COMBINING A WATER SPRAY COOLING SYSTEM WITH HEPTAFLUOROPROPANE FOR TOTAL FLOODING FIRE SUPPRESSION

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INTRODUCTION

The Navy Technology Center for Safety and Survivability (NTCSS) at the Naval Research Laboratory (NRL) has extensively studied Halon 1301 total flooding replacement technologies. Recent efforts have focused on improving re-entry conditions after 1,1,1,2,3,3,3-heptafluoropropane (HFP, CF_3CHFCF_3, HFC-227ea) fire suppression using the NRL-patented water spray cooling system (WSCS) [1]. While hydrofluorocarbon (HFC) agents such as HFP can serve as Halon 1301 replacements, fire suppressions generate considerably more hydrogen fluoride (HF) acid gas. Also, gaseous agents like HFP and halon provide little compartment cooling unlike water. WSCS was devised as a low technology, low-pressure water spray system to produce water drops large enough to reach the deck from high compartment overheads but small enough to vaporize readily. When used with a fluorinated gaseous agent such as HFP, WSCS greatly decreases HF concentrations and provides cooling. The capability WSCS provides in facilitating post-fire rapid and safe re-entry and reclamation is essential to allow securing any casualties and resuming compartment function. These are critical needs for military platforms.

Initial tests on HFP with WSCS were first performed onboard the ex-USS Shadwell [2]. This work concluded that WSCS successfully reduced HF concentrations in machinery space diesel and heptane fires. This work also led the US Army to replace Halon 1301 systems with HFP and WSCS systems in over 60 watercraft machinery spaces. Further development on WSCS continued with testing in flammable liquid storerooms (FLSRs). FLSRs represent a difficult challenge for a suppression system with their high degree of clutter and variety of flammable liquids. Testing conducted in a cubic compartment with a total volume of 28 m^3 and a single HFP nozzle produced HFP design guidance for small FLSRs, evaluated WSCS nozzles, and again showed the success of WSCS in reducing HF concentrations [3]. Testing of WSCS continued in a medium sized, 126 m^3 FLSR with an overhead of 3 m. Comparing the results from these tests series showed that HFP design concentrations sufficient in smaller compartments might not be sufficient in larger compartments resulting in longer fire extinguishment times and very high HF concentrations [4]. Because of this, NAVSEA 05P6‡ decided that high HF concentrations in large FLSRs are too great of a concern and WSCS will be used to protect these spaces.

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The NTCSS was asked to provide the necessary design guidance for protecting large FLSRs on future naval construction platforms, such as the CVN 76 and LPD 17. To accomplish this a third and current FLSR test series was begun in a 297 m^3 compartment at NRL's Chesapeake Bay Detachment (CBD) to provide the necessary HFP and WSCS design guidance for fire suppression and doctrine guidance for compartment re-entry.

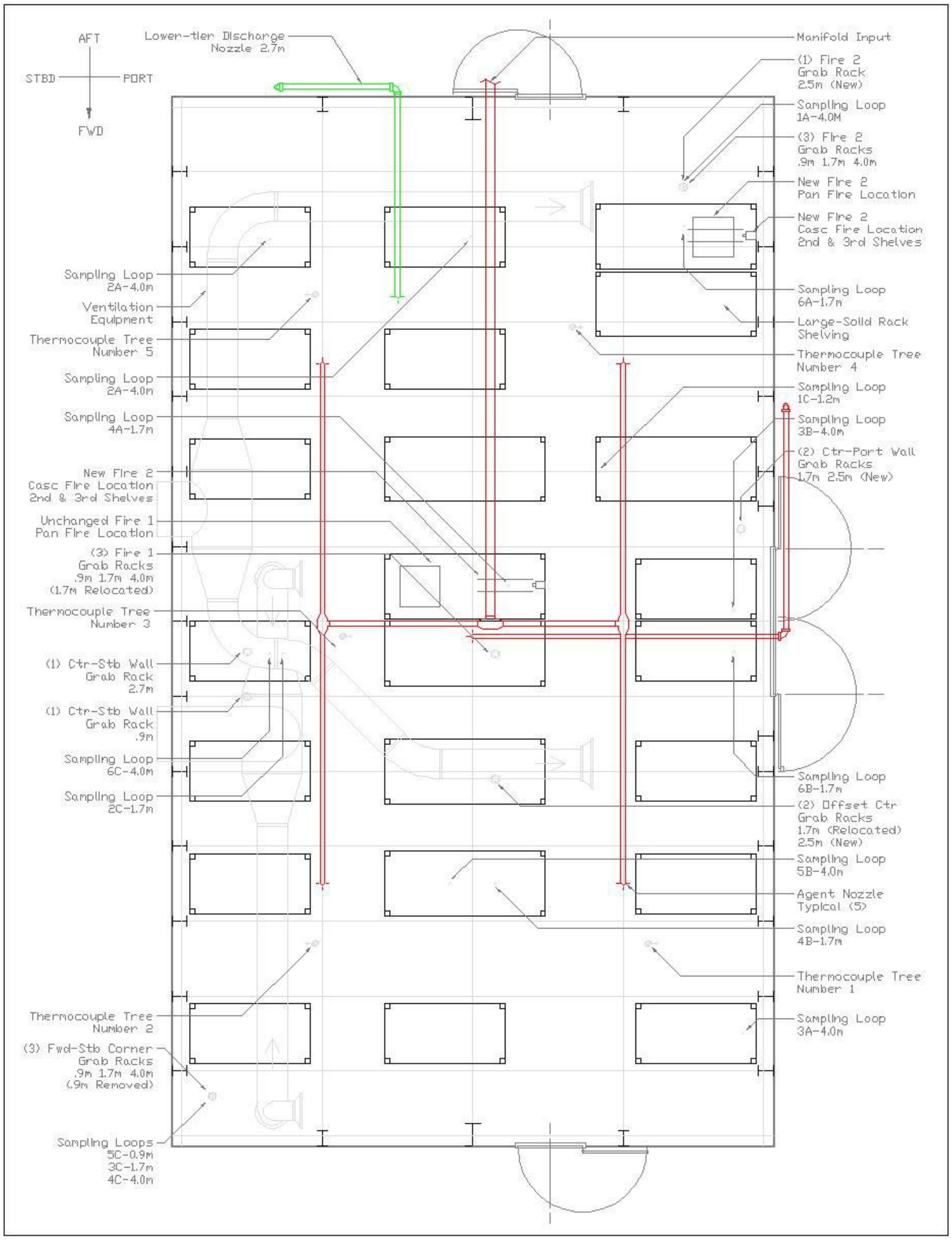

Figure 1. 297 m^3 test compartment, simulating a large Navy FLSR

TESTING

TEST SETUP

The compartment, see Figure 1, was 10.7 m long by 6.1 m wide by 4.6 m high and incorporated standard Navy hardware. Twenty-three shelving assemblies with 20 L buckets on four levels of shelves and 210 L drums on the deck were arranged to simulate shipboard conditions. These realistic scenarios restricted agent distribution while minimizing occupied volume. Volume occupied by obstructions artificially raises the design concentration, which is calculated using the empty compartment volume. Figure 2 and Figure 3 illustrate the shelving assemblies. Single rows of double-stacked buckets were used on the non-fire shelves to block agent but leave open space to keep the agent concentration close to the design concentration. The ventilation system provided one air exchange every four minutes with the supply high and the balanced exhaust split one-third high and two-thirds low. Four-hole, cross-type, standard Navy halon nozzles were used for the HFP discharge system. Commercial water nozzles were used for the WSCS.

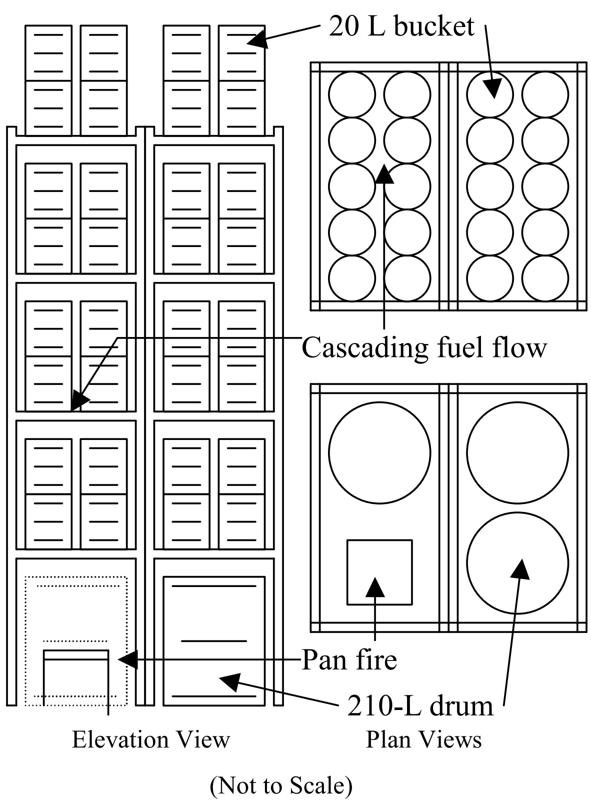

Figure 2. Shelving Assembly at the Corner Fire Location

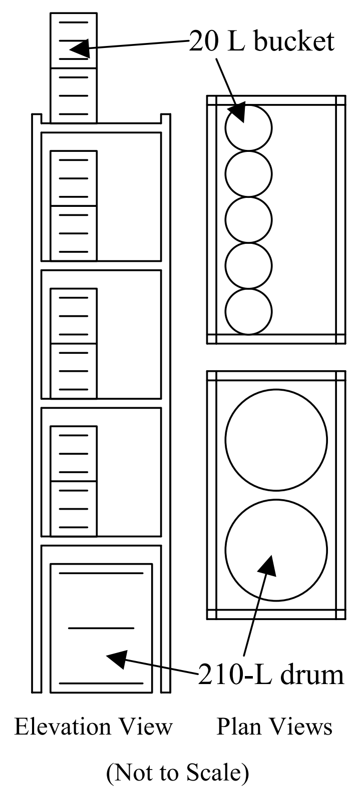

Figure 3. Typical Shelving Assembly for Non-Fire Locations

The compartment was instrumented to measure multiple parameters and analytes. Over 80 thermocouples were employed to measure temperatures throughout the compartment and near the fire locations. Six extractive gas loops continuously removed, conditioned and routed compartment gas to dedicated gas analyzers, which quantified oxygen, carbon monoxide, carbon dioxide and HFP. Over 80 evacuated, stainless steel canisters with computer-actuated solenoid valves captured "instantaneous" gaseous grab samples. Post-test analysis of these grab samples measured oxygen, carbon monoxide, carbon dioxide, nitrogen and HFP utilizing a gas chromatograph equipped with a 96-position autosampler. A hardened Fourier Transform Infrared Spectrometer (FTIR) was positioned inside the compartment to quantify HF, carbonyl fluoride and HFP near the fire. Six continuous acid analyzers were employed to measure HF at various locations in the compartment. Seven video cassette recorders monitored the fire events each with a time stamp generator, recorded the outputs of five visible and two infrared cameras.

Two fire sizes were used: a smaller 400 kW fire scenario challenged the HFP suppression and a larger 1900 kW fire scenario challenged the post-fire compartment re-entry. The 400 kW fire consumes less oxygen and heats the atmosphere less making suppression more difficult, the larger 1900 kW fire produces much more HF. Methanol was chosen as the primary fuel over other flammable liquids present in FLSRs because of its high cup burner extinguishment agent concentration value [5]. n-Heptane was chosen as the secondary fuel because it is characteristic of a wide variety of flammable liquids in FLSRs. The fire consisted of two parts, a 46 cm square pan fire just above the deck and a three-dimensional cascading flowing fuel fire in the shelves. Table 1 details the components for the fires tested. The pan fire simulated a small, contained spill; the cascading fire simulated a continuing spill. Prior to each test all systems were exercised and calibrated to ensure desired function.

Table 1. Fire Specifics

Fuel	*Fire Size (kW)*	*Pan Fire Size (kW)*	*Cascading Fire Size (kW)*	*Cascading Fire Flow Rate (Lpm)*
Methanol	400	70	330	1.3
Methanol	1900	70	1830	6.9
n-Heptane	1900	370	1530	3.0

Previous testing in the 28 m^3 and 126 m^3 compartments used a water pressure of 1.02 MPa in the WSCS. However water pressures that high may not be guaranteed in the fleet. A parametric study was conducted in the 297 m^3compartment looking at the impact of the WSCS water pressure on a fire. Results showed little variation in compartment temperatures with the water pressure ranging from 0.69 MPa to 1.02 MPa. Therefore the decision was made with NAVSEA 05P6 to use a water pressure of 0.86 MPa with a total water flow rate of 56 Lpm for the WSCS in the 297 m^3 compartment testing.

TEST PROCEDURES

The tests were designed to simulate a fire scenario onboard a Navy ship with quick fire detection minimizing oxygen depletion by the fire. Navy doctrine was followed with realistic times selected for all the events.

Immediately prior to the test start, the pan was fueled and a small, 3 cm cup fire was ignited at the base of the cascading trough. The doors were then sealed and the test was immediately started. Four minutes of baseline data were gathered followed by ignition of the pan fire via electrical spark and the cascading fire via 3 cm cup fire. Thirty seconds later the ventilation was shut down and the WSCS (if used) was activated. Thirty seconds later the HFP discharged. Gaseous grab samples were taken at –2, 4, 7, 10, 25, 710 seconds relative to the HFP discharge initiation. The cascading fuel continued to flow for one minute following the discharge. Attempts to re-ignite the cascading fire were made until re-ignition by flowing fuel over a heated element at 2, 3, 4, 5, 10, 14, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25 minutes after the HFP discharge. Re-ignition of the pan fire was by continuous exposure to a heated element. The ventilation was reactivated 15 minutes after the discharge, simulating re-entry effects. The tests were terminated when the cascading and pan fires were both re-ignited. Table 2 lists the sequence of steps to the tests.

Table 2. Test Procedure Timeline Relative to HFP Discharge

Time (Sec)	*Event*	*Time (Sec)*	*Event*
-240	Data acquisition start	60	Cascading flow stop
-60	Fire start	120	Cascading re-ignition attempt
-30	WSCS start (when used)	180	Cascading re-ignition attempt
-30	Ventilation shutdown begun	240	Cascading re-ignition attempt
-3	Ventilation confirmed closed	300	Cascading re-ignition attempt
-2	First gaseous grab sample	600	Cascading re-ignition attempt
0	HFP discharge	710	Sixth gaseous grab sample
4	Second gaseous grab sample	840	Cascading re-ignition attempt
7	Third gaseous grab sample	900	Ventilation startup begun
10	Fourth gaseous grab sample	960	Cascading re-ignition attempt
25	Fifth gaseous grab sample	1020+	Cascading re-ignition attempt

TEST VARIABLES AND MATRIX

Fire location, HFP design concentration, HFP nozzle configuration, fire size, fire fuel, and the effects of a WSCS with a water pressure of 0.86 MPa were primary test variables. Fire locations were studied to find where extinguishment would be most difficult. HFP concentrations were measured using gaseous grab samples to determine if the design concentration produced sufficient concentrations in all areas. HFP nozzle configuration was modified to minimize the HFP inhomogeneities in the compartment. The suppression effectiveness and re-entry conditions for different fire sizes and fuels were also assessed. The 1900 kW fires were also conducted with a WSCS to quantify the effect on HF concentrations.

RESULTS

To date, a total of nine suppression tests with HFP have been conducted. Nineteen fires without HFP were conducted to provide baseline data. Table 3 details the suppression test matrix.

Table 3. Suppression Test Matrix

Test	*Fuel Type*	*Fire Size (kW)*	*Fire Location*	*Design Concentration*	*Nozzle Tiers*	*WSCS*
M1	Methanol	400	Center	11.5%	1	No
M2	Methanol	400	Corner	11.4%	1	No
M3	Methanol	400	Corner	10.7%	1	No
M4	Methanol	400	Corner	12.3%	1	No
M5	Methanol	400	Corner	12.9%	2	No
M6	Methanol	1900	Corner	13.2%	2	No
M7	Methanol	1900	Corner	13.1%	2	Yes
H1	n-Heptane	1900	Corner	11.5%	2	No
H2	n-Heptane	1900	Corner	11.5%	2	Yes

FIRE LOCATION

The fire in test M1 was located in the center of the compartment with the cascading fuel falling on the top shelf. Results showed that this section of the compartment had a high concentration of HFP resulting in quick fire extinguishment and reduced HF production. Test data indicated other areas, such as the aft-port corner, had low HFP concentrations. It was decided to move the fire to the aft-port corner due to this. It was further decided to introduce the cascading flow onto the second shelf, since the shelving would obstruct HFP access to the fire. The new fire location, in a low HFP concentration area of the compartment, with the added obstructions provided a realistic yet more challenging fire suppression scenario.

DESIGN CONCENTRATION AND HFP NOZZLE TIERS

Tests M2, M3, and M4 were conducted in the corner fire location to challenge the HFP design concentration to ensure sufficient HFP concentrations throughout. Conclusions from earlier work showed that an HFP design concentration of 11.6 % was appropriate in medium sized FLSRs [6]. Test M2 was conducted at that concentration (actual concentrations varies slightly from desired design concentrations due to variations in HFP bottle filling). However as with test M1, results from test M2 showed pockets of low HFP concentration. To increase the HFP concentration in these areas, the design concentration was raised as suggested at HOTWC 2002 [4]. Test M3 was to be conducted with 12.5 % HFP design concentration, but a faulty valve prevented one of five HFP bottles from discharging, resulting in an effective design concentration of 10.7 %. Test M4 was conducted at a design concentration of 12.3 %. Results from this test still showed areas of insufficient, low HFP concentrations. An inhomogeneity factor was calculated from the gaseous grab data by normalizing the difference between the maximum and minimum HFP concentrations by the average HFP concentration measured at each sample time. Figure 4 shows that the inhomogeneities increased considerably from the small and medium sized FLSRs to the large FLSR with its increasingly complex obstructions. The increased design concentration was not sufficient to overcome the inhomogeneity effects, so a second nozzle tier was added, as suggested at HOTWC 2002 [4].

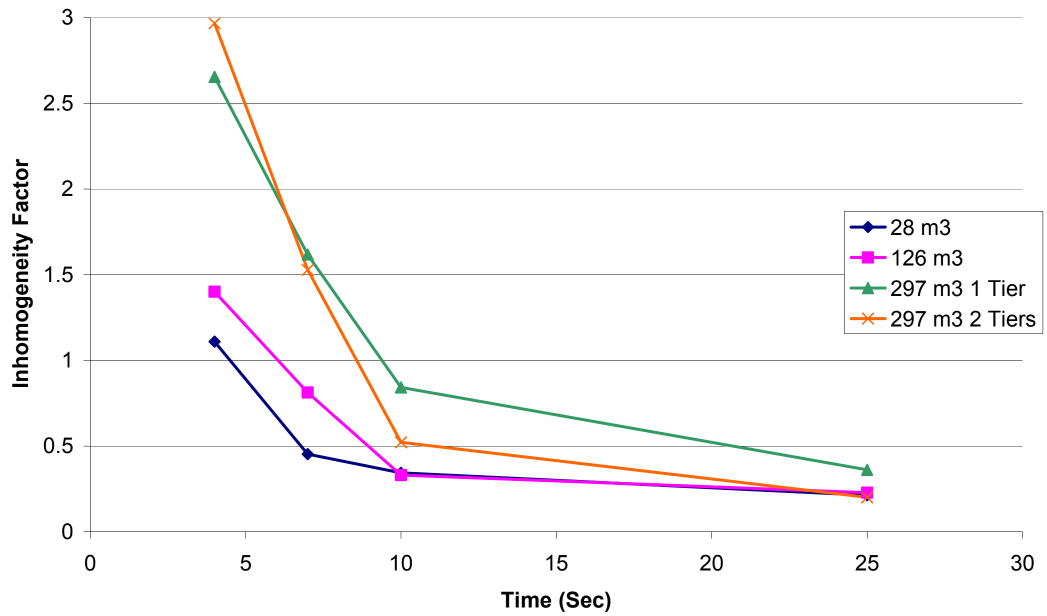

Figure 4. Inhomogeneity factor (difference between maximum HFP concentration and minimum HFP concentration normalized by the average HFP concentration of all gaseous grab samples at each collection time) as a function of time after HFP discharge for each FLSR. 297 m^3 compartment data given for single and double tier configurations.

The designed HFP two-tiered nozzle system incorporated the same four overhead nozzles 4.0 m from the deck used in tests M1, M2, M3, and M4 and added three nozzles along the center axis of the compartment at a height of 2.8 m from the deck. The agent design concentration was increased from 12.5 % to 13.0 % to increase agent concentration in the remaining low areas. The 13.0 % was distributed 10.0 % from high nozzles and 3.0 % from low nozzles. Due to budget and time limitations, only the lower tier nozzle closest to the fire was installed. The reasoning was that on the time scale of the fire extinguishment, well less than 30 seconds, the HFP discharged from that nozzle would not significantly migrate from the aft third of the compartment where the fire was located. Discharge testing of the single lower tier nozzle alone showed that the appropriate concentration was present at the fire location on that time scale.

Test M5 was conducted with the second nozzle tier. Figure 4 shows that the second tier decreased the inhomogeneity factor after 7 seconds bringing it closer to the values seen in the 28 m^3 and 126 m^3 compartments. This decrease led to improved HFP distribution with more areas having sufficient concentration faster. Figure 5 shows that the average HFP concentration near the fire reached the cup burner value faster with the second tier. This allowed for quicker fire extinguishment.

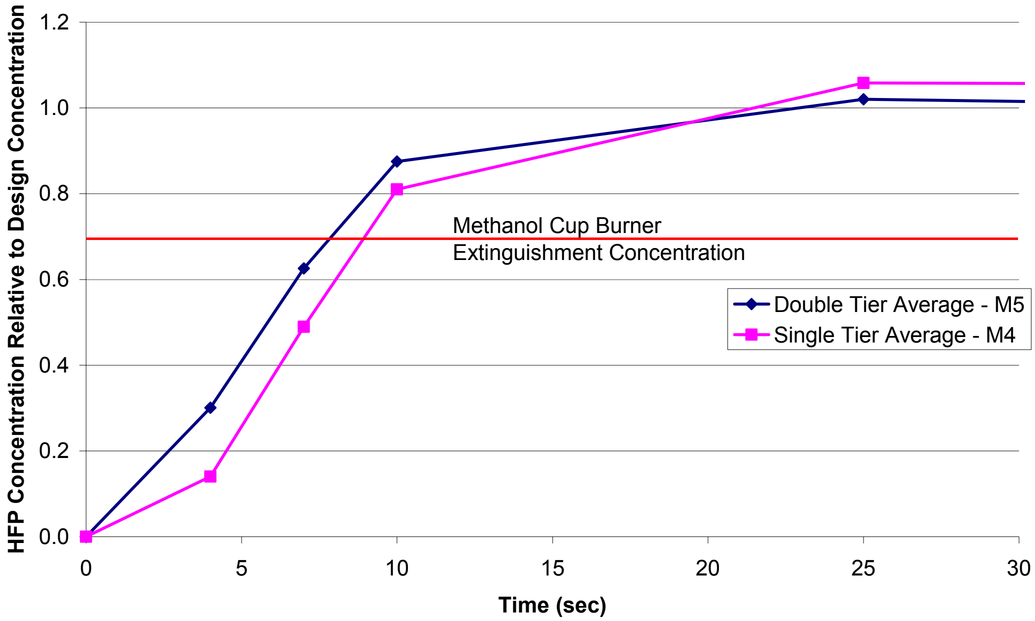

Figure 5. Comparison of HFP concentrations from double and single tier discharge systems scaled to 13.0 % design concentration. Methanol cup burner extinguishment concentration is 8.9 %, indicated relative to 13.0 % design concentration.

FIRE SIZE

Test M5 was conducted with a 400 kW fire. The 400 kW fire represents a challenge for the suppression system; smaller fires consume less oxygen and heat the atmosphere less making gaseous extinguishment more challenging. A larger 1900 kW fire is easier to extinguish, however there is a dramatic increase in HF concentrations. This is because the larger fires have more interaction area with the agent during suppression, allowing for more HFP to react/decompose. The change in peak HF concentration between a 400 kW fire, test M5, and a 1900 kW fire, test M6, with the increased HFP design concentration and two tiers documented the difference.

Results seen in Figure 6 show that the 1900 kW fire produced higher peak and long term HF. The instrument delay time for all the HF concentration measurements have not been included. The peak HF concentration near the 400 kW fire was 3,000 ppm; the peak HF concentration near the 1900 kW fire was above 18,000 ppm, the linearity limit of the instrument. The HF concentrations after 15 minutes in the 1900 kW fire were 2,000 ppm higher than in the 400 kW fire. The higher HF concentrations seen in Figure 7 and temperature increase seen in Figure 7 document the much greater re-entry hazard for the 1900 kW fire extinguished with HFP.

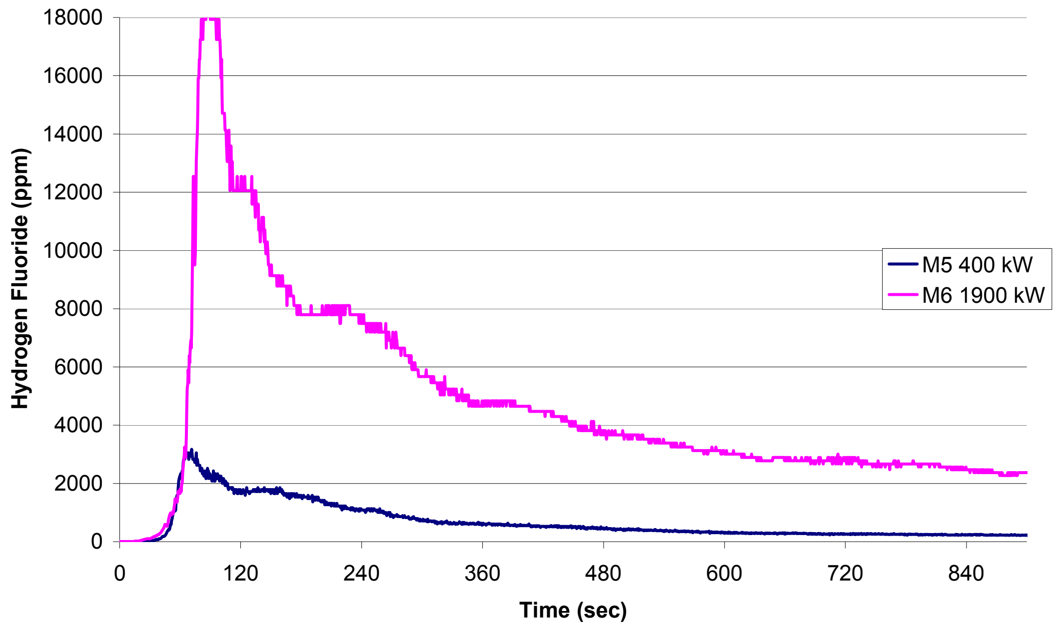

Figure 6. Comparison of HF concentration for two fire sizes measured near the fire, 1.7 m above the deck with a nominal 13.0% HFP design concentration. HFP discharge occurs at time zero, data not corrected for instrument delay time.

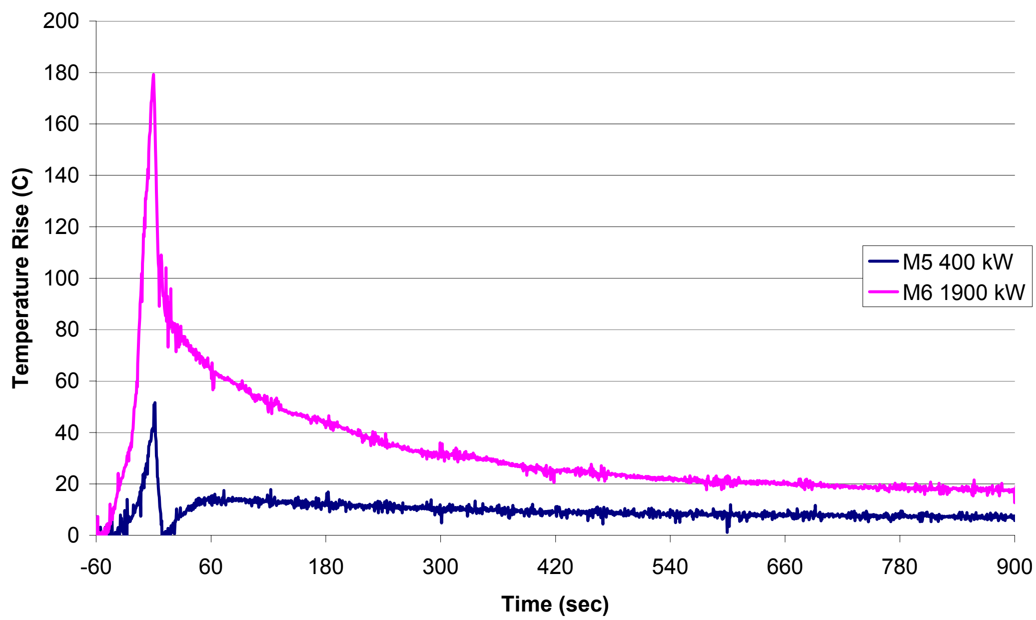

Figure 7. Comparison of temperature rise above initial temperature near the fire, 4.3 m above the deck. HFP discharge occurs at time zero. Steep temperature declines at discharge are from cooling by vaporizing HFP

FUEL TYPE

All the tests until this point involved methanol fires. The next step was to examine the suppression process and re-entry conditions from an n-heptane fire suppressed by HFP. This was done so that guidance could be established for FLSRs without alcohol fire threats. The cup burner value with HFP for methanol is 8.9 % and for n-heptane it is 6.6 % [7]. Scaling the design concentration for an n-heptane fire by the ratio of cup burner values, would lead to a design concentration of 9.6 %. However a higher value of 11.5 %, which is a factor of 0.74 above the cup burner instead of 0.46, as with the methanol tests was chosen. The cup burner is only a small diffusion flame burner used for reference in selecting the design concentration; other larger scale turbulent fire factors contribute. FLSRs without methanol could be protected by an HFP design concentration closer to 11.5 %, and by interpolating these results with previous machinery space fire suppression results guidance could be given for a variety of compartments and fire threats. Since the relative concentrations of HFP were higher for the n-heptane tests, less HF generation was expected.

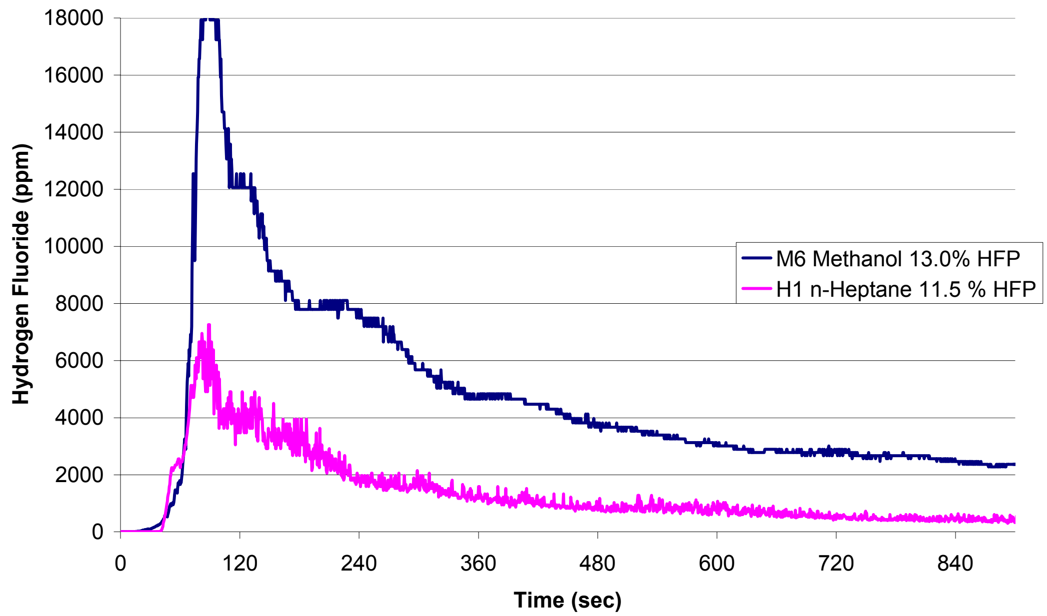

Figure 8. Comparison of HF concentration of methanol and n-heptane measured near the fire, 1.7 m above the deck with a nominal 13.0% HFP design concentration. HFP discharge occurs at time zero, data not corrected for instrument delay time.

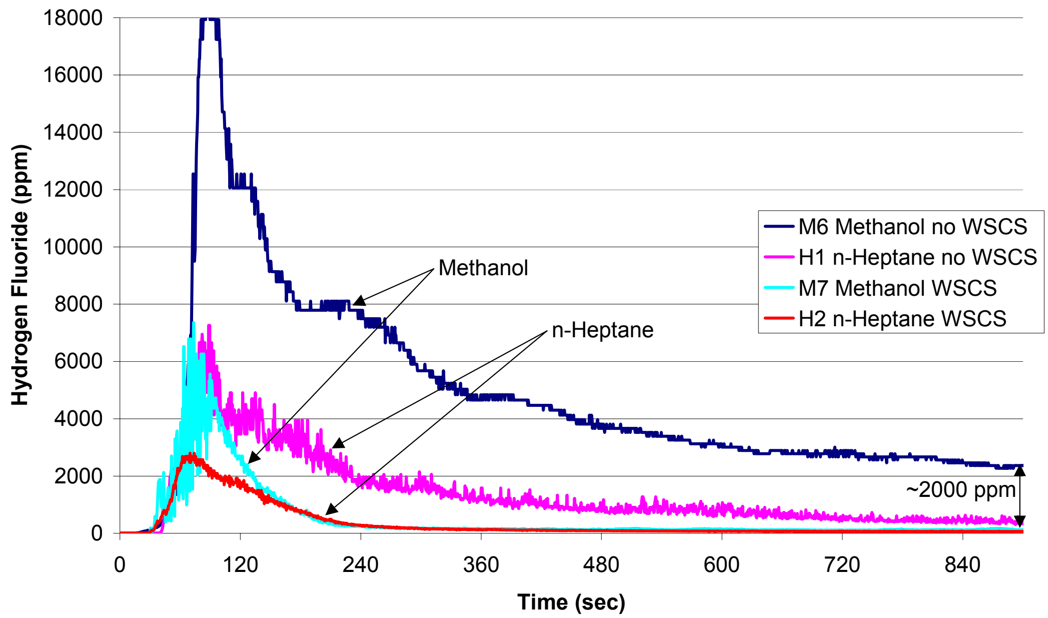

Figure 9. Comparison of HF concentration for methanol and n-heptane suppressed fires with and without a WSCS. HF measured near the fire, 1.7 m above the deck, with a nominal 13.0% HFP design concentration. HFP discharge occurs at time zero, data not corrected for instrument delay time.

Figure 8 shows that the n-heptane fire suppressions did produce lower peak and long term HF concentrations because of the higher HFP concentration relative to cup burner. A peak HF concentration above 18,000 ppm was measured for the methanol fire suppression test, while a peak of only 7,000 ppm was measured for the n-heptane fire suppression test. For the suppressed n-heptane fire, the HF concentration after 15 minutes was 400 ppm rather than 2,400 ppm seen in the methanol fire suppression. This was still significantly above the National Institute of Occupational Safety and Health's IDLH (immediate danger to life and health) value of 32 ppm for HF.

EFFECTS OF WSCS

Two tests have been conducted with a WSCS having a water pressure of 0.86 MPa: tests M7 and H2. These are identical to tests M6 and H1, respectively, except that a WSCS was employed to specifically reduce HF concentrations and improve re-entry conditions.

The three important effects of a WSCS on HF concentrations observed in these tests and shown in Figure 9 are a reduction in peak HF concentration by a factor of two to three, a rapid decrease of HF concentration within five minutes after HFP discharge, and significantly less HF at 15 minutes. For the methanol tests, the peak HF concentration near the fire was reduced from above 18,000 ppm to ~7,000 ppm and the HF concentration after 15 minutes was reduced from ~2,000 ppm to under 100 ppm. WSCS also reduced temperatures at re-entry by 20 C.

SUMMARY AND CONCLUSIONS

Table 4 summarizes results from the 297 m^3 compartment fire suppression tests to date. Tests M7 and H2 each used WSCS and each saw a significant reduction in HF concentrations after 15 minutes compared to the tests without the WSCS. The HFP design concentrations listed for tests M5, M6, M7, H1, and H2 were adjusted to simulate discharge from all three lower tier nozzles.

Table 4. Results Matrix

Test	*Fuel Type*	*Fire Size (kW)*	*Location*	*HFP*	*Peak Suppression HF (ppm)*		*15 Minute HF (ppm)*	
					*Max**	*Ave*†	*Max**	*Ave*†
M1	Methanol	400	Center	11.5%	1400	700	50	25
M2	Methanol	400	Corner	11.4%	>12000	4200	3300	1200
M3	Methanol	400	Corner	10.7%	9000	2500	400	250
M4	Methanol	400	Corner	12.3%	>12000	4300	950	450
M5	Methanol	400	Corner	12.9%	>18000	6000	1400	410
M6	Methanol	1900	Corner	13.2%	20000	12000	2800	1400
M7‡	Methanol	1900	Corner	13.1%	>18000	7500	150	55
H1	n-Heptane	1900	Corner	11.5%	>18000	8100	910	430
H2‡	n-Heptane	1900	Corner	11.5%	>18000	5500	140	40

Fire extinguishment and compartment re-entry are two concepts that must be addressed in the design of any fire suppression system for a Navy ship. Not exceeding HF concentrations that would have been present with a Halon 1301 fire extinguishment, including upon re-entry, is an essential element for halon replacement. For FLSRs and other compartments that will use a halon replacement total flooding clean agent, a WSCS has been shown to effectively reduce HF concentrations. Not only does a WSCS reduce the quantity of HF produced during the fire suppression process, but also it significantly reduces HF concentrations within five minutes. It may then be feasible to stop the WSCS water flow if water accumulation is a significant issue. Considering the low flow rates employed, water accumulation will typically not be an issue. In any event the WSCS should be employed during compartment re-entry to reduce reflash potential as entering the compartment will allow gaseous HFP to escape and fresh air to enter. A WSCS also provides a significant amount of compartment cooling which gaseous total flooding agents including Halon 1301, cannot provide. This helps reduce the high temperature of potential ignition sources and reduce the volatility of residual fuels.

Combining a WSCS with a hydrofluorocarbon gaseous agent such as HFP for total flooding fire suppression applications guarantees fire extinguishment, substantially decreases the HF concentrations and temperatures, and reduces the re-entry hazard the crew must face following a fire event.

*Maximum measured HF from the seven sample points
†Average measured HF from the seven sample points
‡Tests with WSCS

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