# ANALYTICAL METHODS FOR MODELING DISCHARGE CHARACTERISTICS OF HALON 1301 FIRE PROTECTION SYSTEMS

Robert N. Coward and John A. Hillaert, MPR Associates, Inc., Washington, DC
Dennis M. McCrory, Naval Sea Systems Command, Washington, DC

## ABSTRACT

A computer program method has been developed to model the thermal hydraulic behavior of fluid systems containing Halon 1301 pressurized by nitrogen. This analysis method has been developed to Serve the U.S. Navy as a design tool for Halon 1301 distribution systems installed on ships. The method is used to predict the two-phase discharge behavior of Halon 1301 in piping systems and determine the consequence of changes in distribution system configuration (such as pipe size, cylinder size, nozzle size and overall arrangement variations) on discharge characteristics (such as nozzle pressure, flow rate, and discharge time).

The method utilizes a control volume and connector approach to solve the transient mass, momentum and energy conservation equations, and is based on first-principle thermodynamics. The method was qualified by comparing calculated results to results from full-scale shipboard discharge tests conducted by the Navy. Both simple and complex distribution systems were used. For each case, agreement between calculated and measured results was good Based on experience obtained with the detailed transient analysis approach, a simplified, easy to utilize approach was developed using a quasi steady-state analysis to determine discharge time and flow distribution for complex systems.

Although developed specifically for Halon 1301, this calculational approach can also be used for Halon alternatives (super-pressurized fluids) by incorporating appropriate equations of state for the alternative fluid and pressurizing agent. This analysis method permits evaluation of discharge characteristics of Halon alternative agents in existing Halon 1301 distribution systems.

## INTRODUCITON

Halon 1301 flooding systems are widely used in U.S. Navy shipboard machinery spaces for fire protection. These systems (or alternative agent systems) may provide the only effectual means to fight a three-dimensional fuel spray fire in a highly confined shipboard machinery space. prior to 1989, all Navy-installed Halon flooding systems required a full acceptance discharge test to verify that the performance requirement was met by the system design. In 1988, the Navy sponsored an engineering assessment into improved analytical approaches to determine Halon discharge effectiveness. The goal of this assessment was to provide the Navy with a reliable design tool to assess the distribution effectiveness of complex Halon systems without performing costly full-scale acceptance testing. Previous Navy experience with shipboard installations had indicated some problems with poor distribution of Halon in the compartments, even though the average concentration of agent in the compartment was typically within specified design requirements.

This paper describes a system of computer programs that analytically model two-phase flow of Halon 1301 from nitrogen loaded storage cylinders through a piping distribution system to discharge nozzles. The results from these programs compare favorably to results from actual full-scale Halon 1301 discharge tests.

## ANALYTICAL METHOD

The primary analytical method to address the Halon 1301 transient two-phase flow problem consists of the use of a system of computer programs (named TFHAL) designed to model thermal hydraulic behavior of fluid systems containing Halon 1301 and nitrogen. The solution technique uses a control volume and flow connector approach to solve the transient mass, energy and momentum conservation equations. The analytical method 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 to determine the mass and energy in each 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 Halon 1301 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 details of the analytical approach are discussed in Reference (1). In this analytical method, the Halon-nitrogen system is considered to include Halon liquid and vapor, nitrogen gas dissolved in the liquid Halon, and nitrogen gas mixed with the Halon vapor. Seven equations, which are integrated forms of the conservation equations, are used to describe the system. These equations reduce to:

## Conservation of Mass of Halon

$$\dot{MH}_i = \Sigma\,(1 - XG_k)\,W_k$$

where the summation is over all flow connectors into and out of each control volume, subscripts i and j refer to control volumes and subscript k refers to a flow connector, and

| | |
|---|---|
| MH | is the mass of Halon, |
| XG | is the fraction of the system that is nitrogen (mass of nitrogen/total mass), and |
| W | is the mass flow rate in a connector. |

## Conservation of Energy of Halon

$$\dot{UH}_i = \Sigma hH_k\,(1 - XG_k)\,W_k - QHG_i$$

where:

| | |
|---|---|
| UH | is the energy of the Halon, |
| hH | is the specific enthalpy of Halon, and |
| QHG | is the heat energy transferred from Halon to nitrogen. |

## Conservation of Mass of Dissolved Nitrogen

$$\dot{MGL}_i = -\,SLG_i + \Sigma\,XG_k\,(1 - XGV_k)\,W_k$$

where:

| | |
|---|---|
| MGL | is the mass of nitrogen dissolved in the liquid Halon, |
| SLG | is the rate at which dissolved nitrogen comes out of solution from the liquid phase to the vapor phase (at a rate proportional to the difference between the current |

| | |
|---|---|
| | quantity of nitrogen dissolved in the liquid and the quantity predicted by Henry's Law at equilibrium), and |
| XGV | is the fraction of the nitrogen that is in the vapor phase (mass of nitrogen gas/mass of nitrogen). |

### Conservation of Energy of Dissolved Nitrogen

$$\dot{UGL}_i = -hG_i + SLG_i + \sum hG_k \, XG_k \, (1 - XGV_k) \, W_k + QHG_i \, (1 - XGV_i)$$

where:

| | |
|---|---|
| ULG | is the energy of the nitrogen dissolved in the liquid Halon, and |
| hG | is the specific enthalpy of nitrogen. |

### Conservation of Mass of Nitrogen Gas

$$\dot{MGV}_i = SLG_i + \sum \; XG_k \, XGV_k \, W_k$$

where:

| | |
|---|---|
| MGV | is the mass of nitrogen gas. |

### Conservation of Energy of Nitrogen Gas

$$\dot{UGV}_i = hG_i \, SLG_i + \sum hG_k \, XG_k \, XGV_k \, W_k + QHG_i \, XGV_i$$

where:

| | |
|---|---|
| UGV | is the energy of the nitrogen gas. |

### Conservation of Momentum (Halon and Nitrogen Combined)

$$\dot{W}_k = (1/L_k) \, (P_i - P_j - F_k \, W_k \, [\, W_k \,] + FE_i \, WN_i^2 - FE_j \, WN_i^2 + HD_k)$$

where:

| | |
|---|---|
| L | is the inertial length of the connector, |
| P | is the pressure, |

**F** is the pressure drop coefficient for friction and form loss,
**FE** is the expansion pressure drop coefficient,
**WN** is the mass flow rate at the center of a control volume, and
**HD** is the elevation pressure head.

The integrated equations can be written in a generalized form as a set of first order differential equations by defining a state vector for the system. The set of differential equations is then solved using a partially implicit backward difference technique. The pressure, temperature, enthalpy, density and void fraction in each control volume are obtained from the mass, energy and volume of each control volume using appropriate equations of state. The solution is generated incrementally over each time step until the required time interval is completed.

## QUALIFICATION OF METHOD

To demonstrate the use of this analytical method, a two nozzle balanced Halon distribution system and a two nozzle unbalanced Halon distribution system were analyzed and tested. The balanced system consisted of approximately 75 feet of schedule 80 pipe of varying diameters (1" to 3" nominal) and two symmetrically placed nozzles, as shown in Figure 1. The Halon cylinder contained 125 pounds of Halon 1301 with a fill density of 70 lbs/ft$^3$, pressurized with nitrogen to 600 psig. Each nozzle consisted of four orifices with a diameter of 0.4 in, or a total orifice area of 0.5 in$^2$ per nozzle. The system was divided into 15 control volumes and 14 flow connectors. The unbalanced system was identical in geometry to the balanced system, except that one of the nozzles was replaced by a smaller nozzle with an orifice area of 0.196 in$^2$.

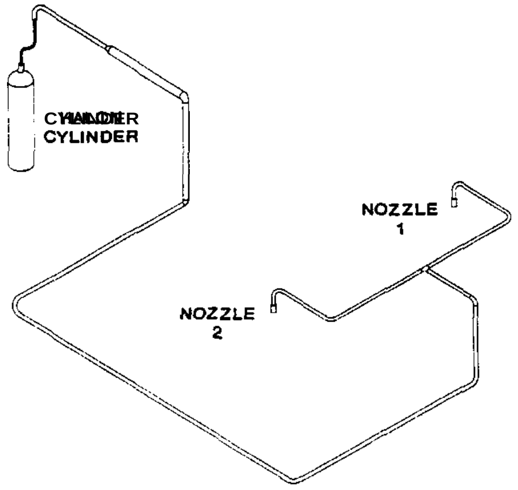

Figure 1 - General Configuration of the Two Nozzle Halon Distribution System

The TFHAL calculated results for nozzle pressures and flow distributions as compared to the measured data **for** the unbalanced system are provided in Figures **2** through **4.** These results indicate:

- The analytical model accurately predicts the distribution of flow to each nozzle,
- The analytical model tends to predict the time of the discharge transient within about 10 percent, and
- The analytical model predicts nozzle pressures within about **20** percent of those actually measured.

The analytical method was also demonstrated on a highly complex system through an analysis of a **full** scale Halon discharge into a main engine room on a modern guided missile cruiser. This distribution system consists of eleven 125-pound storage cylinders in a banked configuration that feed a common header and discharge piping network. The model consisted of approximately 600 feet of pipe grouped into 93 control volumes. Figures 5 through **7** show a comparison **of** the calculated and measured pressures at the main discharge header and upstream and downstream of the main Halon stop valve.

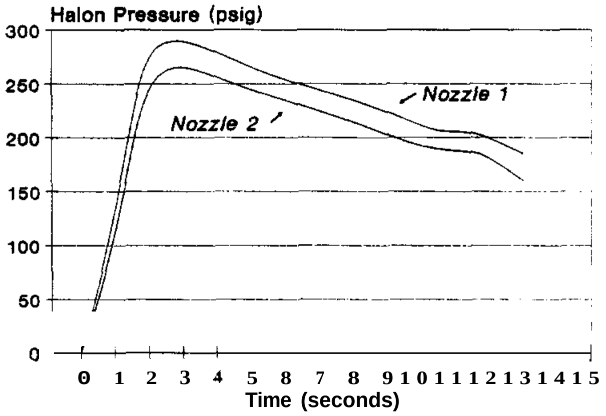

Figure **2** - TFHAL Predicted Nozzle Pressure for Unbalanced System

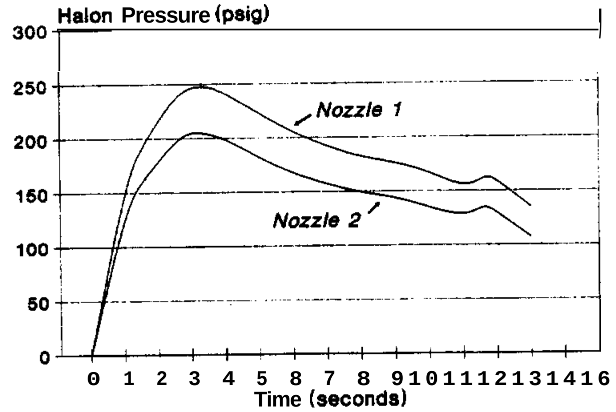

Figure 3 - Measured Nozzle Pressure for Unbalanced System

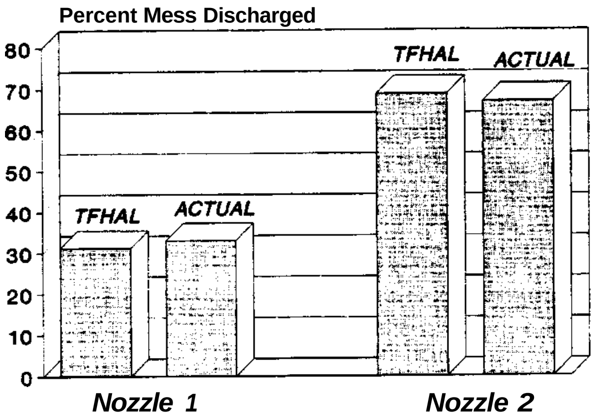

Figure 4 - Comparison of Nozzle Flow Distribution for Unbalanced System

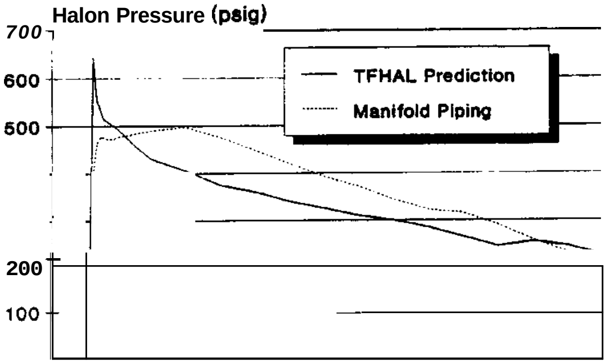

Figure 5 - Comparison of TFHAL Results to Test Data from a Complex Halon Distribution System

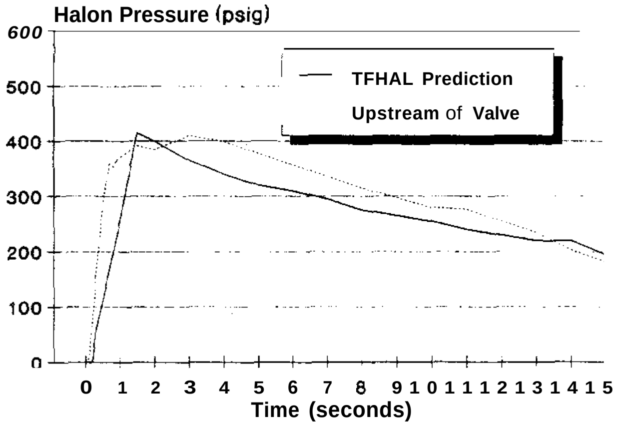

Figure 6. Comparison of TFHAL Results to Test Data from a Complex Halon Distribution System

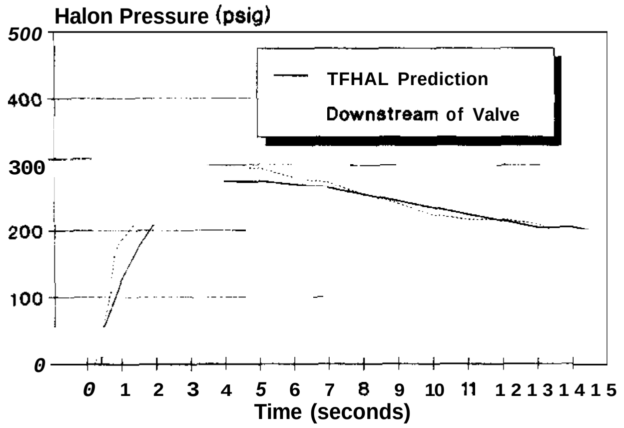

Figure 7. Comparison of TFHAL Results to Test Data from a Complex Halon Distribution System

For this system, peak predicted pressures were within about 10 percent of the measured pressures and generally show good agreement with the test results. An enigma with the calculated pressure at the very early part of the transient was that the model over predicts the pressure spike by 30% due to an artificial water hammer effect that the calculation predicts will occur in the manifold when the control volume fills with liquid Halon. A significant water hammer event was not observed during the test. This anomaly had no significant effect on the calculated flow distribution or the overall results.

The calculated nozzle discharge times for this complex system correlated well with the test data. The calculated nozzle pressures show a pressure transition region occurring at 14 to 16 seconds, caused by the nearly complete flashing of the liquid Halon remaining in the piping system. The shipboard test data indicated a marked change in nozzle discharge temperature at about 14 seconds into the transient, which is indicative of flashing and local cooling at the region of the nozzles.

## SIMPLIFIED ANALYTICAL METHOD

Experience in development of the transient flow analysis system, described above, indicated that a quasi steady-state approach to the solution method was feasible for determination of fundamental discharge characteristics, such as overall discharge time, average nozzle pressures and mass flow rate through each branch of the system. Another computer program, named FLONET, Reference (2), was developed to analyze system discharge characteristics using this simplified approach. In **FLONET,** the average thermodynamic conditions in the storage cylinder(s) and distribution piping during a blowdown are used *to* calculate the Halon discharge time, the system mass flow rates and the system pressures. This simplification (using average conditions) is possible due to the nature of the blowdown transient.

The discharge of Halon 1301 from nitrogen pressurized cylinders results in a two-phase discharge of Halon out of the cylinders and through the distribution piping. The pressure/time history in a typical cylinder is shown in Figure 8. Upon actuation, the cylinder pressure decreases rapidly as the distribution piping is filled with agent. Once the piping is filled, the flow resistance across the nozzles and in the piping reduces the discharge rate. The rate at which the Halon is discharged through the nozzle during the primary blowdown period is relatively constant. Finally, after the liquid Halon has been emptied from the cylinders (i.e., the level of Halon liquid falls below the bottom of the syphon tube), the cylinder pressure decreases rapidly.

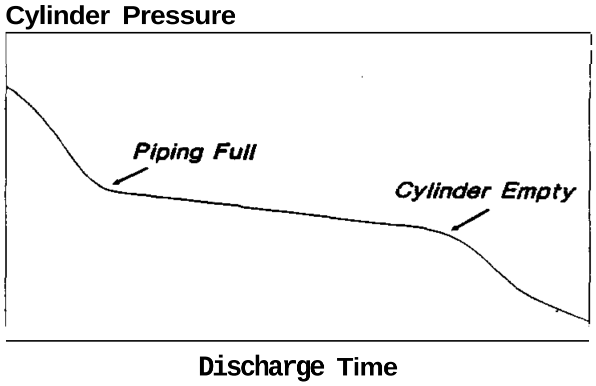

Figure 8 - Typical Pressure/Time History for a Halon Cylinder During a Discharge

Figure 9 is representative of the mass flow rate of Halon out of a typical cylinder during blowdown. After the piping has been filed, the mass flow rate of Halon out of the cylinder is predictable and varies linearly with time until nearly all the liquid Halon has been discharged from the cylinder. Thus, during this discharge period, the change in the cylinder conditions is relatively small and average conditions can be used as a fair representation of the event.

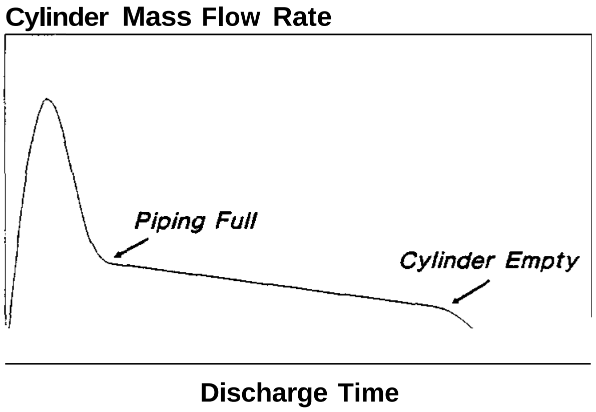

Figure 9 - Typical Halon Cylinder Mass Flow Rate During a Discharge

Use of this quasi steady-state solution method contributes significantly to the utility of the approach by simplifying the model input requirements and minimizing the computation time. For example, the modeling data for a relatively complex dismbution system consisting of over 200 feet of pipe and 10 nozzles can be fully input and analyzed by FLONET in less than one hour using a personal computer.

FLONET calculates the discharge conditions in the dismbution system by dividing the distribution piping into control volumes which are linked by flow connectors. The mass flow rates in each connector and the pressure in each control volume are calculated by iteratively solving the steady-state conservation of energy, mass, and momentum equations for the average cylinder conditions.

For steady-state flow through piping systems, neglecting heat transfer effects, these equations reduce to:

### Conservation of Energy

$$\sum W_k h_k = 0$$

where the summation is over all flow connectors into and out of each control volume, and

$W$ is the mass flow rate in a connector, and
$h$ is the enthalpy of the mass flow in the connector.

### Conservation of Mass

$$\sum W_k = 0$$

### Conservation of Momentum

$$\Delta P_k = F_k W_k^2$$

where:

$\Delta P$ is the pressure drop in the flow connector, and
$F$ is the hydraulic loss form factor for the connector.

The hydraulic loss form factor, F, is used to account for the irreversible pressure losses due to flow through pipes, pipe fittings, and nozzles. This factor is calculated as the product of a single-phase form loss factor and a two-phase multiplier. The two-phase multiplier accounts for variations in the hydraulic pressure drop due to different two-phase flow regimes and is a function of the fluid properties in the connectors.

As can be seen in the momentum equation, the effects of body forces (gravity) have been neglected for this calculation. This approximation, which significantly reduces the quantity of input data required to describe a piping system, was shown to have very little effect on the accuracy of the flow and pressure solution.

Choked flow is common in Halon distribution systems, especially at the nozzles. FLONET includes correlations for choked mass flow rates of Halon. Each solution is compared to these choked flow rates, and if any calculated flow rate is greater than the choked flow rate, the flow rate is reduced and the iterative solution continues until all flow rates are equal to or below the choked mass flow rates.

The solution method used in FLONET was verified by comparing FLONET results to results from the U.S. Navy full-scale discharge testing described above, to National Fire Protection Association methods, and to the detailed transient analysis program TFHAL results. In each case, agreement was good. A comparison between analytical and test results are summarized in Table 1 for the two nozzle unbalanced system. FLONET is currently used by Navy engineers as a design assessment tool for Halon 1301 distribution systems.

Table 1.
Comparison of Results Between Analytical Methods and
Test Data for a Simple Unbalanced System

| | TFHAL | FLONET | TEST |
|---|---|---|---|
| Discharge Time* (sec) | 11 | 13 | 12 |
| % Flow | | | |
| Nozzle 1 | 31% | 30% | 33% |
| Nozzle 2 | 69% | 70% | 67% |
| Avg. Pressure (psig) | | | |
| Nozzle 1 | 230 | 250 | 225 |
| Nozzle 2 | 203 | 233 | 185 |

* Determination of discharge times is based on NFPA methods, but is considered to be somewhat subjective.

## CONCLUSIONS

Since the analytical methods discussed in this paper are based on first-principle thermodynamics and fundamental equations of state for the fluids (Halon and nitrogen), the techniques can readily be applied to other types of fluid systems. Similar analytical techniques have been successfully used in the past to solve complex two-phase steam/water system problems in nuclear and fossil power application as well as other complex hydraulic applications, Reference **(3).** The analytical methods described can similarly be applied to Halon alternative agents.

As Halon alternatives are designated, there will be a need to assess the capability to release the agent through a piping distribution system and to define achievable discharge requirements regarding nozzle pressures and discharge times. The methods used in the TFHAL and FLONET computer programs provide a means to effectively analyze distribution characteristics of new agents and to assess the impact of the use of new agents on design practices. These methods can also be used as a design tool to assess the impact of using Halon alternatives in existing Halon distribution systems. With minimal effort, an analytical approach can be developed to predict the discharge characteristics of Halon alternatives as long as equations of state (or fluid properties) are available for the alternative agents.

## ACKNOWLEDGMENTS

The work reported in this paper was sponsored by the Naval Sea Systems Command Fire Protection Division, Code 56Y5, Washington, DC.

## REFERENCES

1. **TFHAL,** Version 1.10, ***A Computer Thermal Hydraulic Analysis System for the Transient Flow of Halon*** 1301, Prepared for NAVSEA 56Y5 by MPR Associates, Inc., October 1989.
2. **FLONET, HALON 1301, Version 1.0,** ***Two-Phase Flow and Pressure Loss Analysis for Halon 1301 Piping Distribution Networks,*** Prepared for NAVSEA 56Y5 by MPR Associates, Inc., December 1990.
3. Giesecke, ***H. D., An Analytic Technique for the Calculation of Transient Thermal Hydraulic*** *Loads* ***on Piping Systems,*** ASME Journal 89-JPGC/Pwr-23.