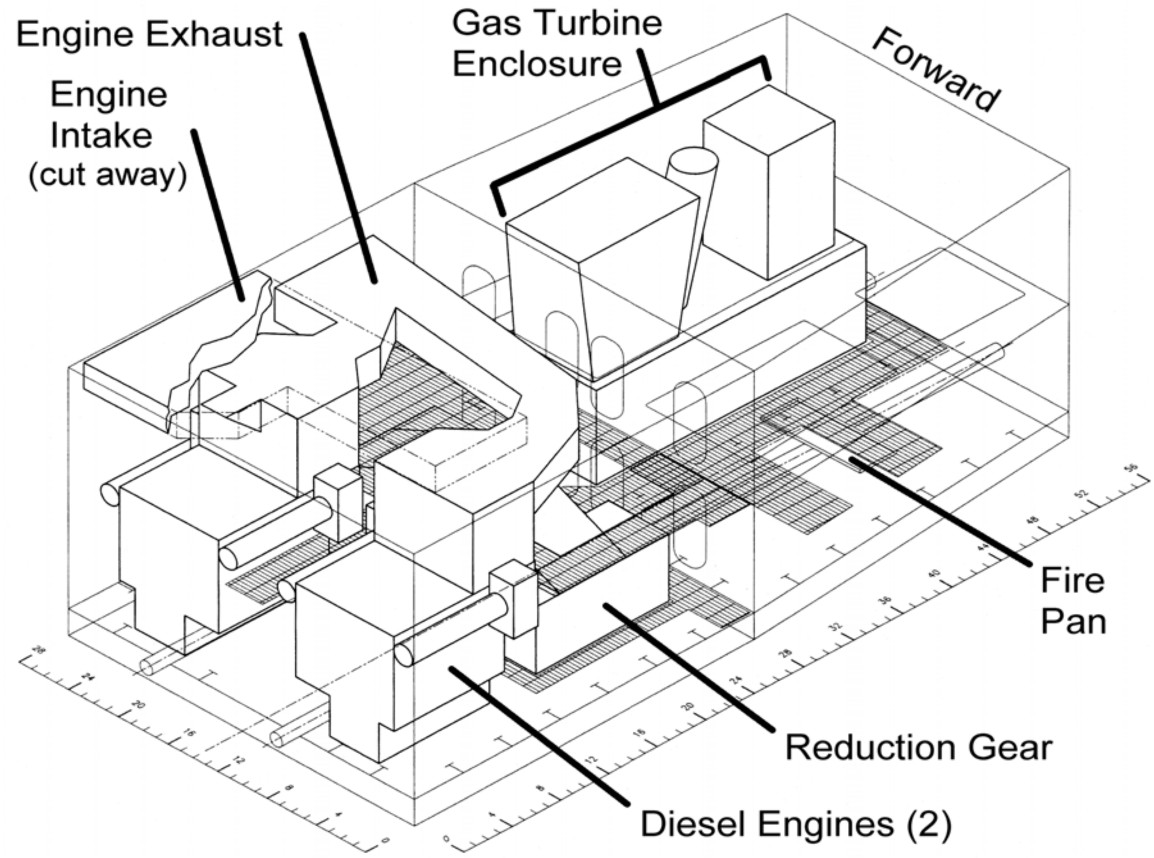

Figure 3. Configuration of ex-USS SHADWELL engine room mockups.

We recommended HFC-227ea be used for shipboard engine room total flooding fire protection. While other hydrofluorocarbons might have performed satisfactorily for extinguishment, they would have needed to be safe for use in an occupied space at the high design concentrations we recommended. HFC-23, then manufactured as FE-13, would have been safe and effective, but it has a higher inherent vapor pressure. In order to not exceed standard tank pressurization limits, especially at elevated machinery room temperatures, the fill density would have to be reduced. This meant more tanks would be required to hold the same amount of agent. System space and weight would then have an increased adverse impact compared to HFC-227ea [12].

Even with relatively high agent design concentrations, the HF concentrations observed in the full scale shipboard extinguishment tests were unacceptably high. This we combated by developing our patented Water Spray Cooling System (WSCS) [13]. Tests of a simple single tier low-pressure water spray system aboard the ex-USS SHADWELL demonstrated the tremendous HF concentration reductions achieved [14]. A key point is the activation of the WSCS prior to HFC agent discharge. To the limited extent the water spray inhibits the fires, the HFC has that much an easier task, and consequently does not react as much in the fire to generate HF. Thus, WSCS action is far more effective than just ‘washing out’ the HF formed; WSCS minimizes its formation in the first place. This effect holds for all reacting fluorine containing suppressants.

FLAMMABLE LIQUID STOREROOM FIRE PROTECTION

The program then addressed developing guidance for using HFC-227ea and WSCS as a Flammable Liquid Storeroom (FLSR) Halon 1301 replacement. FLSRs present very challenging difficulties. Issues include the presence of highly volatile flammable liquids, such as difficult to extinguish alcohols, and the very obstructed nature of shelving stacked with containers. Alcohols, particularly methanol, require significantly higher concentrations of suppressant agents. The more complex obstructions cause increased agent distribution inhomgeneities. These factors can cause delayed extinguishment and increased HF concentrations, even with increased agent design concentrations [15].

While the large ex-USS SHADWELL test compartment contained obstacles, the nature of these obstacles simulated large engine components, allowing for large open spaces. Therefore the results could not be extrapolated to more cluttered compartments such as a flammable liquid storage room (FLSR). We constructed a series of three compartments of increasing sizes. These mimicked a small FLSR, one twice the maximum size that would be protected with a single Halon 1301 system nozzle to explore single nozzle distributions and nozzle-nozzle distribution interactions, and a larger, and more importantly, higher height compartment [16]. The dimensions, nozzle number, and resulting HF levels observed from HFC-227ea extinguished fires are given in Table 1. Even though the agent design concentrations used were above 11 per cent and increased slightly with increasing compartment size, the resulting HF concentrations increased considerably more with compartment size.

Table 1. FLSR Configurations

Volume	Length	Width	Height	Nozzles	HF (ppm)
28 m^3	3.05 m	3.05 m	3.05m	1	2500
126	10.7	3.86	3.05	2	4000
297	10.7	6.10	4.57	4 (7)	>18000

FLSRs push the limits of the agent's capability to suppress highly obstructed fires in cluttered spaces. Increasing compartment size allowed more shelving, increasing obstacle complexity which in turn affected agent distribution inhomogeneity. HFC-227ea (as well as O_2, N_2, CO and CO_2) concentrations were determined using sets of pre-evacuated sampling bottles at a number of locations throughout the test compartments. Solenoid activation was under control of the test running computer. Subsequent gas chromatograph analysis gave concentrations with second time interval resolution during and following the agent discharge.

Figure 4 shows a metric for the deviation from uniform agent concentration distribution at each sampling time slice. The ordinate is the compartment concentration maximum minus minimum divided by the average concentration for all sampling locations. The spread is greatest at the start of the agent discharge, becoming more uniform following completion of discharge. The two smaller compartment agent concentration deviations merge at 10 seconds and continue to decrease but still remain above 20 per cent. The deviation spread in the large compartment is much greater under the single tier discharge system configuration, remaining an unacceptable 80 per cent at the conclusion of the discharge. This means there will be compartment areas with inadequate agent, generating large quantities of HF.

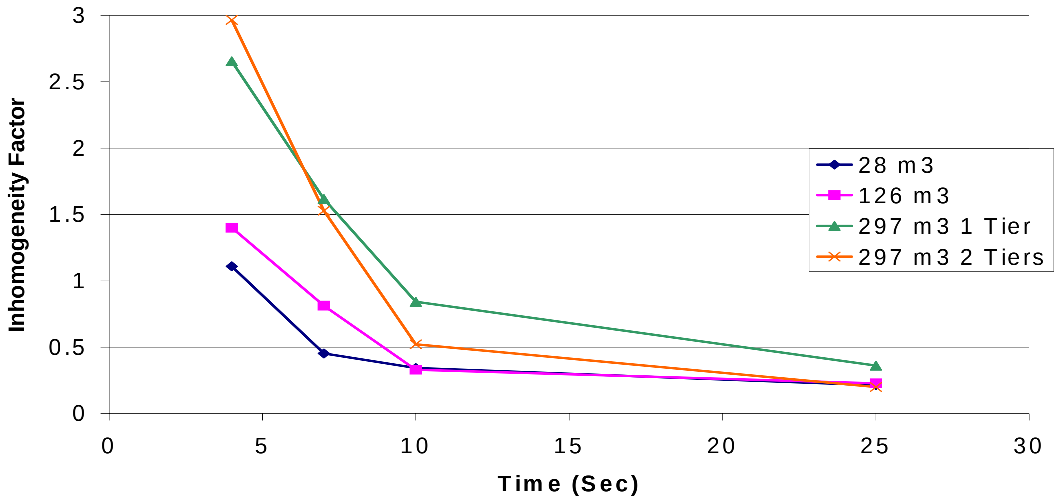

Figure 4. Inhomogeneity factor (difference between maximum and minimum HFP concentration normalized by the average HFP concentration (all sample locations) with time. HFP discharge at time = 0. 297 m^3 compartment data given for single and double tier configurations.

Figure 4 also shows the effect of having a second tier of discharge nozzles. Our evaluation showed that a single tier overhead discharge system, employing the Navy horizontal discharge direction agent nozzle, is not satisfactory for compartment heights above ~3.7 m (~12 ft). Addition of a second discharge nozzle tier above head height greatly reduced agent inhomogeneity. Even with less than a quarter of the total agent discharged released via the lower tier, it compensated very well for low concentration regions. The higher overhead compartment then had similar, if not quite as good, distribution characteristics as the smaller compartments.

WATER SPRAY COOLING SYSTEM

Even with HFC-227ea design concentrations of over 11 per cent and greater, unacceptably high HF concentrations were still observed. We further developed the WSCS initiated earlier aboard the ex-USS SHADWELL to reduce the HF levels in the FLSR scenarios. A goal in developing the WSCS was to have a simple to implement and maintain system. Therefore we employed a single overhead nozzle tier using low-pressure water with commercially available nozzles. Testing included a series of different nozzles with different flow rates and different protocols for usage in conjunction with the halon replacement agent. Testing in the 297 m^3 compartment showed dramatic HF reductions for both the n-heptane and the more difficult to extinguish methanol fires. These flammable liquids provided a representative cross section of threats posed by FLSR contents.

WSCS was most effective when initiated 30 seconds to one minute prior to HFC-227ea discharge. As discussed previously, the water spray weakened the fires, making it easier for the gaseous agent to extinguish them, without need to become extensively chemically involved during the process. Figure 5 (below) shows measured HF values for both fuels, without and with WSCS, measured at a height of 1.7 meters (face height) near the main fire during a shipboard HFC-227ea fire extinguishment test. With both fuels, the WSCS reduced HF concentrations below 90 ppm by 15 minutes after discharge initiation at all measured compartment locations. The time interval of 15 minutes represents the earliest time a Navy damage control party will reenter a post-fire casualty space. The concentration of 90 ppm HF is the highest range of a commercially available hand held colorimetric HF concentration indicator, and the highest HF concentration condition recommended by NFPA for reentry by outfitted response personnel.

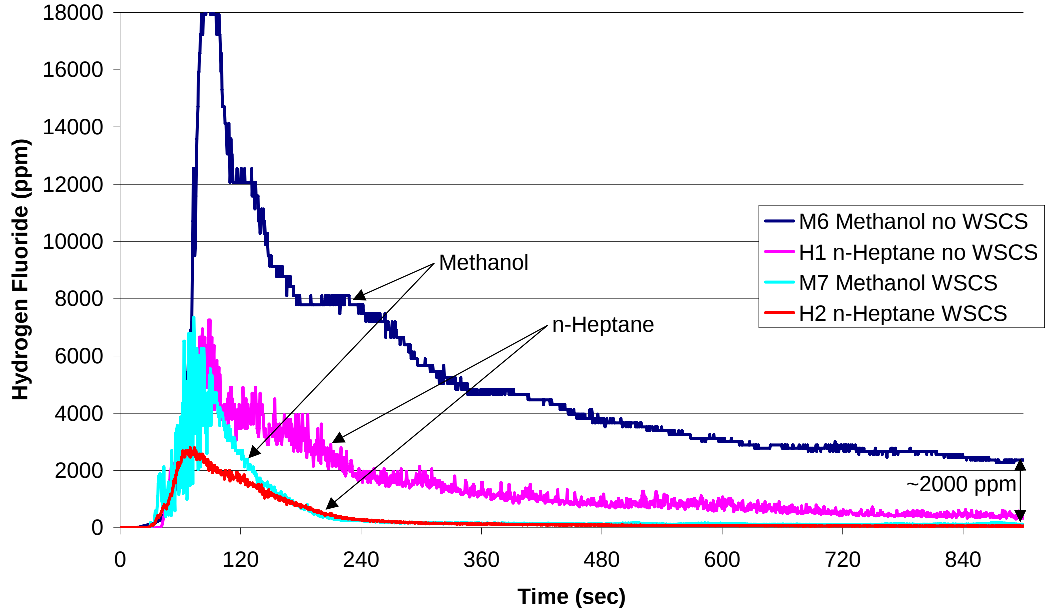

Figure 5. Comparison of HF concentration for methanol and n-heptane suppressed fires with and without a WSCS. HF measured near the fire at face height, with a nominal 13.0% HFP design concentration. HFP discharge occurs at time zero, data not corrected for instrument delay.

US Navy shipboard use of WSCS would employ fire mains for their water source and pressurization. While a fire main may be at a nominal pressure of 0.88 MPa (125 psi), it may be operating at some pressure reduction, especially during a casualty situation. We evaluated WSCS effectiveness at reduced pressures and found that operation was effective down to a tested pressure of 0.32 MPa (45 psi), if nozzle spacing were reduced [17].

Table 2. HF Concentrations as a Function of WSCS Parameters

WSCS	Peak Average	Average (15 min)	# of Nozzles
No	12,000 ppm	1,400 ppm	6
125 psi	7,500 ppm	55 ppm	6
100 psi	8,200 ppm	60 ppm	6
45 psi	7,800 ppm	40 ppm	8

SYSTEM GUIDANCE RECOMMENDATIONS [17]

For ships machinery spaces (engine rooms) with propulsion fuel (and hydraulic and lubricating fluids), an HFC-227ea design concentration of 10.2 per cent should suffice.

For flammable liquid storerooms, especially when containing methanol, the required agent concentrations are higher and a function of compartment size, especially of compartment height:

28 m^3: 10.5 %, nozzles in overhead
126 m^3: 11.5 %, nozzles in overhead
297 m^3: 13.0 % split distribution
–10.0 %, nozzles in overhead
– 3.0 %, additional nozzles at 2.9 m (> 3.8 m)

For WSCS in conjunction with HFC-227ea, where HF mitigation is required:

Water Nozzles
- K-factor 2.2 gpm/psi$^{1/2}$
- ~<200 micron drop size

Water Nozzle spacing
- 8.1 m^2 for 45 psi or greater
- 10.8 m^2 for 100 psi or greater

FUTURE CONSIDERATIONS

Replacements providing the fire protection capabilities of Halon 1301 have been designed for many applications. They can be employed where space, weight and cost considerations allow. There remains a significant degree of environmental and toxicity concerns. Water is safe and one of the most efficient heat capacity agents based on weight. If it can be generated in sufficient quantities in a form that is transportable to the fire locations and is highly efficacious without causing damage, it will become the new universal paradigm. Efforts are continuing.

CONCLUSIONS

We have reached an important milestone in our efforts to replace the fire protection capabilities provided by Halon 1301 for Navy ships. The understanding and technology base we have generated allows us to provide agent selection and system guidelines for the various applications, at least for new construction platforms. The less efficient replacement systems require additional space and weight allowances to be built in at the platform design phase. True drop-in replacements for existing platforms are often very difficult, if not impossible, to achieve.

While viable, implementable solutions are now available for Halon 1301 replacement, they are not without disadvantages. More environmentally acceptable and less toxic alternatives, especially when also contributing heat removal capacities, remain desirable. There continues efforts for enabling various forms of water mist to supplant reactive gaseous agents. Some workable solutions exist. Other scenarios, including the very obstructed flammable liquid storerooms, present challenges for agent distribution that have not yet been adequately addressed.

This has been a survey review of our efforts to understand fire suppression phenomena and to develop approaches for replacing the protective capabilities provided by Halon 1301. It is not at all meant to be inclusive or complete.

ACKNOWLEDGEMENTS

Among the many individuals that have contributed to this extensive effort, Alexander Maranghides, fire protection engineer extraordinaire, deserves special mention. Major funding for systems development was provided by NAVSEA.

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