Results of Benchmark Comparisons of Calculated and Measured Flow Parameters for Discharges of Halon Replacement Chemicals

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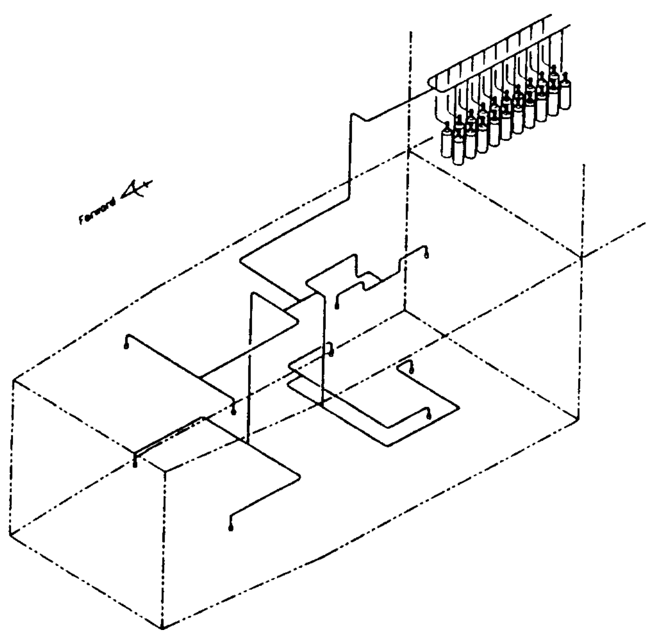
Abstract

A computer program named TFA (Transient Flow Analysis) has been developed to model the transient discharge characteristics of Halon replacement chemicals, including FM-200 and FE-13. The TFA computer program was used to design a large piping distribution system for tests conducted by the US Navy onboard the research vessel ex-USS SHADWELL. This paper evaluates how well TFA's calculated flow parameters correspond to the parameters measured during the discharge tests and includes comparisons of calculated and measured discharge times, nozzle pressures and flow distribution among nozzles. A method for modeling the two-phase pressure drop through piping systems and the effect on the pressure drop of assumptions such as homogeneous velocity modeling (vapor and liquid assumed to have the same velocity) is explored. Models which allow different velocities for the vapor and liquid can result in a different distribution of quality in the piping system, which indirectly effects the two-phase pressure drop and the overall discharge characteristics.



Halon Replacement Discharge System on ex-USS SHADWELL
Figure 1

Introduction

In early 1994, NAVSEA, NRL, Geo-Centers and MPR Associates designed a mock-up of a shipboard machinery space for installation on ex-USS SHADWELL. MPR designed a discharge system to supply Halon replacement chemicals to the mocked-up machinery space (see Figure 1). The discharge system was sized to accommodate Halon 1301, FM-200, FE-13, or other Halon replacement chemicals. The system was designed to permit rapid discharges (6 seconds) as well as more typical discharges (10 seconds) for various fire suppression tests. MPR used the computer program TFA to design the discharge system. Design choices included pipe sizes, locations of flow splits, nozzle sizes, and storage cylinder fill densities and, for Halon 1301 and FM-200, nitrogen super pressure. MPR provided predicted discharge times and nozzle pressures to the Navy prior to the discharge tests (Reference 1). The agreement between those predicted values and the values actually measured in three typical tests of FM-200 and FE-13 are presented in this paper. Also, work performed subsequent to the discharge tests to further improve the agreement between the calculated and measured values is discussed.

Flow Modeling

Flow Patterns - Dispersed versus Separated Gas Phase: Halon and the Halon replacement chemicals discussed here flow as a mixture of liquid and vapor. For flow modeling, it is important to know whether the vapor bubbles remain suspended in the liquid in the form of relatively small bubbles that flow along at the same velocity as the liquid (so-called dispersed flow pattern), or the vapor forms larger pockets that may move through the liquid with a different velocity (so-called separated gas phase). This distinction is important because the amount of vapor in the mixture at any given location in the piping system influences the pressure drop at that location in the piping system.

Accurate modeling of the flow pattern in the storage cylinders is also important to good predictions of discharge times and nozzle pressures. The flow pattern assumed for the storage cylinders influences the amount of vapor that remains in the storage cylinder during the discharge, and the amount of vapor in the piping.

Flow Patterns in Distribution Piping and Storage Containers: For typical fire suppression systems, the flow velocities in the discharge piping are high enough so that the vapor bubbles remain suspended in the liquid in the form of relatively small bubbles that flow along at the same velocity as the liquid. Previous testing has illustrated this dispersed flow pattern by photographing the flow of Halon 1301 through transparent tubing installed in the discharge piping (Reference 2). In general, discharge system piping is carefully designed to obtain high flow velocities to ensure high turbulence and dispersed flow patterns. However, the flow velocity in the storage cylinder may not be highly turbulent in all discharges. In a rapid discharge, the liquid and vapor in the cylinder may exit the cylinder as a dispersed mixture of agent liquid with dissolved nitrogen, agent vapor, and nitrogen vapor. In a slower discharge, the nitrogen that comes out of solution in the storage cylinder may have time to rise to the top of the liquid and join the vapor that is available to continue to drive the discharge.

Modeling Assumptions used in TFA Computer Program: TFA is derived from a computer program originally written by MPR Associates to model steam-water flow, including a separated gas phase in which the vapor and liquid can be modeled with different velocities. TFA is a simplified version of the original program and does not include the capability to model vapor and liquid with different velocities in the piping system. The solution techniques used by TFA are described in Reference 3. Separated gas phase flow capabilities are not included because dispersed flow patterns and homogeneous velocities are obtained in fire suppression systems by careful selection of pipe sizes and other system design details. Accordingly, in planning TFA, we judged it would probably not be necessary to model separated gas flow in the discharge piping to successfbllly design fire suppression systems. *Also,* correlations for the relative velocities (so called slip) are not generally available for nitrogen flowing through Halon replacement chemicals, or for the vapor phase of these chemicals flowing through the liquid phase.

TFA models the liquid and vapor inside the storage cvlinder as separated gas phases. The cylinder contains a vapor bubble on top of liquid. For Halon 1301 and FM-200, the vapor bubble consists of nitrogen and agent vapor: the liquid consists of liquid agent and nitrogen in solution. When the discharge valve opens, the pressure in the cylinder decreases and nitrogen that had been in solution in the liquid agent forms into bubbles. If the liquid level drops relatively slowly, the nitrogen bubbles rise to the liquid's surface and become part of the vapor bubble driving the discharge: TFA uses this approach to calculate the pressure in the storage cylinder during the discharge. However, if the liquid level drops rapidly, some nitrogen bubbles may be carried out of the storage cylinder with the agent. Nitrogen bubbles carried out of the storage cylinder during a rapid discharge can increase the void fraction in the mixture moving down the discharge pipe and increase the friction drop.

Testing

During discharge tests on ex-USS SHADWELL, measurements were made to permit benchmarking of the calculated flow parameters. Measurements included pressures and temperatures of the fluid in the discharge system, weights of storage cylinders, and concentrations of fire suppression agent in the protected compartment.

The pressure and temperature of the mixture inside the discharge system were measured at two locations in the pipe main (one location about 10 feet downstream of the bank of storage cylinders, and one location about 55 feet downstream of the bank of storage cylinders) and at each discharge nozzle. Nozzle pressures were measured at all nine nozzles during tests that did not involve fires, and at four nozzles during tests involving fires.

For each discharge test, two of the storage containers were suspended fiom load cells and the weights of the cylinders were measured during the discharges. The total number of cylinders used in any given test varied from 4 to 14, depending upon the agent and fill density used. The concentration of agent inside the protected space was measured during the discharge. So-called grab samples of air/agent mixture were collected at known time intervals using evacuated containers with solenoid valves at the containers' openings. The air/agent mixtures were analyzed and the concentration of agent was calculated.

Benchmark Comparisons

The information collected during the discharge tests on ex-USS **SHADWELL** is being used to benchmark TFA's performance in predicting discharge time, nozzle pressures, and distribution of agent flow through flow splits in the piping system.

Discharge Time: We used the temperatures and pressures measured at the nozzles to establish discharge time. Specifically, we used the drop in the temperature of the agent at the nozzle as an indication that the flow had changed from predominantly liquid to predominantly vapor, and we confirmed that the inflection in the nozzle pressure curves occurred at nearly the same time. The actual and predicted discharge times, which are listed in Table 1, were within one second.

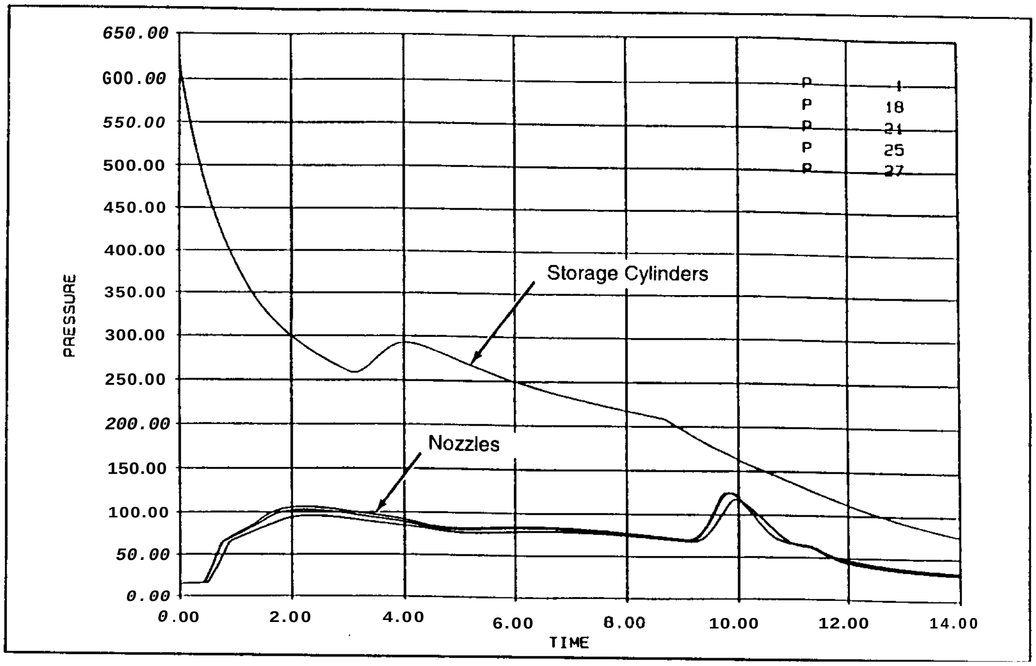
Table 1
Comparison of Actual and Predicted Discharge Times (seconds)

Test	Agent	Actual	Predicted	Difference
HR-20	FM-200	11.1	11.8	0.7
HR-21	FM-200	6.1	5.7	0.4
HR-42	FE-13	9.4	8.8	0.6

Predicted and actual pressure plots are shown in Figures 2 though 7. Note that the plots for FE-13 do not contain a "predicted" plot: we did not retain a predicted plot for this particular case. The plot in Figure 6 is the result of more recent calculations. The more recent calculations include some features to improve overall agreement with test data from both large and small scale tests, and are currently calculating a faster discharge time for this case than we predicted prior to the discharge tests.

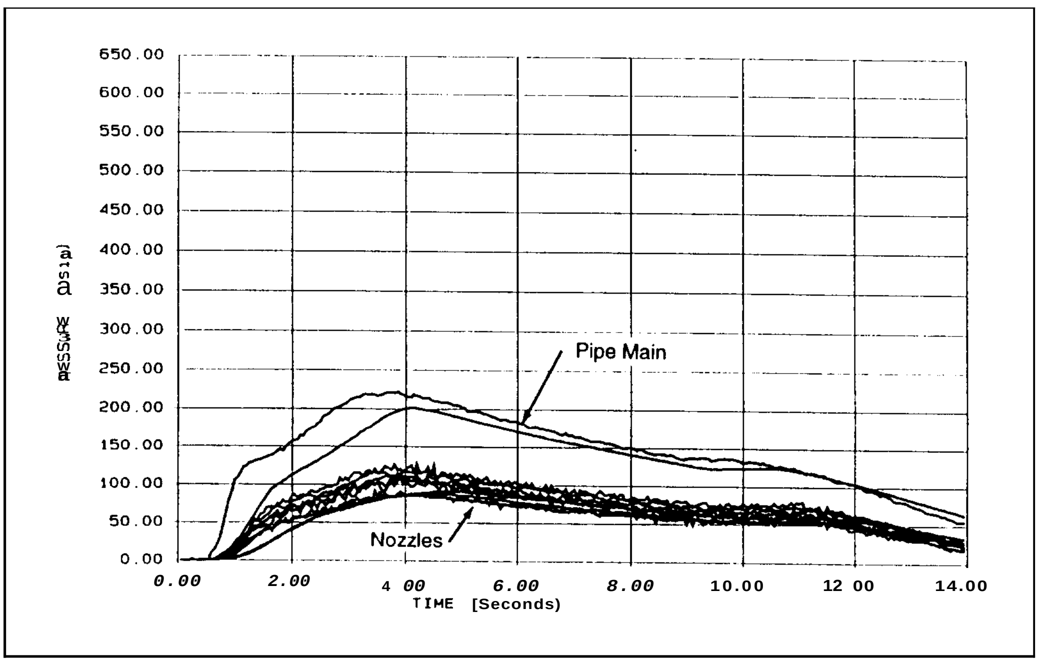
As an additional benchmark for discharge time, the weights of the storage cylinders measured during the actual discharge tests were compared with the predicted weights of agent in the storage cylinders. The actual and predicted times for the cylinders to empty were within one second.

We also used the agent concentration data collected during the discharges as an indirect indication of discharge time. We averaged the concentrations from the five sample locations in the compartment to obtain an estimate of the bulk average concentration in the compartment. Since the grab samples were taken at a number of points in time during the discharge, the level of agent concentration in the space is an indication of the integrated mass flow rate of agent exiting the nozzles. TFA produces plots of integrated mass flow rate through each nozzle: the measured concentrations and the calculated integrated mass flows are compared as a qualitative benchmark for discharge time. Figures 8 and 9 show one typical set of predicted and actual results.



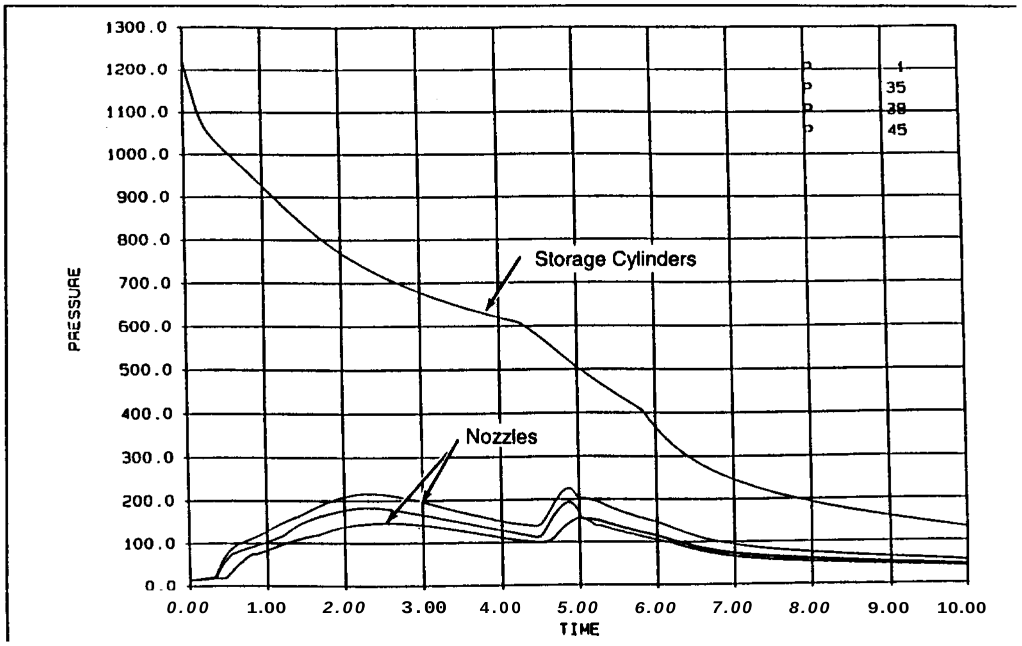
Predicted Pressures - Test HR-20 (FM-200)

Figure 2



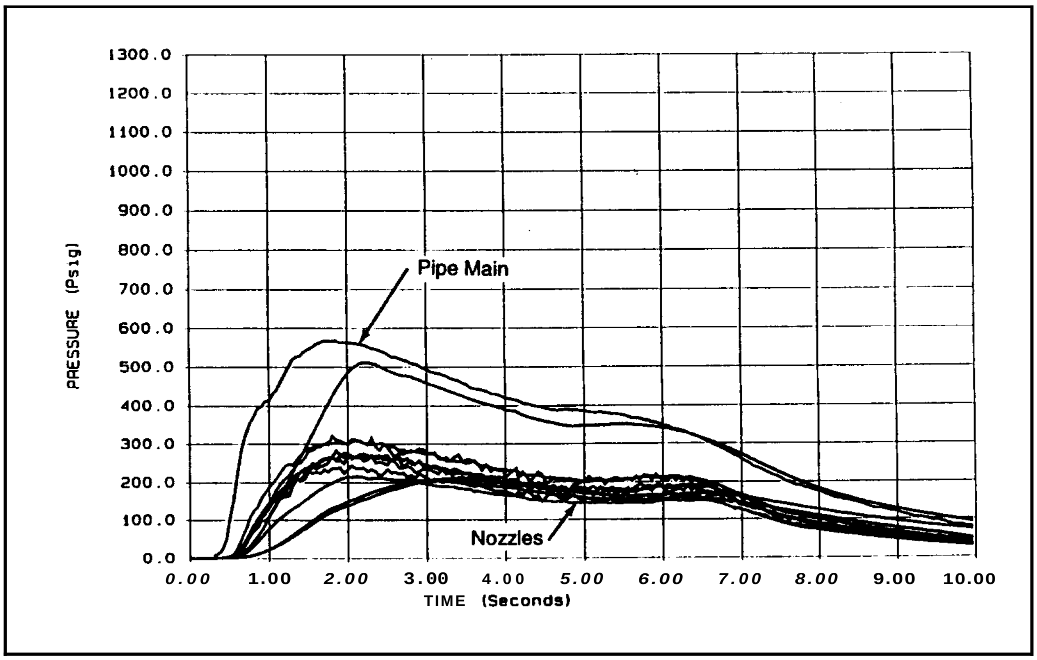
Actual Pressures - Test HR-20 (FM-200)

Figure 3



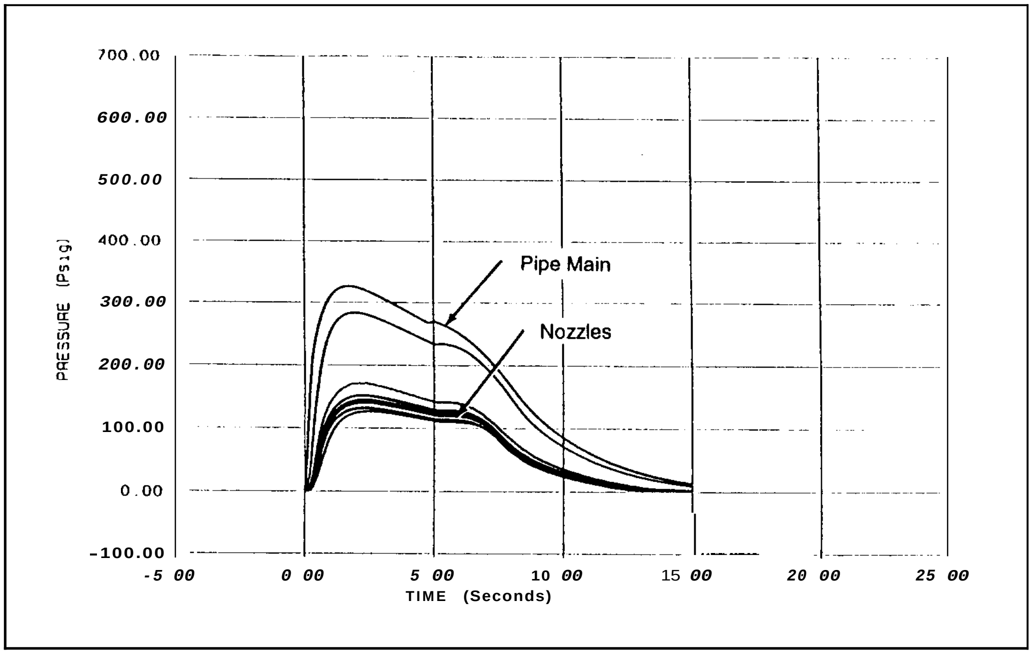
Predicted Pressures - Test HR-21 (FM-200)

Figure 4



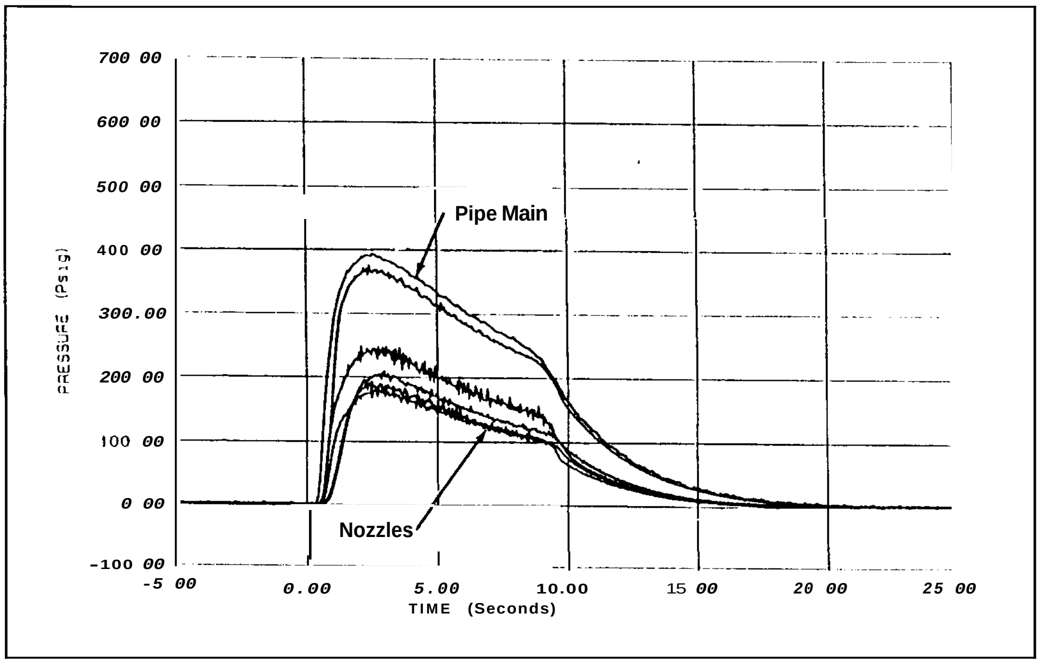
Actual Pressures - Test HR-21 (FM-200)

Figure 5



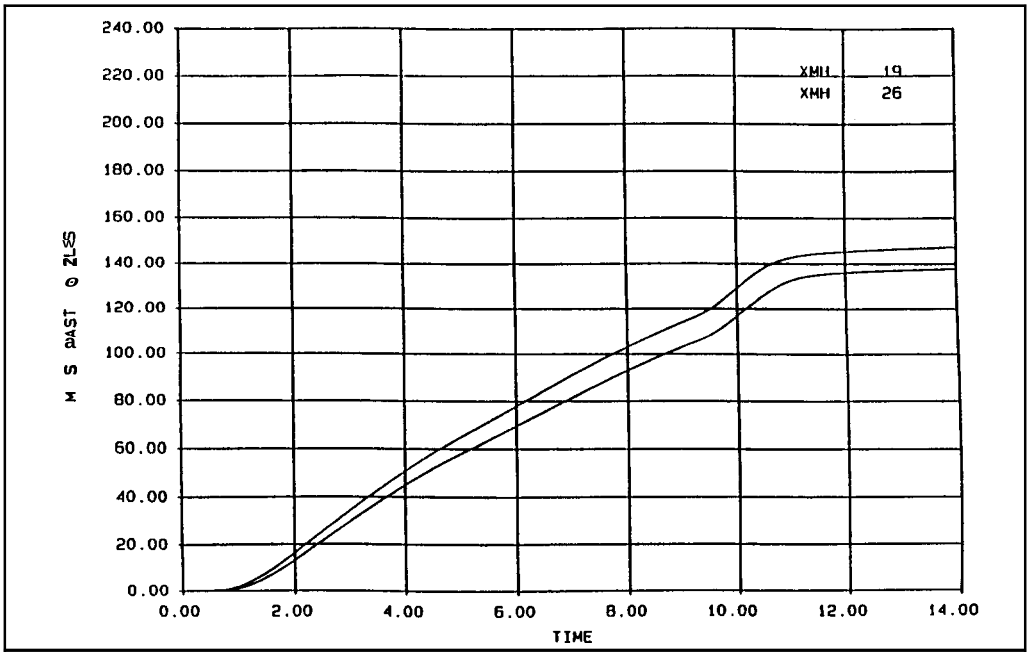
Calculated Pressures - Test HR-42 (FE-13)

Figure 6



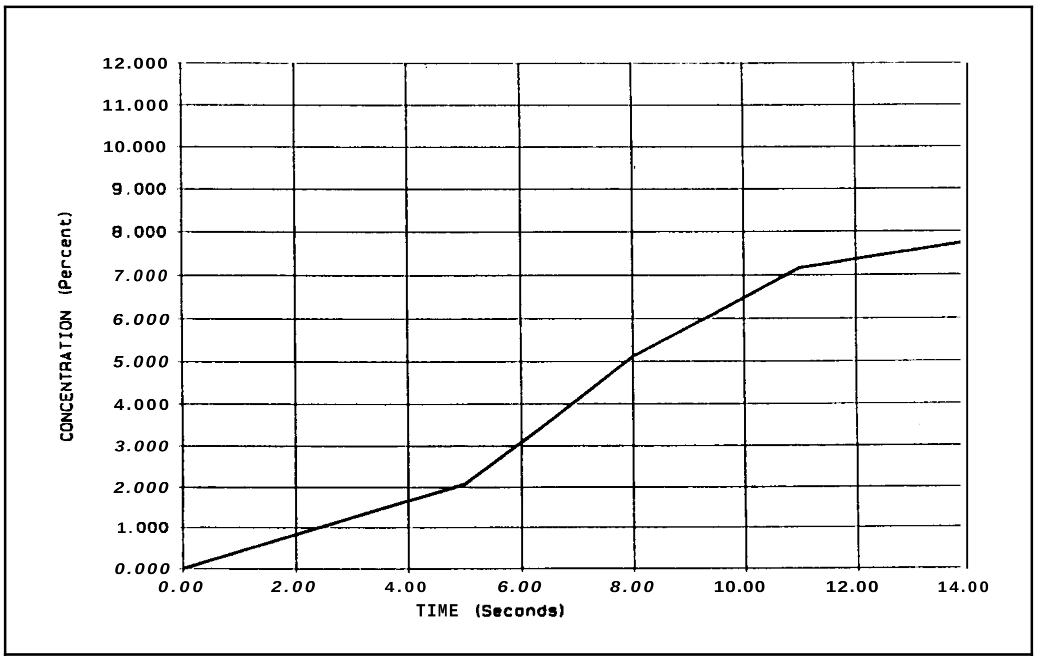
Actual Pressures - Test HR-42 (FE-13)

Figure 7



Predicted Integrated Mass Flow from Two of Nine Nozzles

Figure 8



Actual Avg. Agent Concentration in Compartment - Test HR-20

Figure 9

Comparison of the figures shows that the measured concentrations lag the calculated flow fiom the nozzles by a few seconds, probably due to transport time from the nozzles to the sampling locations. Note that the steady state concentration reached in test HR-20 was about 8.3 percent. The similarities between Figures 8 and 9 suggest that the predicted integrated mass flow rates from the nozzles are reasonably accurate.

Nozzle Pressures: For the actual discharge data, we identified the pressures at the nozzles near the mid-point of the discharge as an approximate, average pressure. The predicted average nozzle pressures listed in Table 2 and reported in Reference 1 are numerical averages of the calculated pressures during the liquid discharge. Predicted pressures were too low in all cases.

Table 2
Comparison of Actual and Predicted Nozzle Pressures (psig)

Test	Agent	Actual	Predicted	Difference
HR-20	FM-200	79	49	-61 %
HR-21	FM-200	199	113	-43 %
HR-42	FE-13	170	126	-25 %

Distribution of the Extinguishing Agent: We used the actual and predicted pressures at the various nozzles to give an indication as to how well the calculations predicted the flow to each nozzle. The actual pressures and predicted pressures were determined as described above in the section titled "Nozzle Pressures." We used the ratios of the individual nozzle pressures to the average of the nozzle pressures as an indication as to how the flow is divided among the nozzles. The comparisons of actual and predicted flow distribution are shown in Tables 3, 4 and 5.

For the discharges that occurred in about 10 seconds, the differences between actual and predicted nozzle pressure ratios are within 10 percent, which suggests that the flow distribution at flow splits in the piping was predicted within 10 percent. For the rapid discharge (6 seconds) in which low fill densities and high nitrogen super pressure were used, the actual pressures differed from the predicted pressures by more than 10 percent (11 and 17 percent) at two nozzles. The affected nozzles (nozzles 5, 6, and 7) are located on the lower level in the aft part of the test compartment. It appears that the flow split at the piping T at the base of the vertical section of pipe supplying these nozzles differed fiom the predicted split for this particular test.

Table 3
Comparison of Actual and Predicted Nozzle Pressure Ratios for Test HR-20 (FM-200)

Nozzle Number	Actual Pressure (psig)	Ratio with Average Pressure	Predicted Pressure (psig)	Ratio with Average Pressure	Difference in Pressure Ratios
1	85	1.07	49	1.00	-6 %
2	79	1.00	49	1.00	0 %
3	90	1.14	52	1.07	-6 %
4	90	1.14	55	1.13	-1 %
5	66	0.83	41	0.84	1 %
6	83	1.05	50	1.03	-2 %
7	80	1.01	50	1.03	2 %
8	70	0.88	46	0.95	7 %
9	70	0.88	46	0.95	7 %

Table 4
Comparison of Actual and Predicted Node Pressure Ratios for Test HR-21 (FM-200)

Nozzle Number	Actual Pressure (psig)	Ratio with Average Pressure	Predicted Pressure (psig)	Ratio with Average Pressure	Difference in Pressure Ratios
1	211	1.06	115	1.02	-4 %
2	198	0.99	115	1.01	2 %
3	234	1.17	131	1.15	-2 %
4	232	1.16	138	1.23	5 %
5	166	0.83	78	0.69	-17 %
6	191	0.96	120	1.07	11%
7	194	0.97	120	1.07	9 %
8	190	0.95	99	0.88	-8 %
9	177	0.89	99	0.88	-1 %

Table 5
Comparison of Actual and Predicted Nozzle Pressure Ratios for Test HR-42 (FE-13)

Nozzle Number	Actual Pressure (psig)	Ratio with Average Pressure	Predicted Pressure (psig)	Ratio with Average Pressure	Difference in Pressure Ratios
2	173	1.02	128	1.06	4 %
4	200	1.18	146	1.21	2 %
5	148	0.87	96	0.79	-9 %
8	158	0.93	114	0.94	1 %

Conclusions

Based on the benchmark comparisons discussed in this paper, the developmental version of TFA used to design the discharge system on ex-USS SHADWELL predicted discharge times within 1 second. Also, TFA predicted agent distribution within 10 percent (based on nozzle pressures) for typical discharges, and within 20 percent for rapid discharges. However, TFA under predicted nozzle pressures by as much as 60 percent.

After the tests on ex-USS SHADWELL, we have been working on improving the accuracy of the nozzle pressures calculated by TFA. A number of features within TFA have been revised. We are currently focusing on our assumptions concerning two-phase flow patterns in the system (dispersed versus separated gas phase). Based on the measured pressures for the flow tests run on ex-USS SHADWELL and elsewhere, it appears that the assumption that the two-phase mixture in the discharge piping has a dispersed pattern provides good results. However, it appears that the assumption of separated gas phase in the storage cylinder is only correct for relatively slow discharges and may lead to poor predictions for faster discharges.

Acknowledgments

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