

HEPTAFLUOROPROPANE WITH WATER SPRAY COOLING SYSTEM AS A TOTAL FLOODING HALON 1301 REPLACEMENT: SYSTEM IMPLEMENTATION PARAMETERS

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INTRODUCTION

The United States Army initiated a research project looking for an efficient, non-toxic fire extinguishant after suffering extensive losses due to fire in World War II. This project directly led to the use of halons as fire protection agents. The most widely employed chemical halon agent used for total flooding applications by the United States Navy was Halon 1301 (CF₃Br). But the same bromine atom in Halon 1301 that effectively extinguished fire also reacted with ozone. The Naval Technology Center for Safety and Survivability (NTCSS) at the Naval Research Laboratory estimated in 1976 that bromine containing Halon 1301 would be at least as damaging to the stratospheric ozone layer as chlorine containing CFCs. On January 1, 1989 the concern for stratospheric ozone became international law. The Montreal Protocol banned the production of halon in developed countries including the United States [1]. The United States Navy decided to no longer use ozone depleting materials in new construction platforms.

New technologies were needed to replace Halon 1301. The United States Navy turned to the NTCSS to research and determine suitable replacements for its total flooding needs. A variety of technologies were considered. This paper reviews the successful efforts of the Naval Research Laboratory in generating design guidance for shipboard implementation of fire protection systems developed to provide the capability of the Halon 1301 total flooding systems.

FIRE PROTECTION AGENT SELECTION

The added weight of the high pressure storage cylinders rendered non-condensable gaseous agents as impractical for movable platforms; the toxicity of carbon dioxide as well as its cylinder weight are definite disadvantages. Powder and pyrotechnic-generated aerosols can be effective if properly dispersed, but were not 'clean' agents, leaving behind residues that can hinder many applications. The search focused on fluorinated agents due to their potentially higher vapor pressures and lower toxicities. Perfluorinated agents have too large a global warming impact leaving primarily hydrofluorocarbon (HFC) agents for further study. The HFC replacement agents in sufficient quantity, guarantee extinguishment in the protected space as does Halon 1301. However, they do have significant global warming potentials. And they break down in interacting with fire, leading to significant quantities of hydrogen fluoride (HF), a potent toxic and corrosive acid gas.

Research by the NTCSS concluded that the trifluoromethyl moiety (CF₃) was an effective chemical suppressant. Based on this Great Lakes Chemical Corporation developed their three carbon agent, choosing the molecular structure 1,1,1,2,3,3,3-heptafluoropropane (HFP, HFC-227ea, C₃HF₇) for total flooding applications. As an extinguishant HFP works primarily as a physical agent, removing energy and displacing oxygen. Halon 1301 works 20 % physically and 80 % chemically, 25% radical scavenging and 55% catalytic recombination by Br. Interfering with flame chemistry is more efficient than physical suppression mechanisms. Increased quantities of HFP are needed to extinguish a given fire compared with Halon 1301. For comparison 6.6 % by volume of HFP is needed to extinguish an n-heptane cup burner fire, where only 3.1 % by volume of Halon 1301 is needed [2]. From a practical standpoint over two and a half times the space and weight is required by HFP compared to Halon 1301.

The NTCSS first conducted laboratory scale testing on a large number of chemicals as a potential replacement agent. Preliminary testing in a 56 m³ compartment evaluated ten gaseous agents in total flooding applications [3]. Final down selecting testing was conducted on the ex-*USS Shadwell*, the Navy's full scale damage control facility dedicated to integrating research, development, test, and evaluation studies on active and passive fire protection, flooding, and chemical defense (air purification). The initial test compartment was a machinery space mockup with diesel engine, reduction gear, and gas turbine simulation. It was 18 m by 9 m by 6 m high (but not rectangular) leading to a total volume of 840 m³ with nine four-hole horizontal, cross type agent nozzles in two tiers designed according to Navy standards. The forward 370 m³ portion of the machinery space mockup proved adequate for evaluating performance in subsequent testing on the ex-*USS Shadwell*, thereby reducing agent requirement and allowing greater instrumentation density. The Navy chose HFP as the optimum total flooding clean agent replacement for its shipboard needs based on this research.

The concern remained that HFP did produce five to eight times as much HF as Halon 1301 in similar fires. Not-in-kind non-gaseous agent technologies were also investigated. This included water mist as a non-environmental damaging material.

PRACTICALITY OF HALON REPLACEMENT USE

The NTCSS determined that HFP and water mist were the best Halon 1301 replacements, neither of which were ideal but both useful. The Navy chose to use both in the LPD 17, a new construction platform to be built without containing ozone depleting materials. It was decided that two water mist systems would be used for redundancy, leveraged for protecting the five adjacent machinery spaces based on space, weight, and cost considerations. In individual compartments (such as flammable liquid storage rooms), HFP was determined to be more space, weight, and cost effective. HFP will be used to protect the remaining compartments aboard the LPD 17 and all compartments aboard the new aircraft carrier, CVN 76 that would have used Halon 1301. But the question of HFP limitations remains. Research into practical ways to improve safety upon re-entry was needed.

HFP WITH WSCS

The Combustion Dynamics Section of the NTCSS proposed a new total flooding system combining a gaseous agent for guaranteeing extinguishment with a low-technology water spray that can operate off of a ship's watermain to provide cooling and facilitate re-entry and ventilation. The goal was to generate a water spray with sufficient momentum to allow using a single tier of nozzles even in high overhead spaces. The water drop diameters produced from the commercial nozzles, about 200 μm , are small enough to evaporate relatively quickly, but have sufficient momentum for rapid distribution, and do not require a more complex, greater ship impact system that fine water mist would require. This system was termed Water Spray Cooling System (WSCS) and later patented by the NTCSS [4]. The key benefits of the addition of WSCS are to greatly reduce the HF produced from a fire extinguished by HFP and to provide cooling. The WSCS concept was explored aboard the ex-*USS Shadwell*.

MACHINERY SPACE WSCS TESTING

A test series of WSCS combined with HFP was conducted in the 370 m^3 machinery space mockup [5]. The purpose was to evaluate and validate fire extinguishment using WSCS with HFP and evaluate the re-entry protection provided. The fire scenarios used a heat release rate of about 9 MW using marine diesel as the fuel. The WSCS was empirically designed with thirteen commercial, off-the-shelf nozzles on a single tier near the compartment overhead. The total application rate of water was varied between 40 and 60 Lpm. The WSCS initiation was varied before, at, and after the HFP discharge. The HFP design concentration tested was 10.2% by volume with the discharge time varying from ~ 6 to ~ 10 seconds.

The results showed that 10.2 % HFP in a machinery space was acceptable and that WSCS reduced peak and hold time (time before compartment re-entry) HF concentrations. WSCS also reduced peak compartment temperatures after HFP discharge from 70 C to 40 C. These decreases in HF and temperature established safer re-entry conditions, reduced reflash potential and safer ventilation.

The results from this test series proved WSCS capabilities. As a result the Army replaced Halon 1301 systems with HFP and the NRL patented WSCS in over sixty of their watercraft engine compartments, up to 1700 m³ in volume. While WSCS was quite successful when used with HFP, the limited testing on the *ex-USS Shadwell* was not meant to be comprehensive. Compartment size, obstruction configuration and fire fuel threat were appropriate to simulate a propulsion fuel machinery space. Other compartment types and configurations may present fire threats requiring different design guidance.

MORE CHALLENGING FIRE SCENARIOS

In order to provide design guidance for the implementation of HFP total flooding systems in the LPD 17 and CVN 76, the NTCSS began a several compartment size progression series of HFP alone and HFP with WSCS tests at the Naval Research Laboratory's Chesapeake Bay Detachment (CBD) near Chesapeake Beach, Maryland. A variety of fire threats were explored to bound the threat scenarios. Due to the extreme clutter that hinders agent distribution and variety of flammable liquids present, the flammable liquid storage room (FLSR) was chosen as a challenging scenario. Each test sequence was designed to first provide the appropriate HFP design guidance and then study the effect of WSCS used with HFP.

The FLSRs were very cluttered with containers throughout, hindering agent distribution. The agent discharge system was designed generically based on existing Halon 1301 system design guidance. The primary fuel tested was methyl alcohol, which presents a particularly difficult threat to any total flooding agent including Halon 1301 and HFP, as it requires significantly higher concentrations of agent for extinguishment. N-heptane (n-C₇H₁₆) fuel was also tested; this is representative of many other flammable liquids found in FLSRs. Because these FLSR test scenarios were the most challenging that a shipboard total flooding system would face, conclusions drawn would be transferable to other compartments providing overall general design guidance. The testing began with a test series in a 28 m³ compartment followed by test series in 63 m³ and 126 m³ compartments. The final test series was conducted in a 297 m³ compartment. The compartment size progression approach allowed evaluation of HFP nozzle placement and coverage for different compartment volumes and heights as well as WSCS parameters such as operating pressure and WSCS nozzle density.

INITIAL FLSR TEST SERIES

Testing was first conducted in a 3 m by 3 m by 3 m compartment with a total volume of 28 m³, representative of a small shipboard compartment [6]. A single four-hole horizontal cross type agent overhead HFP nozzle was located in the center of the compartment. A 200 kW fire was used as an extinguishment challenge, and a larger 400 kW fire was used as a tenability challenge. WSCS application was varied too as was the fire heat release rate.

The second test series was conducted in two phases, first in a 63 m³ compartment then in a 126 m³ compartment [7]. Each compartment had a 3 m overhead. This test series built on the previous by first looking at the maximum size for which a single halon nozzle would be used and then studying the interaction of agent nozzles. In the 63 m³ compartment, agent distribution was explored without fires to determine the best nozzle placement in the 126 m³ compartment. In the

126 m³ compartment 400 kW fires and 800 kW fires were tested as extinguishment and tenability challenges, respectively.

HFP only tests were conducted first to determine the concentrations needed to ensure quick extinguishment with minimal agent and provide background data for temperature and HF concentrations. Results from these test series showed that HFP design concentrations sufficient in smaller spaces might not be sufficient in larger spaces due to increased agent inhomogeneities caused by the increased compartment volume and complexity.

These test series provided the general design guidance on HFP systems needed in the LPD 17. With completed HFP only tests, the series then explored WSCS. Several WSCS variables were examined including WSCS initiation time and application amount needed for sufficient protection. A WSCS initiation time of thirty seconds prior to HFP discharge was found to be appropriate; this was important because it could be easily implemented into the current standard operation procedures as Halon 1301 system activation typically has a 30 second delay. The WSCS greatly reduced HF concentrations and compartment temperatures facilitating safe re-entry.

HFP design concentrations of 10.5 % and 11.5 % were found to be acceptable in the 63 m³ and 126 m³ compartments respectively. The increase in design concentration with compartment size was a direct result of the increased inhomogeneity with compartment size. The increased inhomogeneity can lead to greatly increased HF production in larger compartments [8]. The Navy decided that while HF production in small compartments did not justify the inclusion of WSCS, HF production in large FLSRs was a concern. NAVSEA 05P4 determined that WSCS should be used with HFP in large FLSRs in the LPD 17 and especially in the higher overhead of the CVN 76 large FLSRs. Due to the significant non-linear scaling observed, larger size compartment testing was needed to provide the necessary design guidance.

WSCS WITH HFP TESTING FOR NAVY IMPLEMENTATION

The third test series at CBD was in a large 297 m³ compartment simulating an FLSR with a 4.6 m overhead to validate design guidance for the CVN 76 [9]. The test series began with HFP only tests to determine the proper HFP system requirements followed by tests of HFP with WSCS to quantify the effect. First studied was nozzle coverage using a single tiered overhead HFP discharge system. However early testing indicated that HFP inhomogeneities were too great and better distribution was needed. Figure 1 shows that improved short time distribution was achieved with the addition of a second nozzle tier at 2.9 m above the deck. The fire size used to challenge the extinguishment was 400 kW; this fire size maintained consistency with testing in the previous compartments. The fire size challenging tenability was scaled from the 800 kW fire in the 126 m³ compartment to 1900 kW in the 297 m³ compartment. The larger fire produces more HF and heat but is easier to extinguish. Initial testing determined that 13.0 % by volume of HFP was the appropriate design concentration with a two tiered HFP system in a large compartment containing methyl alcohol, with 10.0 % from the overhead and 3.0 % from the lower tier. If methyl or ethyl alcohol were not present, the design concentration could be reduced as demonstrated in Figure 2.

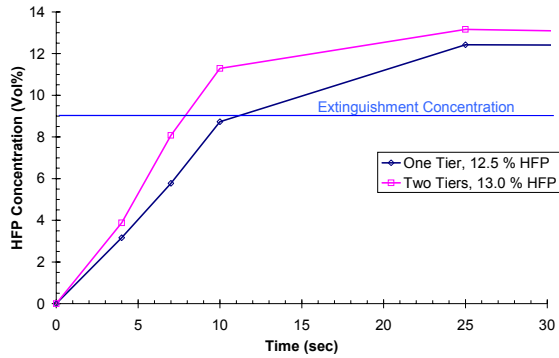


FIGURE 1

HFP concentrations near the fire location in the 297 m³ FLSR, using one and two tier discharge systems.

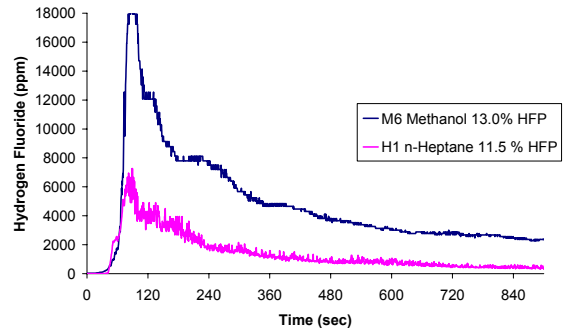


FIGURE 2

HF concentrations from HFP extinguished methanol and heptane fires in the 297 m³ FLSR. Note the reduced levels of HF from the heptane fuel fire despite the reduced HFP concentration.

The appropriate WSCS system requirements were then determined. Application rates and patterns were evaluated in the 28 m³ compartment to down-select to two nozzles with similar k-factors (2.2 gpm/psi^{1/2}) and spray patterns for testing in the 126 m³ compartment. The nozzle chosen for further testing in the 297 m³ compartment was the Bete TF6FC. Two fire sizes were employed. Testing began with a 1900 kW fire to produce more heat and HF to challenge the WSCS. A smaller and more difficult to extinguish fire of 400 kW was used to verify acceptable extinguishment times. Results showed that in the 1900 kW fire scenario, WSCS greatly reduces both the peak HF and the hold time HF. As seen in Figure 3, WSCS reduced the peak HF concentration near the fire by a factor of more than 2. WSCS reduced HF concentrations five minutes after HFP discharge to nearly the immediate danger to life and health (IDLH) level of 30 ppm rather than 5000 ppm without WSCS. This could lead to shorter hold times and faster re-entry. Figure 4 depicts the HF measurement locations. Table 1 shows that this HF reduction was seen throughout the compartment in methyl alcohol fire extinguishments with peak concentrations of less than half and HF concentrations fifteen minutes after HFP discharge more than an order of magnitude less with WSCS. Table 1 also shows that lower HF concentrations were observed in n-heptane fire extinguishments. Less HF is produced with lower HFP concentration, as n-heptane is significantly easier to extinguish with HFP than methyl alcohol. Figure 5 shows that WSCS reduced both the peak overhead temperature and the temperature several minutes after HFP discharge. This reduction protects the compartment by helping lower the compartment temperature below the flashpoint of the fuel.

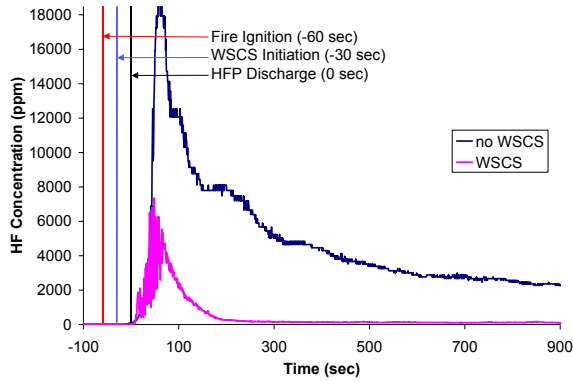


FIGURE 3

HF from HFP extinguished methyl alcohol fires in the 297 m³ FLSR with and without WSCS, at location A 1.7 m height

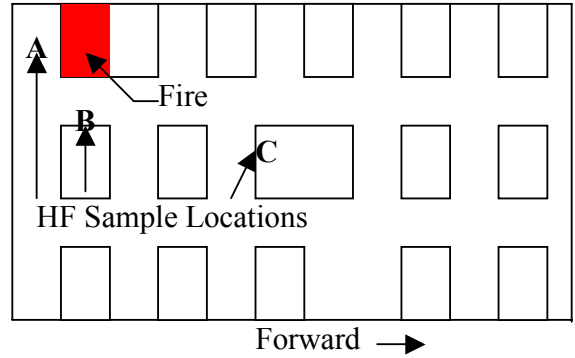


FIGURE 4

Layout of fire location and HF sampling locations in the 297 m³ FLSR compartment (not to scale)

Together these results show that WSCS complements the extinguishment capabilities of HFP with assurance of safer re-entry.

TABLE 1

HF Concentrations from a 1900 kW Fire in the 297 m³ Compartment

Fuel	WSCS	HFP (%)	Peak HF (ppm)		
			HF After 15 Minutes (ppm)		
			A [1.7 m]	B [2.5 m]	C [4.0 m]
Methyl Alcohol	No	13.2	18,000	20,000	14,000
			2,000	1,000	1,000
Methyl Alcohol	Yes	13.1	7,000	8,000	6,000
			100	10	40
n-Heptane	No	11.5	7,000	10,000	6,000
			400	200	100
n-Heptane	Yes	11.5	3,000	7,000	2,000
			60	10	100

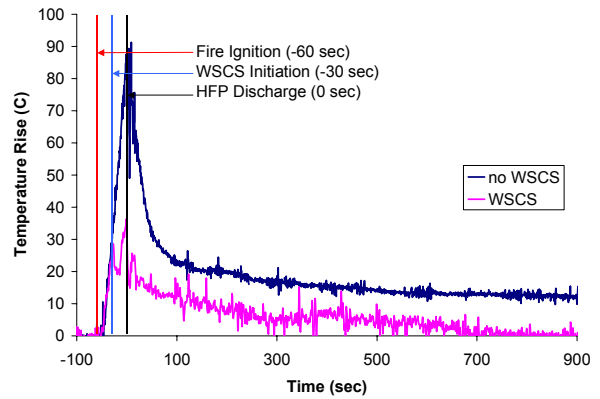


FIGURE 5

Temperature comparison for HFP extinguished 1900 kW methyl alcohol fires with and without WSCS, location B 4.0 m height

A variety of nozzle spacing and operating pressures were tested to determine the best WSCS guidance. Changes in the fire main pressure due to compartment location with respect to the fire main, system age, concurrent water demand, or damage could affect the WSCS performance. While ship watermain pressure may be adequate for WSCS requirements, pressure available at a distant WSCS nozzle may be significantly less. We tested WSCS at pressures as low as 0.3 MPa (45 psi), decreasing 297 m³ compartment nozzle spacing from 10.8 m² to 8.1 m² to counteract decreased flow at lower pressure. Table 2 (overall average HF concentrations) and Figure 6 (HF concentration near fire) show that for all evaluated input water pressures, the WSCS

satisfactorily reduced HF concentrations below 90 ppm within 15 minutes. An HF concentration of 90 ppm is the proposed maximum allowable HF concentration for re-entry by equipped response personnel and is measurable with commercially available hand-held colorimetric analyzers.

TABLE 2

HF Concentrations and WSCS water pressure

WSCS		Peak HF Average (ppm)	15-min HF Average (ppm)
Pressure	Nozzles		
None		12000	1400
125 psi	6	7500	55
100 psi	6	8200	60
45 psi	8	7800	40

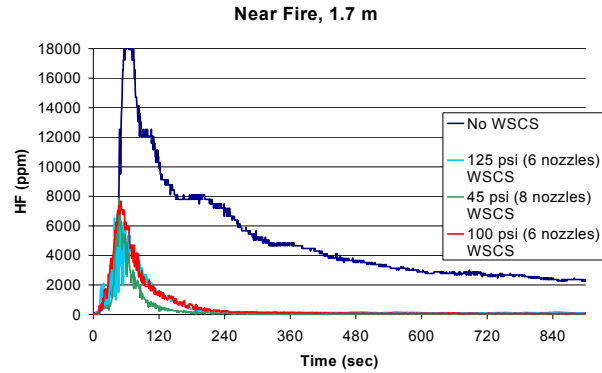


FIGURE 6

HF with and without WSCS

CONCLUSION

Halon 1301 is an effective fire extinguishant but it depletes the stratospheric ozone layer. The NTCSS was tasked by the Navy to investigate Halon 1301 replacements for total flooding applications. Acceptable Halon 1301 drop-in replacements did not exist. Research into a gaseous replacement by the NTCSS has shown that HFP can be used as an effective halon replacement in new ship designs. On new Navy construction platforms, HFP will be used in all total flooding applications except the five adjacent machinery spaces of the LPD 17 where water mist will be used due to leveraging shared system space, weight, and cost. Since HFP is a less efficient replacement than Halon 1301, it cannot be employed with the large safety margins that Halon 1301 systems had without having significant ship impact. The HFP systems needed to be optimized. Through a comprehensive program, the NTCSS was able to provide the required HFP design guidance.

To address the significant HF concentrations and high temperatures resulting after HFP fire extinguishment, the NTCSS has developed and validated the complementary WSCS for use with gaseous agents. WSCS is a low pressure, low technology, water mist system that produces water drops large enough to reach the fire from even a high overhead but small enough to vaporize readily. A progression of testing examining different compartment geometries and obstructions has shown the effectiveness of WSCS used in conjunction with total flooding gaseous agent systems. Based on this NTCSS testing, NAVSEA 05P4 has recommended implementation of WSCS used with HFP in large FLSRs on the new construction platforms. The Army replaced Halon 1301 systems with HFP and the NRL patented WSCS in over sixty of their watercraft engine compartments up to 1700 m³ in volume.

The HFP design guidance provided to the Navy states that in machinery spaces with propulsion fuels as the fire threat, 10.2 % HFP is the acceptable design concentration. In small FLSRs with

3 m overheads, 10.5 % HFP design concentration is acceptable. In medium FLSRs with 3 m overheads, 11.5 % HFP design concentration is acceptable. In large FLSRs with high overheads, 13.0 % HFP design concentration with 10.0 % high and 3.0 % at 2.9 m off the deck is acceptable. The WSCS design guidance provided to the Navy states that a WSCS nozzle k-factor of $2.2 \text{ gpm/psi}^{1/2}$ is appropriate creating drops sizes of about 200 μm . The WSCS nozzle spacing should be 8.1 m^2 if the minimum operating pressure is between 45 and 100 psi. If the minimum operating pressure is above 100 psi, the spacing can be increased to 10.8 m^2 .

Machinery space fires, with relatively open volumes and less volatile flammable liquids, and FLSR fires, with complex obstructed spaces and very volatile flammable liquids, form two bounding extremes in fire threat scenarios. With the technical base developed by this effort, it is possible to interpolate design guidance for a variety of compartment configurations and threat scenarios. WSCS can be implemented when needed to reduce the impact of unacceptable HF concentrations and / or temperature conditions.

ACKNOWLEDGEMENTS

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