Development of a Computer Model to Predict the Transient Discharge Characteristics of Halon Alternatives

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Abstract

A computer program named TFA (Transient Flow Analysis) has been developed to model the transient discharge characteristics of halon alternatives. The program includes software modules of thermodynamic properties and accepts piping system geometric data to calculate the discharge time history. Property modules have been developed for HFC-227ea, superpressurized by nitrogen. Additional halon alternatives modeling is also under development. The program uses a discretized control volume and connector approach to represent the fire protection system storage cylinders and discharge piping. The mass, energy and momentum conservation equations are integrated over each control volume and flow connector and the resulting system of equations is solved to obtain the transient solution. The agent/nitrogen system includes agent liquid and vapor, nitrogen gas dissolved in the liquid agent, and nitrogen gas mixed with the agent vapor.

Full-scale discharge tests using three candidate halon alternatives were performed between November 1993 and March 1994 at the Naval Research Laboratory's Chesapeake Bay Detachment. The agents tested were:

- HFC-227ea (FM-200).
- HFC-23 (FE-13), and
- FC-3-1-10 (CEA-410).

This paper presents measured pressures, temperatures, and flow rate characteristics from these discharge tests. Predictions from the computer model are compared to measured test data for HFC-227ea. Also, the computer program is used to generate comparative analyses of alternative designs for shipboard halon alternative systems.

Introduction

Halon 1301 flooding systems are widely used for fire protection in Navy shipboard machinery spaces where pressurized fuel and hydraulic fluid spray hazards exist. Due to concern that the emission of bromofluorocarbons, including Halon 1301, can affect stratospheric ozone, the manufacture of Halon 1301 was severely restricted after January 1, 1994. Consequently, efforts to identify and test environmentally acceptable replacements for Halon 1301 for use in critical Navy fire protection systems are under way.

In the 1980's the Navy sponsored the development of computer programs to accurately predict the discharge characteristics of shipboard Halon 1301 systems. Those computer programs significantly reduced the need for repetitive testing of discharge systems to select correct nozzle sizes and piping details. For Halon 1301, the disincentives for testing were environmental concerns and cost. Despite the fact that the halon alternative agents have reduced the concern regarding ozone depletion, the need for accurate flow modeling to optimize the design of discharge systems, and reduce the amount (and cost] of agent used remains. Accordingly, the existing computer programs originally used for Halon 1301 are being modified to use the halon replacements. For alternative agents such as HFC-227ea, accurate modeling of flow distribution in piping is needed because the minimum concentration of agent required for fire extinguishing may be only a few percentage points lower than the maximum concentration permitted to avoid toxic effects to personnel. The system designer may not be able to overdesign the system (i.e., select a higher concentration than is needed to cover uncertainty in the analyses) as was usually done with Halon 1301. Also, some of the halon replacements place a premium on accurate prediction of discharge times; when discharged slowly into a fire, HFC-227ea produces much higher concentrations of undesirable decomposition products (e.g., acid gases) than Halon 1301.

Analytical Method

A computer program has been modified to model the transient discharge characteristics of halon alternatives. The early development efforts have concentrated on modeling the discharge characteristics of HFC-227ea. The computer program and the transient flow equations used to describe the two-phase flow in the discharge piping systems are described in Reference 1. The solution technique uses a control volume and connector approach to solve the transient mass, momentum, and energy conservation equations and is summarized by the following five steps:

1. Division of the piping system into control volumes and flow connectors;

2. Integration of the mass and energy conservation equations over each control volume;

3. Integration of the momentum conservation equation over each flow connector to determine mass flow between control volumes;

4. Use of equations of state for agent and nitrogen to obtain pressure, temperature, and other thermodynamic properties in each control volume; and

5. Solution of the resulting transient equations using a partially implicit backward difference numerical technique.

The conservation equations employed include mass and energy conservation for the agent, dissolved nitrogen, and free nitrogen in each control volume. The final conservation equation is a combined momentum equation for each fluid connector. The partially implicit backward difference technique utilized to integrate this set of equations in time solves for the mass and energy of each constituent in each control volume and the total mass flow rate in each fluid connector. Thermodynamic properties such as pressures, temperatures, densities, and enthalpies are obtained from the masses and energies in each control volume and the volume of the control volume. These properties are used to define the conservation equations for the next time step.

To incorporate the fluid characteristics of various halon alternatives into the computer program, thermodynamic models of the P-V-T behavior of halon alternatives have been developed based on the data provided in Reference 2. The thermodynamic properties necessary for the solution include pressure as a function of the masses and energies of the components of the mixture in a control volume. This correlation is normally not available from standard thermodynamic tables and is difficult to obtain because distribution of the phases of the agent must be obtained as part of this solution. In addition, choked flow correlations must be provided for the complex mixture of agent and nitrogen. Critical flow rates are strongly influenced by agent phase change and release of dissolved nitrogen as the pressure drops through the choke point.

The effect of these complications has been to make it necessary to develop a separate set of computer programs which are used to generate the appropriate thermodynamic properties and critical flow rates from standard thermodynamic tables for use by the transient analysis package. This technique has simplified the process of incorporating new alternative agents into the transient analysis program.

Test *Facility*

To assess the accuracy of the first-principles analyses performed by the computer program, a number of discharge tests were performed. Two full-scale piping arrangements were designed to allow basic agent discharge characteristics to be measured. These piping systems were fabricated at the Naval Research Laboratory (NRL) Chesapeake Bay Detachment (CBD). Figures 1 and **2** show the configuration of the single nozzle and double nozzle arrangements. The double nozzle system was deliberately designed as an unbalanced system to provide data for comparison to computer predictions. The piping components and assembly methods used were typical of shipboard installations and are equivalent to systems currently used for Halon 1301, Each piping arrangement included a single 60-pound cylinder, a cylinder discharge valve, a flexible hose, socket welded schedule 80 steel piping, and either one or two nozzles. A check valve was included in the double nozzle system in order to collect pressure drop data for the valve.

The two piping arrangements were instrumented to measure and record the pressure and temperature of the agent and the weight of the storage cylinder during the discharge tests. To help visualize the agent flow in the pipe, a sight tube was installed immediately upstream of the discharge nozzle and the flow through the tube was videotaped. A second video camera was positioned to record the visible discharge from the nozzles.

A series of 16 discharge tests without fires were performed. The tests involved HFC-227ea, HFC-23, and FC-3-1-10. Prior to each test the storage cylinder was filled with approximately 60 pounds of agent. HFC-227ea and FC-3-1-10 were super-pressurized with nitrogen. The nominal initial cylinder pressure was 600 psig at 70°F.

For most tests the cylinder was oriented upright, with a siphon tube. A few tests were run with inverted cylinders without siphon tubes to evaluate the effect of the siphon tube on discharge times. One test was conducted where the discharge piping was heated with electrical resistance heat tape to simulate the heating that would occur in the top of a compartment after a fire has burned for a few minutes. Table 1 identifies the 16 tests and lists pertinent test parameters.

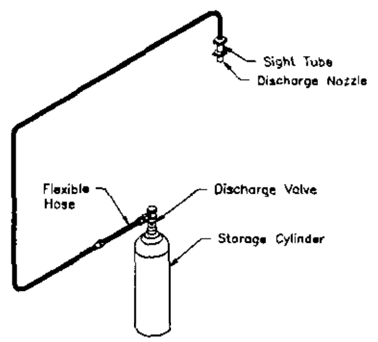

Figure 1: Single Nozzle Discharge System

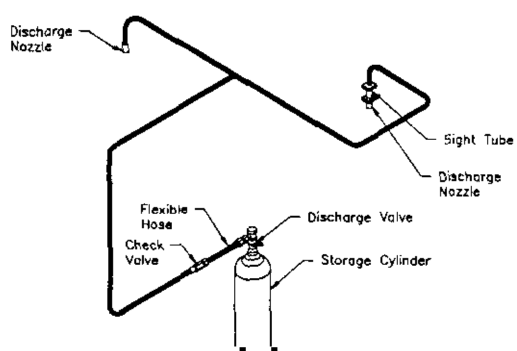

Figure **2:** Double Nozzle Discharge System

Table 1

Test **Matrix**

Test	Agent	Piping System (Nozzles)	Nozzle Type Size[1] (inch)	Bottle Position	Weight of Agent (lb)	Storage Pressure (psig)	Initial Temperature (°F)		Measured Discharge Time[2] (sec)
							Cylinder	Pipe	
1	HFC-227ea	Single	4-Port, 3/16	Upright	60	555	57	66	19
2	HFC-227ea	Single	4-Port, 3/8	Upright	60	590	64	75	8
3	HFC-227ea	Single	4-Port, 3/8	Inverted w/o siphon tube	62	600	70	80	8
4	HFC-227ea	Double	4-Port, 1/4	Upright	62	640	77	90	10
5	HFC-227ea	Double	4-Port, 1/4	Inverted w/o siphon tube	63	590	76	82	11
6	HFC-23	Double	4-Port, 1/4	Upright	50	530	57	57	7
7	HFC-23	Single	4-Port, 3/8	Upright	50	540	55	68	7
8	HFC-227ea	Single	4-Port, 3/8	Upright	62	630	43	47	9
9	HFC-227ea	Single	4-Port, 3/8	Upright	60	790	88	72	8
10	HFC-227ea	Single	4-Port, 3/8	Upright	61	660	67	200	9
11	FC-3-1-10	Single	4-Port, 3/8	Upright	74	630	60	68	10
12	HFC-227ea	Single	8-Port, 1/4	Upright	61	650	65	70	9
13	HFC-227ea	Double	4-Port, 13/32	Upright	41	1210	64	(3)	2
14	HFC-23	Double	4-Port, 13/32	Upright	47	598	63	(3)	4
15	HFC-227ea	Double	4-Port, 13/32	Upright	62	1160	50	(3)	4
16	HFC-23	Double	4-Port, 3/16	Upright	49	535	52	(3)	10

Note.:

1. Size listed is the diameter of each port.
2. Discharge time is measured from the beginning to the and of visible discharge at the nozzle(s).
3. Data not recorded.

Test Results

Table 1 presents discharge times based on videotape data for the discharge tests. The data indicates that for the single nozzle system with HFC-227ea, there was no significant difference in discharge times for cylinders with and without siphon tubes. The data also indicates that storage cylinder temperature variations (43°F to 88°F) and heating the discharge pipe (200°F) had no significant effect on the discharge time of HFC-227ea.

Cylinder pressure during a discharge transient for three halon alternatives is presented in Figure 3. Two of the agents, HFC-227ea and FC-3-1-10, have similar pressure response during the discharge. These two agents have similar vapor pressures of approximately 45 psig and 25 psig respectively at 70°F and were both superpressurized to 600 psig with nitrogen. As shown in Figure 3, HFC-23, with a vapor pressure of 615 psig at 70°F, maintains a relatively high cylinder pressure during the discharge.

All three agents exhibit non-equilibrium behavior early in the discharge transient. Cylinder pressure initially drops rapidly, increases at about 1 or 2 seconds and then gradually decreases to atmospheric pressure. For the two agents that were superpressurized with nitrogen, this behavior is partially due to nitrogen coming out of solution and repressurizing the storage cylinder.

Comparison of Measured and Predicted Results

A comparison of measured and predicted results is shown in Table 2. In general, the table illustrates that the computer program in its present form provides reasonably good predictions for discharge time and nozzle pressure for those tests which have cylinder storage pressures, fill densities, and discharge times (5 to 10 seconds) that have traditionally been used for Halon 1301 in the Navy (Tests 2 and 4). However, performance of the program outside this range is not as favorable (Tests 1, 13, and 15). For the system with a relatively long discharge time (Test 1), the program overpredicted nozzle pressure. For the systems with relatively short discharge times (Tests 13 and 15), the program underpredicted nozzle pressure. The current version of the computer model may not adequately model the rates at which nitrogen moves in and out of solution in HFC-227ea, and the choked flow correlation used in the program may need to be refined as more test data is obtained and further comparisons are evaluated.

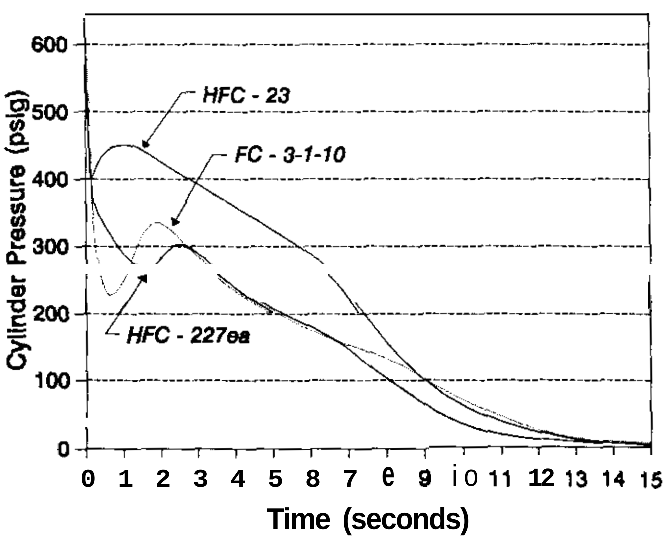

Figure **3:** Cylinder Pressure During Discharge of HFC-23 (Test 7), FC-3-1-10 (Test 11), and HFC-227ea (Test 2)

Table 2

Comparison of **Measured and Predicted Results**

Test	Agent	Piping System (Nozzles)	Nozzle Type Size[1] (inch)	Weight of Agent (lb)	Storage Pressure (psig)	Measured Discharge Time (sec)	Predicted Discharge Time (sec)	Measured Nozzle Pressure[2] (psig)	Predicted Nozzle Pressure[2] (psig)
1	HFC-227ea	Single	4-Port, 3/16	60	555	19	30	190	235
2	HFC-227ea	Single	4-Port, 3/8	60	590	8	8	140	135
4	HFC-227ea	Double	4-Port, 1/4	62	640	10	9	170 180	160 175
13	HFC-227ea	Double	4-Port, 13/32	41	1210	2	2	200 290	105 185
15	HFC-277ea	Double	4-Port, 13/32	62	1160	4	4	150 200	75 105

Notes:

1. Si20 listed is the diameter of each port.

2. Nozzle pressures are reported at the mid point of the quasi-steady-state portion of the discharge. Where 2 values are reponed. these are for the 2 legs of the double nozzle system.

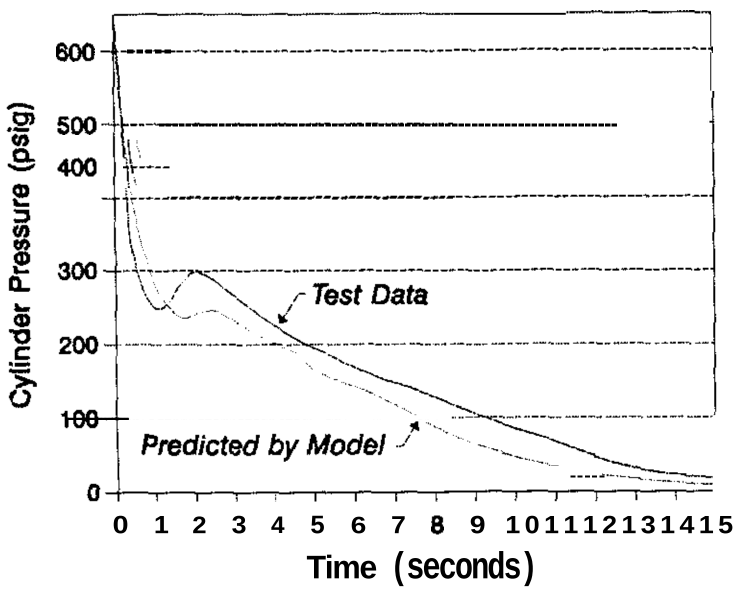

Figure 4 Comparison of Measured and Predicted Cylinder Pressures for *Test* 4 (HFC-227ea)

Figures 4 and 5 show the time history of measured and predicted data for Test 4, a baseline test with HFC-227ea for the double nozzle system. Cylinder pressure is shown in Figure 4 and weight of agent in the cylinder is shown in Figure 5. Changes in weight of the storage cylinder during the discharge provide an indication of the flow rate of agent through the system. Note that although the cylinder is nearly empty after 5 seconds, the visible discharge from the nozzles continues for 10 seconds due to HFC-227ea resident in the piping.

Figure 6 shows the time history of measured and predicted data for Test 13. The overall comparison of cylinder pressures shown in Figure 6 is favorable. The predicted depressurization at the start of the transient is somewhat slower than was measured. Consequently, the slight pressure recovery due to nitrogen release predicted by the model occurs later and at a lower pressure than was measured.

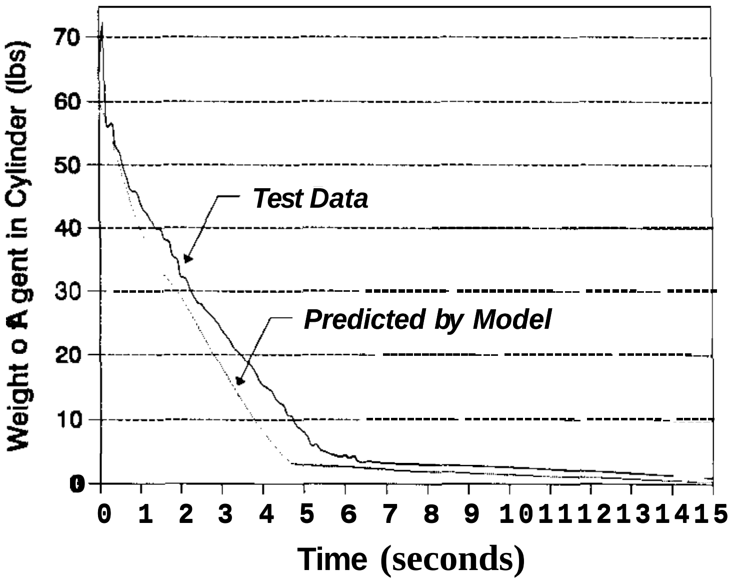

Figure *5:* Comparison of Measured and Predicted Weights of Agent in Cylinder for Test 4 (HFC-227ea)

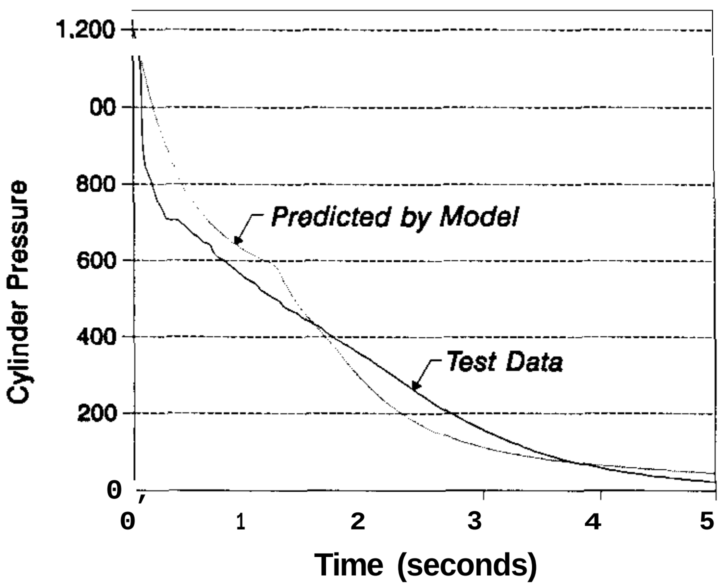

Figure 6: Comparison of Measured and Predicted Cylinder Pressures for Test 13 (HFC-227ea)

Comparative Analyses to Reduce Discharge limes

The TFA computer program is being used to compare discharge system design alternatives. Comparative analyses are being performed to:

- minimize discharge time while retaining existing storage cylinderlvalve assemblies, and
- minimize the total weight and space needed for shipboard storage of fire extinguishing agents.

Existing storage cylinder/discharge valve assemblies use one size valve for a range of cylinder sizes. The comparative analyses focused on using this existing hardware, and speeding up the discharge by (1) decreasing the amount of agent required to flow through each cylinder valve, and (2) increasing the stored energy available to drive the discharge. The amount of agent required to flow through each cylinder valve can be reduced by using an increased number of cylinders. This can be implemented by using an increased number of large cylinders (nominal 125-pound cylinders) with reduced fill densities, or an increased number of small cylinders (e.g., nominal 60-pound cylinders) with the maximum fill density. The stored energy available to drive the discharge can be increased by using additional nitrogen superpressure.

Figure 7 illustrates the results of some of the comparative analyses. The baseline case (slowest discharge) models an existing storage cylinder design filled to the maximum fill density suggested for HFC-227ea, and superpressurized with nitrogen to 600 psig at 70°F. The model includes the double nozzle piping system described earlier in this paper and a four-port discharge nozzle with 3/16 inch diameter drillings.

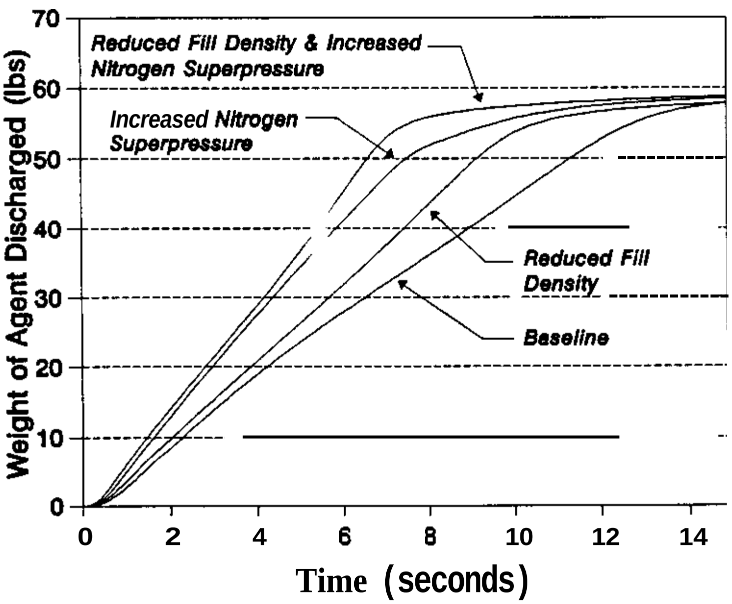

Figure 7: Predicted Discharge Characteristics for Alternate Fill Densities and Storage Pressures (HFC-227ea)

Table 3

Results of Comparative Analyses
to Reduce Discharge Times

Alternate Designs (HFC-227ea)	Weight of Agent (lbs)	Fill Density (lb/ft^3)	Storage Pressure (psig)	Predicted Discharge Time[1] (sec)	Change from Baseline (sec)
Baseline	60	70	600	12	-----
Reduced fill density	60	44	600	10	-2
Increased nitrogen superpressure	60	70	1200	9	-3
Reduced fill density and increased nitrogen superpressure	60	44	1200	7	-5

Note:

1. **For this Comparative analysis, discharge time is defined to be when 90 percent of the weight of agent (54 lbs) has flowed out of the nozzle.**

For purposes of this comparison, the discharge time is selected from Figure 7 as the time when 90 percent of the weight of material has exited the discharge nozzle. In the baseline case, the discharge is predicted to occur in 12 seconds. In the first alternative design (fill density reduced to 2/3 of the suggested maximum), the discharge is predicted to occur in 10 seconds. In the second alternative design (nitrogen superpressurization increased from 600 to 1200 psig). the discharge time is predicted to be 9 seconds. The combination of reducing the fill density and increasing the nitrogen superpressure is predicted to produce a discharge time of 7 seconds. Table 3 summarizes these predicted discharge times.

Several discharge tests were performed to learn whether or not these predicted changes in discharge time can be obtained. The results of these tests, which are reported as Tests 13 and 15 in Table 2, suggest that the predicted changes can be obtained.

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