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Real Scale Halon Replacement Testing Aboard the ex-USS SHADWELL: Post Fire Suppression Compartment Characterization

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INTRODUCTION

During initial real scale Halon 1301 replacement testing (Phase 1) aboard the ex-USS SHADWELL,[1] tests were conducted to identify the clean replacement agent of choice for U.S. Navy shipboard machinery spaces.[2-4] The primary threat in these spaces is pressurized flammable fluids. The characteristics of the candidate replacement agents such as fire suppression, reignition prevention effectiveness. agent pipe flow discharge properties, agent distribution, reaction/decomposition products, materials corrosivity, and materials compatibility were examined. Phase 1 testing also examined the effects on fire suppression and hydrogen fluoride (HF) production by variations in agent discharge rate and design concentration, fire size, fuel type, and nozzle geometry. The clean agent recommended to the Naval Sea Systems Command (NAVSEASYSCOM) for use on new construction U.S. Navy ships is heptafluoropropane, HFP, (HFC-227ea, C_3F_7H, manufactured by Great Lakes Chemical Corporation as FM-200).[5]

The test compartment's floodable volume was reduced from 755m^3 (26,600ft^3) to 370m^3 (13,000ft^3) during Phase 2 testing by isolating and testing in one half the Phase 1 compartment. Parameters such as fire extinguishment, oxygen depletion. agent concentration inhomogeneities, thermal stratification, and HF production were examined as they were in Phase 1 testing, the results of which have been previously reported.[6,7] During this test phase, however, a more detailed study of the post fire suppression compartment characteristics was performed.

Phase 2 testing was conducted according to the Test Plan.[8,9] Phase 2 testing had four main objectives. First, to determine the optimum post-fire suppression firefighting team reentry and hold times. The hold time is the period between agent discharge and subsequent ventilation. Second, to evaluate the use of an NRL innovation, a Water Spray Cooling System (WSCS), to enhance fire extinguishment, suppress reignition potential, reduce HF production, mitigate

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existent gas phase HF, and quickly reduce compartment temperatures. Third, to determine if modified Navy agent delivery hardware (tank valves, check valves, and flexible hoses) can provide a more rapid agent discharge. Fourth, determine the effects of doubling the number of agent discharge nozzles on agent distribution. This paper addresses the first objective. The remaining objectives are addressed in associated papers at this conference.".[11]

Little quantitative information currently exists regarding post-fire suppression compartment reentry (by the firefighting team), desmoking, and venting for Halon 1301 systems. The reduced safety margins of the replacement agents and increased HF threat necessitate such testing. Chapter 555, Section **6,** of the U.S. Naval Ships' Technical Manual (NSTM) is limited to Halon 1301 regarding halogenated total flooding fire suppression agents in machinery space applications.[12] If HFP is ultimately used in US. Navy surface ship machinery total flooding fire suppression systems, the current testing will provide guidance for future NSTM revisions regarding reentry and venting.

Compartment reentry is the most critical part of the firefighting event, and potentially the most dangerous.[12] If the machinery space fire has been extinguished by Halon 1301, reentry should not be attempted for at least 15 minutes after agent discharge. Desmoking with the installed ventilation system proceeds when the risk of reignition has been minimized by the reentry team. Phase 2 testing explores the sequence with which reentry and ventilation proceeds, and means of decreasing reflash potential. Current Fleet doctrine is that the firefighting team enters first, followed by reinitiation of ventilation when considered appropriate.

During Phase 2 testing, a 15 hold time was most often used, although some tests were conducted with ***5*** minute or 30 minute hold times. Reentry in these tests occurred only after compartment ventilation had been restarted. Reignition attempts were performed at one minute intervals until a successful reignition occurred during venting.

COMPARTMENT

The test compartment was located between Frames 22 and 29 on the upper and lower levels of the 4" deck. The approximate dimensions were 8.5m (28ft) forward and aft, and 6.1m (20ft) high from the keel to the overhead of the upper level. The compartment's width was 8.5m (28ft) at Frame 29 narrowing to 7.0m (23ft) at Frame 22. The test compartment's floodable volume was reduced from 755m^3 (26,600ft^3) to 370m^3 (13,000ft^3) during Phase 2 testing by isolating and testing in one half the Phase 1 compartment. Four agent discharge systems were installed for these tests. One discharge system was for HFP with four discharge nozzles, two on each of the upper and lower levels. A second discharge system was installed for benchmark tests using Halon 1301 with two nozzles on each of the upper and lower levels. The third discharge system tested modified discharge hardware using the 4-nozzle HFP piping. The fourth discharge system was used to investigate the effect of doubling the number of agent discharge nozzles. This discharge system was used with HFP only and was divided into four nozzles in both the upper and lower levels. Details of the agent distribution systems are presented in a separate paper at this conference." An isometric diagram of the compartment is shown in Figure 1. Since the compartment dimensions changed between Phases 1 and 2. there was concern that agent distribution characteristics also changed. Figure 2 shows the agent concentration measured at the primary fire threat location, Fire 1. The measurements were made using a grab sampling technique with subsequent gas chromatographic analyses. The concentrations are normalized to correct for differences in the design concentration used in each test. The sampling times were not the same in each test, so there are points not common to both concentration profiles. The concentration profiles for the two tests are similar.

INSTRUMENTATION

The test compartment and associated systems were highly instrumented with both physical and chemical measuring devices. The agent discharge system was instrumented to measure pressure, temperature, and mass loss from one cylinder at the agent discharge cylinder manifold. Pressure transducers were located at one cylinder valve, one check valve, the agent discharge manifold, the reducing elbow, and at each of the discharge nozzles. Thermocouples were installed in the same locations. Mass loss during agent discharge was measured by a load cell transducer. The WSCS system was equipped with an ultrasonic flow meter and a single thermocouple. Temperature measurements were made throughout the space and at each fire and telltale. Two transducers were used to measure compartment pressure in each test. **A** decibel meter and a microphone were used to measure and record noise levels during agent discharge. Complementary techniques were used to measure gas phase concentrations of the various species of interest. The permanent gases CO, CO_2, and O_2 were measured by both continuous flow analyzers, and intermittent grab sampling with subsequent gas chromatographic analyses. Agent concentration was measured by continuous flow analyzers, grab sample/gas chromatography (GC), and by a Fourier Transform Infrared Spectrometer (FTIR). Both HF and HBr (generated during Halon 1301 tests) were measured by continuous flow electrochemical cell halogen acid gas analyzers," grab sample/ion chromatography (IC). and FTIR. Each test was videotaped using both visible and infrared wavelength cameras.

A UNIX-based Massachusetts Computer Corporation (MASSCOMP) computer, Model 5600, acquired data from fire, telltale, compartment, WSCS and reignition TCs, continuous analyzers, and WSCS flow transducers. An MS/DOS-based Experiment Running PC (ERPC). with LabVIEW Full Development data acquisition software, was used for both data acquisition and instrumentation / activation control. The ERPC acquired data from air flow measurement devices, compartment and agent discharge system pressure transducers. agent discharge system TCs, the decibel meter, and the agent discharge bottle load cells. The ERPC also activated the agent discharge system, and both agent and acid grab sample solenoids.

COMPARTMENT FIRES

The fire specifications are listed in Table 1. Three simultaneous test fires and 17 telltale fires were ignited in the compartment. Fire 1. which was the largest fire threat. was a combination pan and spray fire. Fires 2 and 4 were low flow rate spray fires that may have also contained some class **A** combustible material. Fire 3. which was used during Phase 1 testing," was not used due to compartment modifications that limited access and personnel safety at its location. Naval Distillate F-76 was used as the test fire fuel. The telltales were fueled with n-heptane.

Table 1: Fire Specifications

Fire	Pan Size (m x m)	Pan **Area** (m^2)	Pan Fire Size	F-76 Diesel Spray Flow Rate (L/m)	F-76 Diesel Spray Fire Size (MW)
1	**2.44 X** 0.91	*2 23*	4 5 [a]	**5.7 -** 7.9	3.3 - **4.7** [a]
2		' -		0.7 - 0.8	0.09 - 0.1
4				0.7 - 0.8	0.09 - 0.1
TT	6.4cm diam	0.0032	0.003	**N.A.** [b]	**N.A.** [b]

Table 2: Test Series Overview

Series No.	Agent	Discharge System	Number of Nozzles	Fires	WSCS Application			Hold Time (time prior to venting) (min)
					Before Agent Discharge	During Agent Discharge	Prior/ During Venting	
1	No	No	No	Yes	---	---	No	---
2	HFP	Standard Navy	4, 8	No	No	No	No	30
3	HFP	Standard Navy	4	Yes	No	No	No	5, 15, 3(
4	HFP	Standard Navy	4	Yes	No	Yes	Yes/No	15
5	HFP	Standard Navy	4	Yes	Yes	Yes	Yes/No	15
6	Halon 1301	Standard Navy	4	Yes	Yes/No	Yes/No	Yes/No	15
7	HFP	Modified [a]	4	No	No	No	No	30

a. Larger cylinder valve. flexible hose. and check valve compared to standard U.S. Navy hardware.

The sequence with which critical events occurred during the progression of a test is given in Table **3.** The fire pan and spray ignition times are approximate values and are within 10 seconds of the reported value. The Fire 1 pan was manually ignited by the safety team before exiting the space. Fires 1, 2, and 4 sprays were remotely ignited when the safety team had exited. Table **3** does not list the time at which the WSCS system was activated, which varied between tests. Details of WSCS activation variables can be found in an associated paper at this conference.[10]

Compartment supply ventilation (limited protection supply system - LPSS) was $340 m^3$/min (12000cfm) split 1/3 and 2/3 between the upper and lower levels. respectively Compartment exhaust ventilation (limited protection exhaust system - LPES) was also in the overhead of the upper level with a ventilation rate of $340 m^3$/min (12000cfm). The acid stack (elevated stack exhaust - ESE) ventilation system was located in the overhead of the upper level and had an exhaust rate of $140 m^3$/min (5000cfm). At the start of each test all three ventilation systems are in operation.

Table 3: Test Sequence

Part 1 Tests 3.1 - 3.3		Part 2 Tests 3.4 - 3.6, 6.1	
Time (min:sec)	Event	Time (min:sec)	Event
- 5:00	Fire 1 pan fire ignited	- 2:30	Fire 1 pan fire ignited
- 3:00	Spray fires (1,2,4) ignited	- 2:15	Spray fires (1,2,4) ignited
-1:30	ERPC started	-1:30	ERPC started
- 1:10	LPSS, LPES and ESE ventilation secured	-1:00	LPSS, LPES and ESE ventilation secured
-1:00	Ventilation dampers closed	- 0:45	Ventilation dampers closed
0:00	Agent discharge	0:00	Agent discharge
15:00 (3.1, 3.2) 30:00 (3.3)	ESE ventilation initiated	5:00 (3.4) 15:00 (3.5, 3.6, 6.1)	ESE ventilation initiated
20:00 (3.1, 3.2) 35:00 (3.3)	LPSS, LPES ventilation initiated	10:00 (3.4) 20:00 (3.5, 3.6, 6.1)	LPSS, LPES ventilation initiated

FIRE EXTINGUISHMENT AND REIGNITION

Table 4 lists the extinguishment times for the compartment test fires in which WSCS was not activated. Extinguishment and reignition data for tests in which WSCS was used is reported in an associated paper at this conference.'" Fire out times and reignition were based on observation of IR videos. The fires were extinguished in every test conducted. Attempted reignition was done by impinging an F-76 fuel spray on an ignitor resistively heated to approximately 600°C. Reignition attempts started one minute after agent discharge and were attempted at one minute intervals until a reignition occurred during ESE venting. Reignitions were not attempted at Fire 1 in any test, nor were they attempted during ESE venting in tests **3.1** through **3.3.**

During part 1 of Phase 2 testing, in which tests **3.1** through **3.3** were conducted, longer preburn times were used. In addition, inadequate preburn supply ventilation occurred. The combined effect resulted in self extinguishment of Fire 4 (located in the overhead of the upper level) and facilitated extinguishment of Fires 1 and 2. The prebum time was shortened, and more adequate ventilation was supplied during subsequent tests.

HOLD TIME COMPARISON

a) Temperature - Figure **3** is a typical temperature profile from a test in which WSCS is not activated. The temperature in the compartment is approximately 25°C (77°F) at the start of the test. At -150 seconds, the time at which the pan fire is ignited (Fire 1), an immediate rise in Compartment temperature is observed. Fuel sprays at Fires 1, 2, and 4 are ignited approximately

15 seconds later. The temperature in the space rises until a quasi-steady state temperature is reached. This quasi-steady state temperature is maintained until compartment ventilation (LPSS, LPES, and ESE) is secured. The temperatures range from approximately 75°C (170°F) near the deck of the lower level to approximately 250°C (480°F) near the overhead of the upper level. After ventilation is secured the temperature in the space rises until agent discharge is initiated. The peak temperature at the overhead in the upper level is approximately 425°C (800°F). When agent discharge is initiated. a precipitous drop in compartment temperature occurs.

Test No.	Hold Time (min)	Fire 1		Fire 2		Fire 4	
		Fire Out (sec)	Reignition	Fire Out (sec)	Reignition	Fire Out (sec)	Reignition (min)[a]
3.1	15	7	N.A.[b]	Not Lit	Not Attempted	---[c]	Not Attempted
3.2	15	4	N.A.[b]	<8	No[d]	---[c]	No[d]
3.3	30	8	N.A.[b]	<8	No[d]	---[c]	No[d]
3.4	5	8	N.A.[b]	11	No	5	2
3.5	15	10	N.A.[b]	12	No	11	2
3.6	15	10	N.A.[b]	9	No	4	2
6.I	15	9	N.A.[b]	9	No	6	3

Compartment temperature is a critical parameter regarding reentry and compartment reclamation. Table 5 is a comparison of compartment temperatures measured at various heights during the 30 minute hold time test. The temperatures reported were measured at 5, 15, and 30 minutes after agent discharge. The flash point of Naval Distillate F-76 diesel fuel is specified to be 60°C (140°F) or above. Temperatures above the flash point increase the risk of reflash when the compartment is reentered or when ventilation is restarted. Securing the fuel source before exiting the space may not he possible. or unburned fuel may remain on hot decks and bulkhead surfaces, and an ignition source may still exist upon reentry. The NSTM, Chapter 555, states that the primary function of the reentry party is to extinguish the fire (if it has not been extinguished by the Halon 1301 discharge), ensure the source of the oil (fuel) is secured, and cool the space so ventilation may be started."

Table 5: Temperature vs. Hold Time

Height (m)	T (°C) @ 300s	ΔT (°C)	T (°C) @ 900s	ΔT (°C)	T (°C) @ 1800s
4.9	97	11	86	10	76
4.0	90	11	79	8	71
3.0	82	8	74	8	66
2.1	70	6	64	7	57
1.2	64	8	56	4	52
0.3	48	5	43	3	40

Little was gained in terms of temperature reduction when Compartment hold time was increased from the Fleet Doctrine specified minimum reentry time of fifteen minutes to thirty minutes. The temperature measured at the overhead decreased by 10°C (18°F) over that interval. The temperature reduction from five to fifteen minutes is also small compared to the temperature in the compartment at the onset of agent discharge. This does not mean that the compartment reentry time should be reduced from fifteen to five minutes. These temperature data are air temperatures and are specific to these test conditions. Hot deck surfaces may cause more fuel to evaporate increasing reflash risk. The reduction in temperature after fire suppression is dependent on the fire, intensity, and preburn time. The rate at which heat is dissipated (during the hold time), will decrease with longer preburn times and more intense fires due to higher deck, bulkhead, turbine enclosure, etc., temperatures.

b) Hydrogen Fluoride (HF) - Figure 4 is a typical HF concentration profile. The peak concentration is approximately 5000ppm. There is an exponential concentration decay beginning approximately 30 seconds after the maximum concentration is reached. The HF concentration decreases to approximately 2900ppm five minutes after agent discharge. The HF concentration further decreases to approximately 1400ppm in fifteen minutes. Hydrogen fluoride data is not available for the thirty minute hold time test, but would likely be between 500 and 800ppm based on the decay curve in Figure 4. During the Halon 1301 test, the peak HF concentration was approximately 1100ppm. The HF concentration decreased to approximately 300ppm five minutes after agent discharge, and 100ppm fifteen minutes after agent discharge. The higher HF values measured during HFP fire suppression, compared with Halon 1301, are consistent with previous studies.[4, 5, 15] These data indicate that the Fleet Doctrine compartment reentry time of 15 minutes may be too short unless techniques can be used to mitigate HF.

The Threshold Limit Value (TLV), established by the American Conference of Industrial Hygienists, is 3ppm. The Permissible Exposure Limits (PEL), established by OSHA and accepted by the U.S. Navy, is also 3ppm. These values are regarding inhalation toxicity, not percutaneous exposure. Although U.S. Navy shipboard firefighter's have inhalation protection, the Oxygen Breathing Apparatus **(OBA),** current U.S. Navy firefighter ensembles do not adequately protect from gas permeation and percutaneous HF exposure. The percutaneous effect of HF is not well known.

Compartment ventilation, provided it has not been destroyed in the fire incident, could be initiated before compartment reentry to exhaust the high levels of HF. This approach, however, may result in an unwanted reignition if fuel is still present and an ignition source exists. If the fuel source had not been secured before compartment evacuation, and if an ignition source still exists, the compartment's total flooding fire protection will be lost as agent is exhausted and air admitted. Data in Table 4 show that reignitions can occur within three minutes of ventilation system activation. Alternate techniques to mitigate post-fire suppression HF, or reduce initial HF generation should be explored. The innovative WSCS technique shows promise in accomplishing both tasks.[10]

SUMMARY

Several Series of tests were conducted for post-fire suppression compartment characterization. In all of the tests conducted, the compartment test fires were extinguished. Reignitions did not occur before ventilation initiation in any of the tests. Reignitions did occur between two and three minutes after ESE ventilation initiation. The current Fleet Doctrine compartment reentry time is sufficient regarding temperature. based on these test conditions, but may be too short regarding HF concentration during HFP fire suppression. The fifteen minute reentry time is sufficient after Halon 1301 fire suppression under these test conditions, The optimum hold time before ventilation initiation is specific to each fire incident. Initiation of ventilation before reentry can lead to unwanted reignition and loss of total flooding fire protection. Techniques to expedite ventilation. a primary goal after reentry. must be developed to accelerate compartment reclamation. Use of WSCS may render the fifteen minute reentry time sufficient for HFP fire suppression, and expedite ventilation initiation.”’

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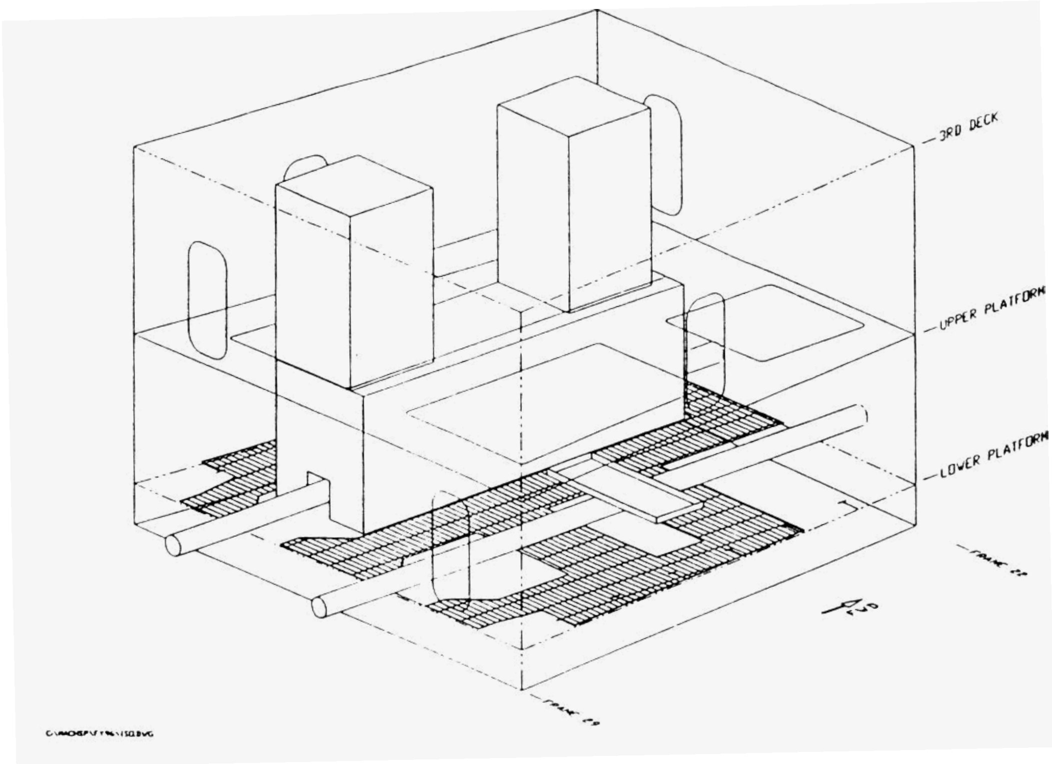
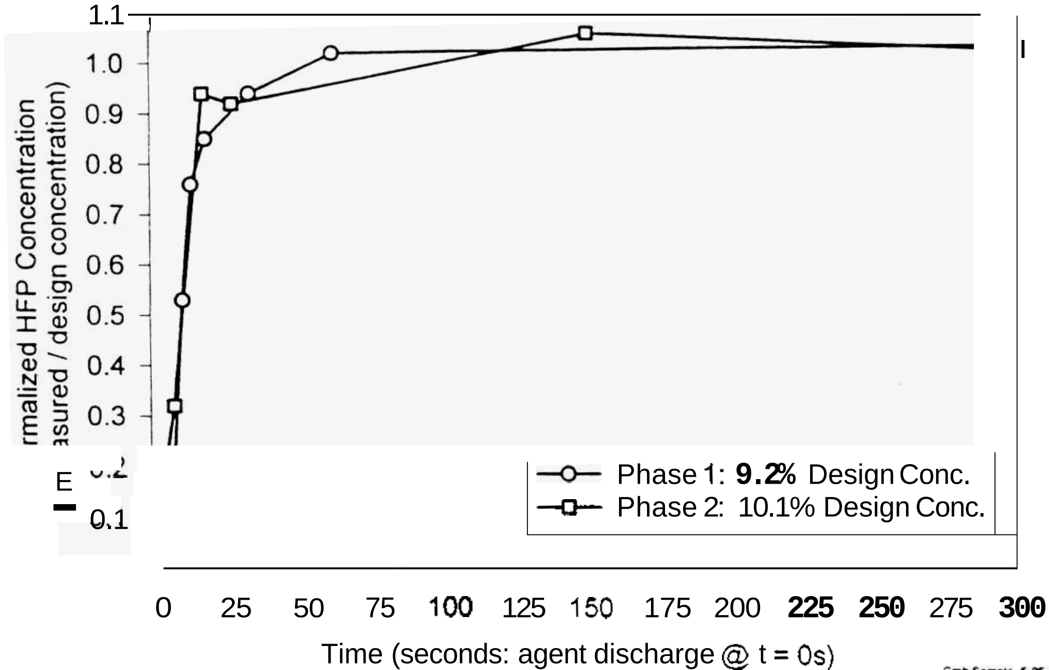


Figure 1

HFP Cold Discharge Agent Concentration Comparison

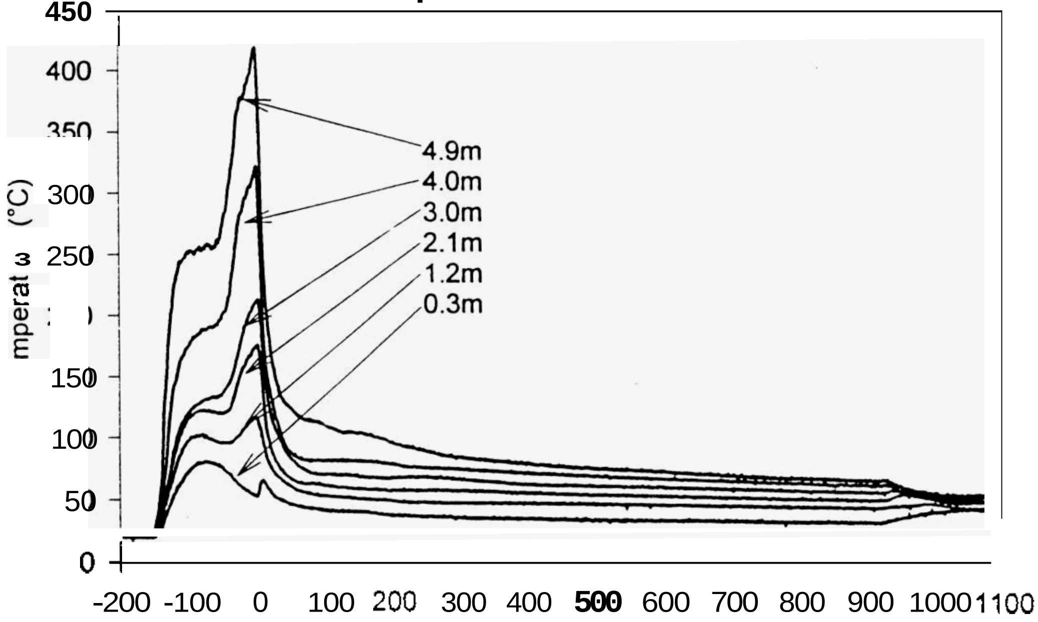


(WSCS not Activated)

Figure 2

Grab Sample 5-25-3 @ 0.6m
ex-USS SHADWELL
Phase 1/Phase 2

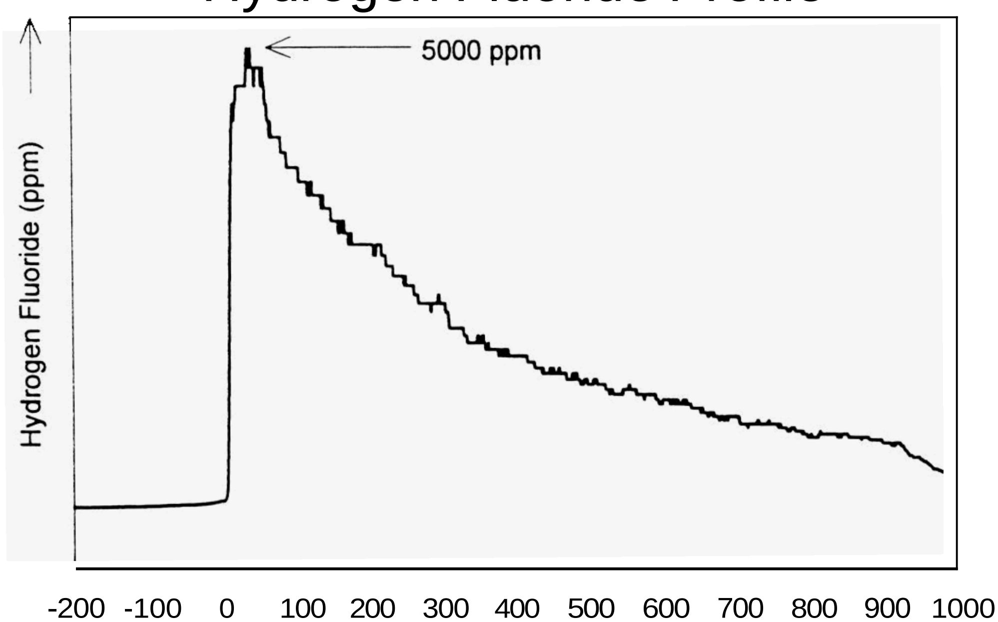
HFP Fire Suppression Ternperature Profiles



Time (seconds: agent discharge @ t = 0s)
(WSCS not Adiated)
Figure 3

Thermocouple Tree 5-27-1
ex-USS

HFP Fire Suppression Hydrogen Fluoride Profile



Time (seconds: agent discharge @ t = 0s)
(WSCS not Activated)
Figure 4

HF Analyzer 4-22-3
ex-USS SHADWELL
Phase 2, Test 3.6