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Discharge System Modifications: Real Scale Halon 1301 Replacement Testing

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ABSTRACT

The Naval Research Laboratory (NRL) has been tasked by the United States Naval Sea Systems Command (NAVSEASYSCOM) to investigate substitutes for shipboard Halon 1301 total flooding fire extinguishing systems. After intermediate and initial (Phase 1) real scale testing, NRL has recommended to NAVSEASYSCOM, heptafluoropropane, HFP (HFC-227ea, C_3F_7H, manufactured by Great Lakes Chemical Corporation as FM-200) as the current clean agent of choice for the Navy's next ship. The task remains to develop guidance on implementation and optimization. Initial real scale testing revealed agent distribution inhomogeneities and discharge time limitations of the standard Navy discharge system components. Obtaining uniform agent distribution provides better fire suppression throughout the compartment. A faster discharge will help achieve faster fire extinguishing and reduce by-product formation. Further full scale tests (Phase 2), conducted aboard the ex-USS SHADWELL located at Little Sand Island, Mobile, AL, were performed with HFP, with limited baseline comparison tests with Halon 1301. Phase 2 tests were performed to determine if modified Navy hardware (cylinder valves, check valves, and flexible hoses) can provide a more rapid discharge time, and to determine the effects on agent distribution of doubling the number of agent discharge nozzles in the compartment. Phase 2 tests were conducted with chamber, ventilation and discharge system modifications. All fires were extinguished for each tested scenario similar to Phase 1 tests. Test results and lessons learned from discharge system hardware and configuration changes are discussed.

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BACKGROUND

The US Navy's halon replacement program includes a project to develop analytical tools for use in designing shipboard fire suppression systems. A computerized flow modeling code was developed, discharge nozzles were scaled up to accommodate HFP instead of Halon 1301, and nozzle spacing criteria were developed. In Phase 1 of this project, discharge systems were designed and real scale tests were performed to check for agent discharge times and agent mixing within the protected compartment. Those tests indicated that variations of about 1 to 2 percent absolute (out of 10 percent agent design concentration) can occur within the protected compartment. The Phase 1 tests also showed that rapid discharges helped to create good mixing and provide uniform agent distribution within the protected space. The rapid discharges were accomplished using **8.27** MPa (1,200 psig) nitrogen superpressurization, in conjunction with low fill densities, in place of **4.14** MPa (600 psig) superpressurization typically used in Navy shipboard systems. Although the additional nitrogen provided rapid discharge times and aided mixing, it tended to dilute agent in the upper portions of the test compartment. Accordingly, alterative methods for obtaining rapid discharges and improved mixing were desired. The primary approaches were to use larger flow area cylinder valves and to choose the largest discharge pipe sizes possible without risking liquid-gas phase separation (due to low flow rates) and without reducing nozzle pressures excessively. The design lower limit for nozzle pressure typically used in designing these systems is about 0.48 MPa (70 psig). However, lower pressures may be acceptable if the discharge system provides uniform agent distribution in the protected space within the desired discharge time. *Also,* during Phase 1 testing, check valves located between the agent storage cylinders and the piping manifold were found to sustain damage after several discharge tests. The damage caused the valves to stick open or closed. Redesigned, prototype valve internals were installed for evaluation during Phase 2 testing.

OBJECTIVES

The primary objective of the Phase 2 agent flow testing was to obtain rapid discharges and good agent-air mixing without resorting to higher nitrogen superpressures. Accordingly, Phase 2 discharge testing on ex-USS SHADWELL focused on obtaining the following information:

- Flow effects of components with increased flow area (cylinder valves, flexible hoses, and check valves), and

- Agent distribution effects at very low nozzle pressures (to identify the minimum acceptable nozzle pressure).

Additional objectives were as follows:

- Test the redesigned check valves to confirm that the failure modes observed in Phase 1 had been eliminated,
- Evaluate the effects of increased numbers of nozzles on agent distribution and mixing within the protected compartment, and
- Continue to benchmark the computerized flow modeling techniques for the two-phase flow of HFP-nitrogen mixtures through piping systems.

TEST COMPARTMENT

In Phase 1, a test compartment was fabricated in ex-USS SHADWELL to represent typical fire threats in shipboard machinery spaces (Reference 1). The original compartment was 840 cubic meters (29,700 cubic feet) in size. The compartment was modified for the Phase 2 tests by closing off a bulkhead in the center to obtain a test compartment with a volume of about 395 cubic meters (13,950 cubic feet). This test compartment contained a mock-up to represent a shipboard gas turbine generator. The two level compartment also contained decks and other structural interferences typically found in shipboard machinery spaces. The evolution of the halon replacement testing on ex-USS SHADWELL from Phase 1 to Phase 2 is discussed further in Reference 2.

INSTRUMENTATION

The discharge system was instrumented to measure parameters important to benchmarking the computerized flow model and to evaluating agent distribution. These parameters included:

- the weight of agent storage cylinders during the discharge,
- the pressure and temperature within the piping system at each nozzle and at several locations between the nozzles and the storage containers, and
- the concentration of agent in the protected space.

The weights of storage containers and pressure/temperature data were collected using analog-to-digital converters connected to a personal computer (referred to as the Experiment Running PC, or the ERPC). The agent concentration was measured using grab samples of air/agent mixture as well as by using continuous gas analyzers. The grab samples were collected at known time intervals using pre-evacuated containers with solenoid valves at the containers' openings. The air/agent mixtures were analyzed following the tests using a gas chromatograph (GC). The concentration of agent, oxygen, carbon monoxide, and carbon dioxide were obtained.

COMPUTER CODE FOR DESIGN OF DISCHARGE SYSTEMS

A computerized flow modeling code (Transient Flow Analysis -- **TFA)** originally developed to model steam-water transient flow was later modified to model halon-nitrogen transient flow. The code has been further modified to model halon replacement agents, including HFP-nitrogen mixtures. TFA has been used to design discharge systems for the halon replacement discharge tests being performed by the Naval Research Laboratory. System design, discharge testing, and benchmarking of the predicted and actual results progressed from single nozzle systems in early, small scale tests at NRL's Chesepeake Beach Detachment (Reference 3) to nine nozzle systems during Phase 1.

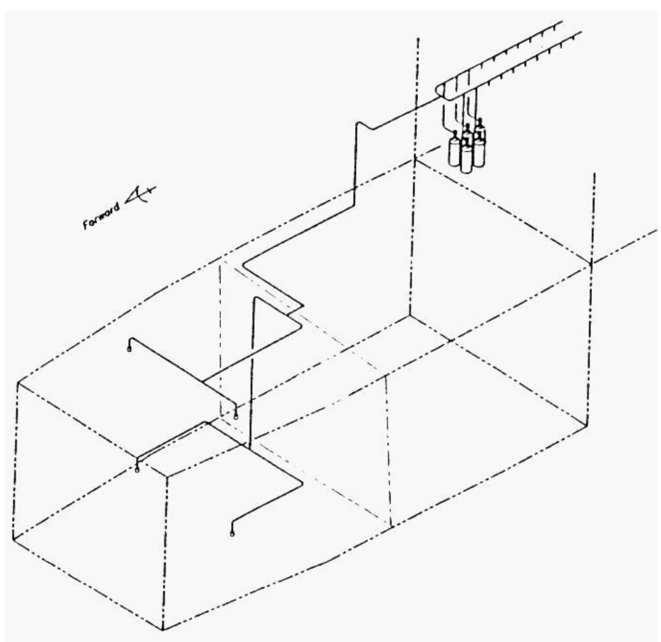
The discharge times and nozzle pressures measured during the Phase 1 discharge tests showed that measured discharge times were within 1 second of the predicted values and that measured nozzle pressures were lower than predicted values (Reference 2). After Phase 1, modifications were made to the computerized flow analysis to improve agreement between predicted and measured pressures. The primary change was in the calculation of nozzle discharge flow rates. The computer code was modified to rely more heavily on conservation of momentum in the expanding discharge jet and less heavily on a choked flow correlation for HIT-nitrogen mixtures. Benchmarking of the revised code indicated improved agreement between calculated and measured pressures. The revised code was then used to design discharge systems for Phase 2 tests planned for ex-USS SHADWELL.

PHASE 2 TESTS

Phase 2 testing occurred during two time periods: September/October 1995 and February/March 1996. The early testing indicated that the changes made to the computer code after Phase 1 resulted in under-prediction of discharge times for certain combinations of nozzle sizes and supply pipe sizes. Further changes were made to the computer program and to the discharge system for the later tests. The discussion below covers the lessons learned during the early Phase 2 testing as well as the results of the late Phase 2 testing. Four discharge system configurations were tested. Table 1 summarizes the distinguishing features of the systems. Additional details are provided in Table 2.

Table 1
Discharge System Configurations for Phase 2 Testing

Configuration	Agent	Number of Storage Cylinders	Number of Nozzles	Cylinder Valve Flow Diameter mm (inches)
1	HFP	5	4	25.4 (1)
2	HFP	5	4	44.5 (1.75)
3	HFP	5	8	25.4 (1)
4	Halon	2	4	25.4 (1)



Halon Replacement Discharge System on ex-USS SHADWELL
Figure 1

To take full advantage of the larger prototype components, the discharge piping downstream of the check valves was redesigned for Phase 2 but made use of some of the existing piping from Phase 1. The Phase 1 tests on ex-USS SHADWELL used a nine nozzle system designed to discharge either Halon 1301, HFP, or other halon replacement agents. The system pipe sizes were selected to obtain flow rates above the minimums required to maintain well mixed, dispersed gas-liquid mixtures. The pipe sizes were small enough to maintain high mass flow rates for the relatively small amount of Halon 1301 used but large enough to minimize frictional pressure drop for the HFP discharged during subsequent tests. The nine nozzle system designed in this way performed as predicted during Phase 1 tests.

The test compartment was partitioned for the Phase 2 tests by completely closing off an existing bulkhead to obtain a test compartment with approximately half the volume of the compartment used in Phase 1 testing. Accordingly, the amount of fire suppression agent was reduced substantially. In planning for the Phase 2 tests, the discharge system piping sizes were evaluated to determine whether or not the mass flow rates through the existing piping system would be high enough to ensure dispersed liquid-gas mixtures for discharges of halon-nitrogen mixtures or HFP-nitrogen mixtures. The 100 mm (4 inch) size main supply pipe was found to be adequate for the HFP discharges, but too large for the halon discharges. Accordingly, a new separate halon discharge system was designed and installed alongside of the existing HFP system.

Discharge test data collected during the early Phase 2 tests indicated a number of new results. These results, and adjustments that were made for the late Phase 2 discharge tests, are discussed below. For the initial cold discharge test (designated HR2-1) the discharge time was about 3 seconds longer than expected. Analysis of the test data and reanalysis of the design calculations indicated that the following factors contributed to the longer than expected discharge:

- There was a partial blockage in the pipe feeding the lower, port side nozzle,
- The redesigned 1-inch check valve, which included a stiffer spring, was not opening fully during the discharge, especially late in the discharge as the rate of flow through the valve decreased, and
- Changes made to the flow modeling computer code (TFA) after the Phase 1 test series resulted in the calculation of discharge time becoming too sensitive to the diameter of the pipe immediately upstream of the discharge nozzles. This caused the discharge time to be under-predicted.

The repeated discharge of HFP through the piping system in the early Phase 2 tests eliminated the blockage. The pressure data for those tests indicates that the lower, port side nozzle was reaching the expected pressure. Pressure drop versus flow measurements at the check valves confirmed that the more rigid, redesigned internals contributed additional pressure drop to the system. The computer program (TFA) used to predict the discharge times and system pressures was revised after the early Phase 2 tests to remove the sensitivity of the discharge time calculation to the diameter of the pipe immediately upstream of the nozzle. A new set of calculations were made to obtain new predictions for the remaining Phase 2 tests, and 63.5 mm (2.5 inch) nozzles with increased exit area were installed in place of the 38 mm (1.5-inch) nozzles for the 4 nozzle discharges of HFP. The resulting discharge times matched the predicted values well. The results are given in Table 2.

Benchmarking: The discharge parameters predicted by the computer code (TFA) and the parameters measured during the discharge tests were compared to benchmark the computer code. The flow calculations performed to design the system are based on the cold conditions [21°C (70°F)]. Accordingly, the tests of interest for benchmarking the flow modeling computer program are the cold tests (i.e. no fire was burning in the compartment at the time of the discharge). The parameters of interest are the discharge time and the nozzle pressure. TFA uses a fully implicit transient flow analysis approach that provides pressures, flows, and temperatures of the pipe contents at locations along the pipes and at all points in time during the discharge. Among these parameters, temperature is usually the simplest to measure and interpret in actual discharge tests. Accordingly, the relatively sudden drop in temperature associated with the end of the liquid flow and the rapid expansion to a predominantly gaseous flow is used to identify the discharge time for both the predictions and the experimental data. The discharge times are summarized in Table 2. For each of the four configurations, the predicted discharge time is within 1 second of the measured time for the cold discharge test. In general, the measured discharge times for the tests with fires are also within 1 second of the predicted value.

Nozzle pressure was benchmarked using the pressure measured at the midpoint of the discharge time. This time is selected because it represents the average pressure during the nearly steady state portion of the discharge. This point also is less susceptible to errors in interpreting the pressure plots since it has a more nearly constant slope than the beginning and end of the plot where the pipe is filling rapidly or the last gas is being expelled quickly. The benchmark comparisons in Table 2 indicate that the predicted pressures are higher than the measured pressures. The differences primarily result from nodalization in the computer model which provides an average pressure some distance upstream of the nozzle as compared to the measured pressure taken much closer to the nozzle. Due to choked flow at the nozzle and the relatively large nozzle exit areas (i.e. nozzle areas nearly as large as the pipe area), the pressure changes rapidly at the approach to the nozzle. The magnitude of this effect is a function of the ratio of the nozzle exit area to the supply pipe area. This effect can be modeled by using additional control volumes (i.e. more detailed nodalization) just upstream of the nozzle to obtain calculated pressures that more closely match the measured pressures.

Table 2
Comparison of Predicted and Actual Discharge Test Results
for HFP and Halon 1301 Tests (Late Phase 2 Tests)

Description	Test	Test Condition	Discharge Time (sec)	Average Nozzle Pressure at 0.5 Discharge Time MPa (psig)	Average ... ent Storage Co... tions	
					Pressure MPa (psig)	Temperature °C (°F)
HFP - Configuration 1	*Predicted*	*Cold*	*9.5*	*0.59 (85)*	*4.14 (600)*	*21 (70)*
Five Size **5** cylinders	HR2-2	Cold	10.0	0.39 (57)	4.41 (640)	21 (70)
Standard Navy ...ardware	HR3-4	Fires	9.4	0.55 (80)	4.67 (677)	22 (72)
	HR3-5	Fires	9.5	0.46 (66)	3.90 (566)	10 (50)
Four nozzles with four 22.3 mm (0.875 inch) ...rillings each	HR3-6	Fires	9.3	0.55 (80)	4.83 (700)	23 (73)
	HR4-2	Fires	10.3	0.41 (60)	3.76 (546)	3 (37)
	HR4-5	Fires	9.8	0.45 (65)	4.14 (600)	24 (75)
	HR5-2	Fires	9.4	0.43 (63)	3.72 (540)	14 (57)
	HR5-3	Fires	10.6	0.45 (65)	3.90 (565)	22 (72)
	HR5-4	Fires	10.8	0.41 (60)	4.05 (588)	18 (64)
***...FP - Configuration** 2*	***Predicted***	***Cold***	*8.1*	***0.69 (100)***	***4.14 (600)***	*21 (70)*
...ive Size 5 cylinders						
...odified hardware	HR7-1	Cold	7.4	0.44 (64)	3.79 (549)	14 (57)
...our nozzles with four ...2.3 mm (0.875 inch) ...rillings each	HR7-2	Cold	8.1	0.48 (70)	3.89 (564)	10 *(50)*
***...FP - Configuration** 3*	***Predicted***	***Cold***	*10.4*	***0.54 (79)***	***4.14 (600)***	*21 (70)*
...ive Size **5** cylinders						
...tandard Navy ...ardware	HR2-3	Cold	10.5	0.29 (42)	3.70 (537)	10 *(50)*
...ight nozzles with four ...5.9 mm (0.625 inch) ...rillings each						

Description	Test	Test Condition	Discharge Time (sec)	Average Nozzle Pressure at 0.5 Discharge Time MPa (psig)	Average Agent Storage Conditions	
					Pressure MPa (psig)	Temperature °C (OF)
Halon - Configuration 4	*Predicted*	*Cold*	*9.2*	*0.83 (120)*	*4.14 (600)*	*21 (70)*
Three Size 4 cylinders Standard Navy hardware	HR6-1	Fires	**8.4**	0.79 (115)	4.14 (600)	**24** (75)
Four nozzles with four 15.9 mm (0.625 inch) drillings each	HR6-2	Fires	**7.9**	0.72 (105)	4.02 (583)	13 *(55)*

RESULTS

Effects of Decreased Discharge Time on Uniformity of Agent Distribution: The modified discharge system hardware provided a faster discharge (about 2 seconds faster out of 10 seconds -- compare Tests HR2-2 and HR7-2 in Table 2). The concentrations of agent-air mixtures from these tests are listed in Table **3.** At 15 seconds after the start of the discharge, it appears that the modified hardware provided higher agent concentrations and more uniform agent distribution than the standard hardware. After 15 seconds, the measured concentrations do not show any marked difference between the standard and modified hardware. **It** is important to note that improvements within the first 15 seconds are very important to the amount of decomposition products (such as hydrogen fluoride) and to the time needed to extinguish the fire.

Table 3
Comparison of HFP Concentrations for Standard and Modified Hardware

Time After Stan of Discharge	Test HR2-2 Standard Hardware			Test HR7-2 Modified Hardware		
	Location 1	Location 2	Location 3	Location 1	Location 2	Location 3
5 sec.	ND	5.7	ND	8.7	6.5	4.4
15 sec.	ND	9.0	4.0	13.0	8.5	9.3
25 sec.	10.8	8.8	8.7	10.9	8.8	ND
2.5 min.	10.5	8.2	8.9	10.2	8.4	9.9
5 min.	ND	8.3	ND	9.6	8.8	ND
15 min.	ND	8.2	9.9	9.8	8.5	10.3
22.5 min	10.3	8.1	9.8	10.5	8.6	ND
30 min.	9.5	8.0	9.7	10.2	7.4	ND

Redesigned Check Valve Internals: In Phase 1, the internal parts of a *25* mm (1 inch) flow diameter check valve typically used in shipboard Halon 1301 systems were damaged during repeated discharge testing on ex-USS SHADWELL. The damage resulted in the valves sticking open or closed. Redesigned prototype internals were tested in Phase 2 and operated without any mechanical failures through the test series. However, it appears that the stiffer parts included in the redesigned internals resulted in increased pressure drop through the valve and extended the discharge time by 1 to 2 seconds.

Benchmarking **of** Computer Code **for Flow** Modeling: The discharge parameters predicted by the computer code (TFA) and the parameters measured during the discharge tests were compared to benchmark the computer code. For each of the four configurations, the predicted discharge time is within 1 second of the measured time for the cold discharge test. In general, the measured discharge times for the tests with fires are also within 1 second of the predicted value.

As for early Phase 2 tests, nozzle pressures were benchmarked at the midpoint of the discharge time. The predicted pressures are higher than the measured pressures. It appears that this difference occurs primarily because the predicted pressure reported by the computer program represents an average pressure at the center of a control volume centered several meters upstream of the nozzle, whereas the measured pressure is for the fluid within about 15 cm of the exit holes in the nozzle. This effect can be modeled by using additional control volumes (i.e. more detailed nodalization) just upstream of the nozzle to obtain calculated pressures that more closely match the measured pressures.

Detailed pressure drop measurements made at the cylinder valves, flexible hoses, and check valves suggest that the pressure drop in these components is higher than expected for HFP-nitrogen mixtures and may require additional changes to the flow modeling computer program to account for the pressure drop.

STATUS

The lessons learned from the Phase I and Phase 2 tests are currently being incorporated into the computer code for flow analysis of discharge systems (TFA). The analytical tools and design guidelines (such as nozzle spacing) for designing shipboard fire suppression systems with HFP are essentially complete and ready for use in designing discharge systems.

ACKNOWLEDGMENTS

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