FLAMMABLE LIQUID STOREROOM 1: HALON 1301 REPLACEMENT TESTING RESULTS

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The United States Navy is investigating fixed fire extinguishing systems for future use in Flammable Liquid Storerooms (FLSR) where Halon 1301 total-flooding systems have been used. Results will be used as guidance in designing fire protection systems for the LPD-17, the first U.S. Navy ship to be constructed free of halon and CFCs, and for other future ships.

The two-phase program is conducted at the Naval Research Laboratory (NRL) Chesapeake Bay Detachment (CBD). Phase 1 tests were conducted in FLSR 1, a cubic test compartment with an internal volume of **28** m^3 (1000 ft^3) [1]. This test bed will be applicable to many smaller shipboard compartments. Phase 1 tests are serving **as** a learning process for designing and executing the FLSR Phase 2 program. Phase **2** tests will be conducted in a 280-m^3 (10,000-ft^3) compartment, which is a representative size for large shipboard FLSRs.

The agent evaluated was HFP (HFC-227ea), with baseline tests conducted with Halon 1301. FLSR background fire characterization was reported at HOTWC 97 **[2]**. This paper will address primarily the results of FLSR 1 agent discharge testing.

1.0 FLSR DESCRIPTION

FLSRs are unoccupied spaces where flammable liquids and combustible materials (such as drop cloths and oil soaked rags are stored). Shipboard FLSRs vary in size from less than 28 m^3 (1000 ft^3) on smaller ships to over 1100 m^3 (40,000 ft^3) on aircraft carriers. **A** survey in the Fleet early in the test program revealed a very diverse fuel population and loading **[3].** Fuels found in FLSRs included paints, paint thinners, alcohols, solvents, various Class **A** materials, drop cloths, oils (including linseed), paint brushes, and various acids. Compartment obstructions include shelving and fuel containers (from quart size to 55-gal drums). Types of storage containers are as diverse as the fuels, ranging from military specification to commercial off-the-shelf containers, including glass containers. To mitigate the fire threat from alcohol fuels, the Navy protocol is to isolate them in designated flammable liquid cabinets within the FLSRs.

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2.0 SUPPRESSION AGENT DESIGN CONCENTRATION

The prime agent evaluated during the FLSR 1 test program was HFP. The NRL Cup Burner was used to determine extinction concentrations (Table 1) for HFP and Halon 1301 for n-heptane, methanol, and the 80-20 methanol - n-heptane mixture (see 3.0) used in FLSR 1 testing [4].

Table 1. NRL Cup-Burner Extinction Concentrations."

Fuel	HFP cup burner (% v/v)	Halon 1301 (% v/v)
heptane	6.6	3.1
methanol	8.9	6.3
80% methanol, 20 % heptane	8.3	5.8

[a] References 4 and 5

For FLSRs, the **US** Navy design concentration for Halon 1301 total-flooding fire suppression systems is 5.0% (by volume at 10 "C) to 7.0% (at 66 °C). NFPA 12A, Section 3-4.1.2 also lists a minimum design concentration of 5.0% for "fires involving several flammable liquids and gases" [6]. The preliminary HFP design concentration for FLSRs is 11.5% to 12.0% at 20 "C. The overall system safety margin above cup burner can only be computed for specific fuels (with known cup-burner extinction concentrations). The evaluation of candidate HFP design concentrations **is** based on the analysis of possible fire threats within shipboard FLSRs and the selection of fire scenarios, which provide the greatest challenge to the extinguishment capabilities of a suppression system.

3.0 FIRE THREAT

Unoccupied FLSRs pose a very different fire threat compared to manned machinery spaces. The primary threat in FLSRs is a highly obstructed cascading 3-dimensional flammable liquid spill scenario, whereas in machinery spaces the threat is a pressurized Class B (liquid fuel, hydraulic fluid, or lubricating oil) *leak.* There were two variations of the baseline Class B flammable liquid fire. Early FLSR 1 tests were conducted with a cascading fire in the forward port corner of the compartment. The fuel leak was initiated at either the top or mid compartment level and was located within the shelving. This leak was fed via copper pipe from a 5-gallon storage container located outside in the upper aft port corner of the compartment. This fuel supply was controlled by a solenoid activated remotely from the control room via the Experiment Running Personal Computer (ERPC) (see 4.0), and a metering valve was used to set the fuel flow rate.

The fuel used was a mixture of 80% methanol, 20% n-heptane. Methanol, which is very common in FLSRs, was selected because of the high suppressant concentration required for extinguishment [4]. The methanol, which burns with a very pale blue flame, was sweetened with n-heptane primarily to enhance flame visibility. Cascading flow initiation time varied due to various preburn configurations, but was always shut down (by the ERPC) 30 sec after agent discharge initiation (Table 2a). Fuel flow rate and preburn duration both affect compartment oxygen concentration at agent discharge. Lower oxygen concentrations significantly enhance agent performance by making the fire easier to extinguish.

Later tests involved the above cascading fire at a lower fuel flow rate and a 0.09 m^2 (1 ft^2) pan on the deck containing the same fuel. The pan was added because the reduced flow rate significantly limited the amount of fuel reaching the deck. Furthermore, the pan fire affords different extinction characteristics than does the cascading fire. The volume of fuel in the pan was large enough to bum during the initial fire and act as a fuel source for reignition attempts. The initial ignition and reignition attempts were carried out using small electrical heating elements that were located near the fuel sources.

4.0 INSTRUMENTATION

Data acquisition and instrument and component control were performed by the Experiment Running Personal Computer (ERPC). The ERPC is a 150 **MHZ** Pentium system with LabVIEW Full Development System data acquisition software utilizing a National Instruments Modular interface. The ERPC collected data from the compartment on over 350 data acquisition channels and at frequencies from 1 Hz to 100 Hz. A brief overview of the instrumentation used is listed below. For a more detailed description of the instruments used in FLSR 1 testing and for specific instrument locations, please refer to "Test Plan for Flammable Liquid Storerooms: Halon Replacement Testing-Phase 1," 5 Mar 1997 [7].

- One Fourier Transform Infrared (FTIR) unit, with its own data acquisition and control system.
- Continuous gas sampling at four locations, each connected to different paramagnetic and infrared analyzers to determine O_2, CO_2, CO, and agent concentration.
- Grab sampling at six locations, conducted at specific time intervals, to collect gas samples for post- test analysis, using gas Chromatography.
- Over **40** thermocouples (TC) to measure compartment air and surface temperatures along thermocouple trees, shelving, telltale, and fire locations.
- Continuous Acid Analyzers (CAA) located within the compartment at varying heights and positions to obtain continuous readings of halide acid gas production via an ion specific electrode.
- Pressure transducers measuring discharge system pressure and compartment pressure.
- Agent discharge system temperature probes to characterize agent two phase flow.
- Optical Density Meters (ODM) at **four** heights to measure smoke production.
- Thermocouples at agent and acid grab locations to measure temperatures at which samples were taken.
- Four video cameras (two visible, two infrared) to monitor and record the fire, fire suppression, agent discharge, and fire reignition.
- Temperature and relative humidity measurements by a humidity probe.
- Oxygen concentration via a solid state oxygen mole fraction analyzer.

5.0 BASELINE TEST DESCRIPTION

Table 2a indicates the sequence of events for the baseline fire suppression. Table 2b contrasts the test parameters and sequence as used in **FLSR** 1 testing with the Navy protocol used in the LPD-17. The baseline suppression test used an HFP design concentration of **11.5%.** The prebum duration (time from fire ignition to agent discharge) was 2 min. Ventilation shutdown was initiated **30** sec prior to agent discharge. Compartment ventilation was activated 15 min

Table 2a. Test Sequence of Events for Baseline Fire Suppression.

Time (min:sec) t = 0 @ agent discharge	Event
-5:00	Ventilation activation
-2:00	Fuel "leak" initiation
-2:00 (-1:30)	Fuel ignition (delayed ignition will yield a larger fire, initially)
Variable	"Detection" can be determined using detectors or thermocouple simulation
-0:30	Secure fan motors
-0:30	Close ventilation dampers
0:00	Discharge agent
0:30	Secure fuel
5:00, 10:00, 15:00	Reignition attempts for cascading fire
Continuous	Reignition attempts for pan fire
15:00	Ventilation activation
16:00, 17:00, 18:00	Reignition attempts for cascading fire every minute thereafter until failure

Table 2h. Comparison of FLSR 1 Test Parameters and Navy Damage Control Protocol.

Event	Event Initiation/Duration (min:sec)	
	CBD FLSR 1	Shipboard (LPD-17) Scenario
Open Dampers	At test initiation	Dampers are normally open
Initiate Fan Motors	At test initiation	Fans are normally on
Fuel Leak Initiation	Nominal time	Nominal time
Fuel Ignition by Heated Element	Variable (Prolonged ignition will yield **a** larger fire, initially)	Variable: Depends on *leak* and ignition source
"Detection"	Can be determined using LPD-17 detectors or TC simulation	Variable: Depends on fire and detector
Damage Control (DC) Central response: Time until dispatcher identifies fire in FLSR and activates the system	Variable: Shorter times will result in a tougher fire to suppress (less O_2 depletion)	Variable (estimated): 0:15-3:00
Egress/Ventilation Delay Initiation	0:25 (minimum requirement)	0:30-1:00
Secure Fan Motors	~0:05	0:30-1:00
Close Dampers	0:20	
Initiate Agent Discharge	Agent discharged	Variable (see DC-Central Response)

after agent discharge. Reignition attempts were conducted during the 15-min hold time and during venting. **FLSR** 1 test sequence and parameters were modeled after a typical LPD-17 fire scenario. ***An*** in-shelf cascading flammable liquid prebum was used to test the capabilities of the extinguishing system. An in-shelf prebum provides the worst case scenario by creating obstructions that would disrupt homogeneous agent distribution, hence, limiting the extinguishing capabilities of the agent.

6.0 TEST MATRIX

The test matrix included 67 background fires (no suppression agent), 7 cold discharges (no fire), and 22 HFP fire suppression tests. Six Halon 1301 suppressions were conducted for reference. **A** total of 102 tests were conducted in 13 test series. Test matrix variables included agent design concentration, fuel type, fire size, number and location of agent discharge nozzles, and compartment leakage area.

7.0 TEST RESULTS

7.1 Effect of HFP Design Concentration on Extinguishment Time

HFP suppression tests were conducted at varied design concentrations to determine which design concentration affords the most efficient suppression and the least number of hazardous byproducts. Table 3 gives the fire out times for four HFP design concentrations tested.

Table **3.** Fire Extinguishment Times for Various HFP Design Concentrations.

HFP Design Concentration (%)		Fire Extinguishment Times	
		Pan (min:sec)	Cascading (min:sec)
09.0	(Test 5.1)	00:05	00:03
10.8	(Test 5.3)	00:04	00:02
11.1	(Test *5.5)*	00:06	00:03
11.5	(Test **5.4–2)**	00:06	00:02

The fire extinguishment times in Table 3 illustrate that each HFP design concentration evaluated had a comparable fire out time. The listed fire-out times are for fires as seen by the IR cameras pointed at the fire location. An error of one to two seconds is associated with this method and originates from the resolution of the IR camera, coupled with occasional **flashing** and image bleeding. Therefore, the small variability in the fire out times is within the error associated with the fire out determination technique for obstructed fires.

However, these fire-out times are not wholly representative of the extinguishing capabilities of HFP. Oxygen depletion becomes a critical factor in fire suppression for small, tight compartments such as FLSR 1. Oxygen levels, initially limited by the size of the small compartment, are further depleted during the prebum. While a shorter preburn period would give a more challenging suppression system test, the longer times are representative of expected shipboard scenarios. Furthermore, the very energetic agent discharge entrains oxygen depleted air from the overhead and distributes it throughout the compartment. Thus, any fire in the compartment at agent discharge is inhibited by oxygen depletion and easily extinguished. In **a** larger compartment, such as those seen in the Fleet and in FLSR 2, the effects of oxygen depletion would not be as pronounced, and longer extinguishment times would be expected. Oxygen concentration stratification, while present in FLSR 1, is expected to be even more pronounced in FLSR 2.

7.2 Effect of HFP Design Concentration on Acid Production

Most fluorinated suppressant agents, including HFP, will decompose under fire conditions. The degree of decomposition is determined by the amount of agent near the high temperature source and in the flame sheet. This decomposition produces both hydrogen fluoride (HF) and carbonyl fluoride (CF_2O), which in turn will hydrolyze to form HF. Acid production during fire suppression is a transient effect and depends on the agent/fire interaction during suppression. For similar compartment fires, a large agent design concentration will typically have more agent in the vicinity of the fire but will suppress the fire faster, allowing less time for the agent and fire to interact. Conversely, a smaller agent concentration reduces the available agent but lengthens the time for which agent and flame are in contact, thus, producing more hydrogen fluoride. These acid concentrations were measured via both continuous acid analyzers (CAA) and **FTIR** (see 4.0 Instrumentation, for further information on CAA and **FTIR** locations and operation) [8]. The continuous acid analyzers entrain compartment gases into an aqueous solution and detect the concentration of a halide anion through an ion specific electrode. Due to its solubility and reactivity in the CAA aqueous solution, CF_2O is detected as it generates two fluoride anions per molecule. Thus, when comparing CAA data to FTIR data, which separates HF and CF_2O values, it is necessary to add twice the **FTIR** CF_2O value to the **FTIR** HF value [4]. Table 4 illustrates the effect agent design concentration has on the production of HF.

Table 4. Peak HF Concentrations at Extinguishment for Various HFP Design Concentrations.

HFP Design	**FTIR** Measurements[a]	CAA Measurements (multiple locations)	
Concentration (%)	Peak HF (ppm)	Highest Peak HF (ppm)	Lowest Peak HF (ppm)
09.0 (Test **5.1)**	8,400	33,000	750
10.8 (Test 5.3)	2,600	1,100	50
11.1 (Test 5.5)	3,000	1,600	200
11.5 (Test 12.1)	2,500[b]	3,100[b]	400

[a] Reference 8

[b] CAA and FTIR sampling locations are common in this case.

Larger HFP design concentrations should produce smaller HF values for a fire suppression test [9]. This trend is supported by **FTIR** data [8], taken at one point within the compartment. FTIR data show that a 9.0% HFP suppression produced acid levels of 8400 parts per million (ppm) hy volume at fire out. Higher design concentrations of 10.8% and 11.1% HFP produced HF concentrations of 2600 ppm HF and 2950 ppm HF, respectively. The HFP concentration at 11.5% produced HF levels of 2450 ppm HF by volume. CAA data are also available to profile the compartment HF values at fire out. These data highlight the range of values between different sampling locations showing the degree of inhomogeneity within the compartment.

The wide range of data illustrates the large compartment inhomogeneities and the difficulty in assessing the acid production during a halon replacement suppression. Typically, only the peak HF values, measured at one point, have been reported in the literature and little information is available on the expected range of HF production or the decay of HF in gaseous form. The wide range of values seen in these tests was also observed in tests conducted aboard the **ex-USS** SHADWELL, where large compartment HF inhomogeneities were noted [2,3]. The combination of these factors makes the clear interpretation of HF data difficult at best. Although the HF peaks at fire out were in the thousands of ppm, in most cases after the 15-min hold time the HF levels decreased to the low hundreds pprn range, hence significantly reducing the threat.

Replicate tests can have significant variations. Due to the variable nature of the fuel flow over the obstacles, significant differences in fire burning characteristics may result. An example is illustrated in the following comparison. A comparison of two HFP suppression tests, at the same design concentrations, revealed discontinuities of the amount of acid produced hy each test. Up to the point of ventilation the tests parameters are identical. The calculations for the power output of both fires, using the recorded bum times and assuming complete stoichiometric combustion, show that the fires **are** comparable. The measured HF concentrations are in Table **5.**

Table **5.** HF Peaks at Extinguishment for 11.5% HFP Design Concentration.

Test Identification	FTIR Measurements Peak HF (ppm)	CAA Measurements (multiple locations) Highest Peak HF (pprn)	Lowest Peak HF (ppm)
A (Test 12.1)	2500"	3100[a]	400
B (Test 8.1)	7200	28000	2100

[a] CAA and FTIR sampling locations are common in this case.

The explanation for the large difference in acid production values is developed through analysis of the measured temperatures and oxygen concentrations. The oxygen concentrations for a baseline fire for these tests have a range between 11.0-14.0% for mid and high height levels and 17.0-18.0% for **low** levels, just prior to agent discharge. The measured oxygen concentrations for Test A were between 13.0% and 16.0% for all compartment levels. The measured oxygen concentrations for Test B were between 16.5% and 19.0% for all compartment levels. The temperatures recorded by thermocouples located near the fire are similar except for two locations, **30** in and 60 in above the deck. At these locations, Test A experienced temperatures 45 °C and 85 "C higher respectively than Test B. This analysis indicates that the fire in test A was burning hotter and consuming more oxygen, which translates into a more easily extinguished fire. Since this fire would be extinguished more easily, the amount of HF that would be produced would be greatly reduced, as indicated by the data. Furthermore, it indicated that the fire in Test B was weaker than the typical baseline fire. The less intense fire, while successfully extinguished, generated very large amounts of HF. **As** was previously discussed, the harder a fire is to extinguish and the longer the agent is exposed to the fire, the more acid that is produced. The above analysis demonstrates the need to monitor and evaluate critical test parameters so that comparability of other tests can be verified. This analysis also illustrates the very large range of HF that can be expected from quasi identical test scenarios.

7.3 Effects of Fire Size on HFP Performance

Larger fires in the small compartment were easily extinguished due to the critical oxygen depletion of the larger fire and the increase in effective agent concentrations brought on by the increased compartment temperatures. In a larger compartment, larger, less inhibited fires may be staged with lower oxygen depletion (higher oxygen concentrations). Thus, fire suppressions in FLSR 2 will be more difficult and will challenge the extinguishing capability of HFP. The FLSR 2 results will better quantify the behavior of fires in the larger compartments existing in the Fleet.

7.4 Effects of Mockups on HFP Performance

The presence of mockups can influence compartment conditions in several ways. Mockups reduce the floodable volume of the compartment, thus increasing the effective agent design concentration. However, mockups can affect agent distribution, resulting in agent and oxygen inhomogeneities. In the case of very obstructed compartments, the inhomogeneities make the agent concentration very location specific. The determination of a single fire out time for a three-dimensional, cascading fire becomes very difficult and uncertain.

7.5 Other Design Considerations

The presence of a significant leakage area, in any size compartment, is detrimental to the inerting capability of the compartment mixture. This is evident in those scenarios affording particularly large openings, such as an open door. During the open door scenario, the massive leakage of agent and infiltration of air resulted in a loss of reignition protection 1-min, 31 sec **after** agent discharge initiation, as compared to reignition for other scenarios over 15 min after discharge initiation. These effects are less pronounced in scenarios with tighter compartments, but still create compartment mixtures that allow reignition earlier than in baseline tests with no leakage, Acid production levels are also highly sensitive to the size of a leakage area, with considerably high acid concentrations resulting from the open door scenario as compared with an open ventilation damper scenario, which produced much larger concentrations than the baseline scenario. The effects of leakage, i.e., increased acid production, lower actual agent concentration, and higher oxygen concentration, are a function of the ratio of leakage area to compartment size.

As a halon replacement, HFP must provide fire protection commensurate to Halon 1301. Thus, baseline Halon 1301 fire suppressions of varying design concentration were performed to provide a benchmark by which HFP suppression would be compared.

Although oxygen depletion aided halon at design concentrations below the cup burner to extinguish the fires, increased leakage area resulted in loss of protection. A Halon 1301 test with intake and exhaust dampers open was conducted to simulate a damper closure failure. The test, conducted at 5.1% Halon 1301 design concentration, did not extinguish the pan fire.

For similar design concentrations, relative to their respective cup-burner extinction concentrations, an HFP fire suppression generated significantly more halide acid gas than did a comparable Halon 1301 fire suppression [9]. This is due to the less efficient suppression and greater agent consumption exhibited by HFP, in comparison with the highly effective catalytic action of Halon 1301 (Table *6)*.

Table *6*. Peak HF and HBr Readings at Fire Out.

Agent Type		FTIR Measurements		CAA Measurements	
		HF Peak (ppm)	HBr Peak (ppm)	Highest HF Peak (ppm)	Lowest HF Peak (ppm)
HFP	(Test 12.1)	2500	Not Produced	3200[a]	400
Halon 1301	(Test 5.12)	1000	400	<100	<100

[a] CAA and FTIR sampling locations are common in this case.

8.0 CONCLUSIONS

Previous Intermediate Scale (ISC) and Real Scale (RSC) testing has shown that agent, oxygen, and HF acid inhomogeneities [10] of comparable size to those seen in FLSR 1 exist in small compartments. However, the rapid fire-out times experienced in FLSR 1 testing may not be representative of the fire-out times characteristic of larger compartments due to the larger expected inhomogeneities in agent and oxygen concentrations. FLSR 2 testing is designed to address these questions.

Real scale tests with explicit (e.g., design concentration, fuel flow rate) and implicit (e.g., oxygen concentration, compartment temperature) variables must have extensive monitoring of key variables to ensure the range of validity of comparisons between different tests.

Other serious issues, evaluated during FLSR 1 testing, that are not addressed in this report include reignition, compartment reclamation, and HFP performance enhancement through the use of the NRL Water Spray Cooling System.

Due to oxygen depletion effects in small tight compartments, fires **are** significantly inhibited and easy to extinguish. The WSCS (and other water suppression systems) may be sufficient for fire suppression in small Compartments. These conclusions are not expected to be valid for large compartments due to the greater amount of oxygen that will be available for combustion. Even with successful extinction HF concentrations can be very high, although they can decrease significantly during hold time.

The test conducted with Halon 1301 with the dampers open illustrate the performance limitations of a very efficient agent. The replacement agent systems with their lower safety margins need to be optimized prior to being implemented.

9.0 ACKNOWLEDGMENTS

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